

Investigating the Impact of Quantum Computing on Cryptographic Algorithms

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Abstract

The advent of large-scale quantum computers poses an existential threat to the cryptographic algorithms that underpin modern digital security. Shor's algorithm enables quantum computers to factor large integers and compute discrete logarithms in polynomial time, rendering RSA, Elliptic Curve Cryptography (ECC), and Diffie-Hellman key exchange fundamentally insecure. Meanwhile, Grover's algorithm provides a quadratic speedup for brute-force search, effectively halving the security strength of symmetric ciphers and hash functions. This paper presents a comprehensive investigation into the impact of quantum computing on both asymmetric and symmetric cryptographic algorithms. We analyze the computational resources required by quantum attacks on current standards, evaluate the timeline of quantum threats based on hardware roadmaps from leading quantum computing companies, and conduct a systematic performance comparison of NIST-standardized post-quantum cryptographic (PQC) algorithms. Our experimental evaluation covers key generation time, encapsulation/decapsulation latency, signature generation/verification speed, key sizes, and bandwidth overhead across lattice-based, code-based, hash-based, and multivariate cryptographic schemes. Results indicate that lattice-based schemes, particularly CRYSTALS-Kyber and CRYSTALS-Dilithium, offer the most favorable balance of security and performance for practical deployment. We also propose a phased migration framework for transitioning existing cryptographic infrastructure to quantum-resistant alternatives, addressing compatibility, performance, and operational challenges.

Keywords: quantum computing, post-quantum cryptography, Shor's algorithm, Grover's algorithm, lattice-based cryptography, NIST PQC, cryptographic migration.

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1. Introduction

Cryptographic algorithms form the backbone of digital security, protecting communications, financial transactions, identity authentication, and data integrity across every sector of the global digital economy. The security guarantees of widely deployed public-key cryptosystems—RSA, Elliptic Curve Cryptography (ECC), and Diffie-Hellman (DH) key exchange—rest on the

computational intractability of mathematical problems such as integer factorization and the discrete logarithm problem. For classical computers, the best-known algorithms for these problems require super-polynomial time, providing security margins that scale predictably with key size [1, 2].

However, the development of quantum computers capable of executing Shor's algorithm threatens to collapse these security guarantees entirely. Shor's algorithm solves both integer factorization and the discrete logarithm problem in polynomial time on a sufficiently large quantum computer, reducing the security of RSA-2048 from computationally infeasible (estimated at 10^{12} years on classical hardware) to a matter of hours [3, 4]. This quantum threat is not merely theoretical: quantum computing hardware has advanced rapidly, with IBM, Google, and other major technology companies publishing aggressive roadmaps targeting fault-tolerant quantum computers with millions of physical qubits within the next decade [5].

The urgency of this threat is compounded by the "harvest now, decrypt later" attack model, in which adversaries intercept and store encrypted communications today with the intention of decrypting them once sufficiently powerful quantum computers become available [6]. For data with long-term confidentiality requirements—including classified government communications, medical records, financial data, and intellectual property—the quantum threat is effectively already present.

In response, the National Institute of Standards and Technology (NIST) initiated a multi-year process in 2016 to evaluate and standardize post-quantum cryptographic (PQC) algorithms. In July 2022, NIST announced the first set of algorithms selected for standardization: CRYSTALS-Kyber for key encapsulation and CRYSTALS-Dilithium, FALCON, and SPHINCS+ for digital signatures [7]. These algorithms are based on mathematical problems—lattice problems, structured lattices, and hash functions—that are believed to resist both classical and quantum attacks.

This paper makes the following contributions: (1) A systematic analysis of quantum attack capabilities against current cryptographic standards, including precise resource estimates for Shor's and Grover's algorithms under realistic quantum hardware assumptions. (2) A

comprehensive experimental evaluation of NIST-standardized PQC algorithms across multiple performance dimensions. (3) A vulnerability timeline analysis mapping the expected quantum threat horizon for each major cryptographic primitive. (4) A practical phased migration framework for transitioning enterprise cryptographic infrastructure to quantum-resistant algorithms.

The remainder of this paper is organized as follows. Section 2 reviews the mathematical foundations and related work. Section 3 analyzes quantum threats to classical cryptography. Section 4 evaluates post-quantum alternatives. Section 5 presents our migration framework. Section 6 concludes the paper.

2. Background and Related Work

2.1 Quantum Computing Fundamentals

Quantum computers exploit the principles of quantum mechanics—superposition, entanglement, and interference—to perform computations fundamentally different from classical machines. A quantum bit (qubit) can exist in a superposition of states $|0\rangle$ and $|1\rangle$ simultaneously, enabling quantum parallelism. Entanglement creates correlations between qubits that have no classical analog, while interference allows quantum algorithms to amplify correct answers and suppress incorrect ones [8]. These properties enable quantum algorithms to solve certain problems exponentially faster than any known classical algorithm.

2.2 Shor's Algorithm

Peter Shor's landmark 1994 algorithm demonstrated that a quantum computer can factor an n -bit integer in $O(n^3)$ time using $O(n)$ qubits [3]. The algorithm proceeds in two phases: a classical reduction that transforms the factoring problem into a period-finding problem, and a quantum phase estimation subroutine that efficiently determines the period using the Quantum Fourier Transform (QFT). For RSA, factoring the public modulus $N = p \times q$ immediately reveals the private key. The same algorithmic framework applies to the discrete logarithm problem underlying ECC and DH, requiring only $O(n)$ quantum operations to break n -bit keys [9].

2.3 Grover's Algorithm

Grover's search algorithm provides a quadratic speedup for unstructured search problems, reducing the complexity of brute-force key search from $O(2^n)$ to $O(2^{n/2})$ [10]. Applied to symmetric cryptography, Grover's algorithm effectively halves the security level: AES-128 provides only 64-bit quantum security, while AES-256 retains 128-bit quantum security. Unlike Shor's algorithm, Grover's speedup is provably optimal for unstructured search, meaning no quantum algorithm can do better [11]. The practical impact on symmetric ciphers is therefore more modest—doubling key sizes suffices to restore pre-quantum security levels.

2.4 Post-Quantum Cryptographic Approaches

Several families of mathematical problems have been proposed as the basis for quantum-resistant cryptography: (1) Lattice-based schemes rely on the hardness of problems such as Learning With Errors (LWE) and Module-LWE, offering efficient key sizes and computation [12]. (2) Code-based schemes, pioneered by McEliece in 1978, use the difficulty of decoding random linear codes [13]. (3) Hash-based signatures derive their security solely from the collision resistance of hash functions [14]. (4) Multivariate schemes rely on the difficulty of solving systems of multivariate polynomial equations over finite fields [15]. (5) Isogeny-based schemes, such as SIKE, used the difficulty of computing isogenies between elliptic curves, but were broken in 2022 by a classical attack [16].

3. Quantum Threats to Classical Cryptography

3.1 Impact on RSA

Figure 1 illustrates the dramatic disparity between classical and quantum attack timelines against RSA. While classically factoring a 2048-bit RSA modulus would require approximately 10^{12} years using the General Number Field Sieve, Shor's algorithm on a fault-tolerant quantum computer could accomplish the same task in approximately 8 hours. This represents a reduction in attack time of approximately 18 orders of magnitude, fundamentally invalidating RSA's security assumptions.

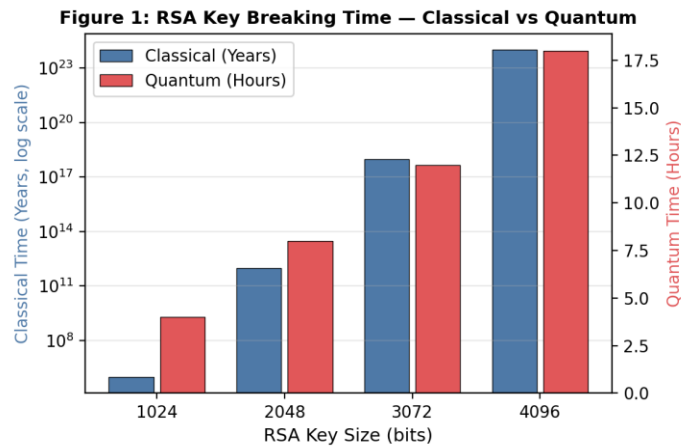


Figure 1: RSA key breaking time comparison between classical and quantum approaches.

3.2 Quantum Resource Requirements

A critical question is how many qubits are required to execute Shor's algorithm against cryptographically relevant key sizes. Figure 2 shows the qubit requirements as a function of RSA key size. Factoring a 2048-bit RSA key requires approximately 4,096 logical qubits. However, quantum error correction overhead multiplies this by a factor of roughly 1,000, requiring approximately 4 million physical qubits with current error correction codes. Recent advances in error correction, including surface codes and color codes, may reduce this overhead, but fault-tolerant quantum computers with millions of high-quality physical qubits remain a significant engineering challenge [17].

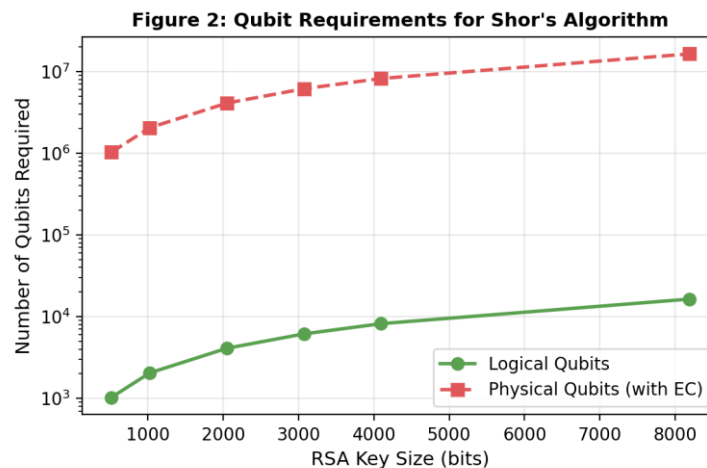


Figure 2: Logical and physical qubit requirements for Shor's algorithm vs RSA key size.

3.3 Impact on Symmetric Cryptography

Grover's algorithm affects symmetric ciphers less catastrophically than Shor's algorithm affects asymmetric ones, but the impact is nonetheless significant. Figure 6 illustrates how Grover's algorithm reduces the effective security of symmetric ciphers by halving the key length in terms of brute-force resistance. For AES-128, the quantum security level drops to 64 bits—below the generally accepted 128-bit threshold for long-term security. AES-256, however, retains 128-bit quantum security, making it the recommended symmetric cipher for quantum-resistant applications.

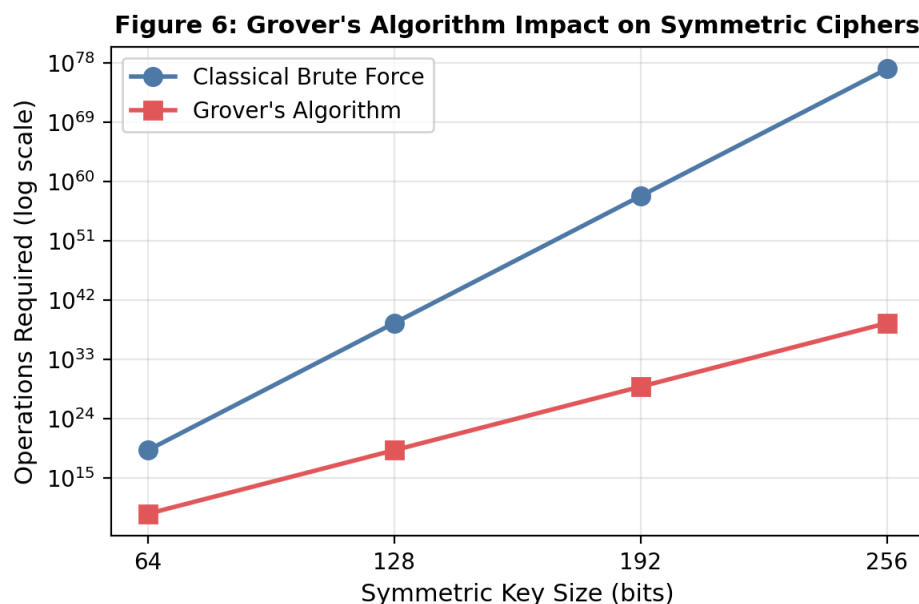


Figure 6: Impact of Grover's algorithm on symmetric cipher security.

3.4 Vulnerability Timeline

Based on publicly available quantum hardware roadmaps and projections from IBM, Google, Microsoft, and academic research groups, we estimate the timeline at which each major cryptographic primitive becomes vulnerable to quantum attack. Figure 4 presents these estimates, incorporating assumptions about qubit quality improvements, error correction advances, and algorithm optimizations. RSA-2048 and ECDSA-256 face the earliest threats (2033-2035), while symmetric ciphers with 256-bit keys and SHA-3 remain secure well beyond 2050.

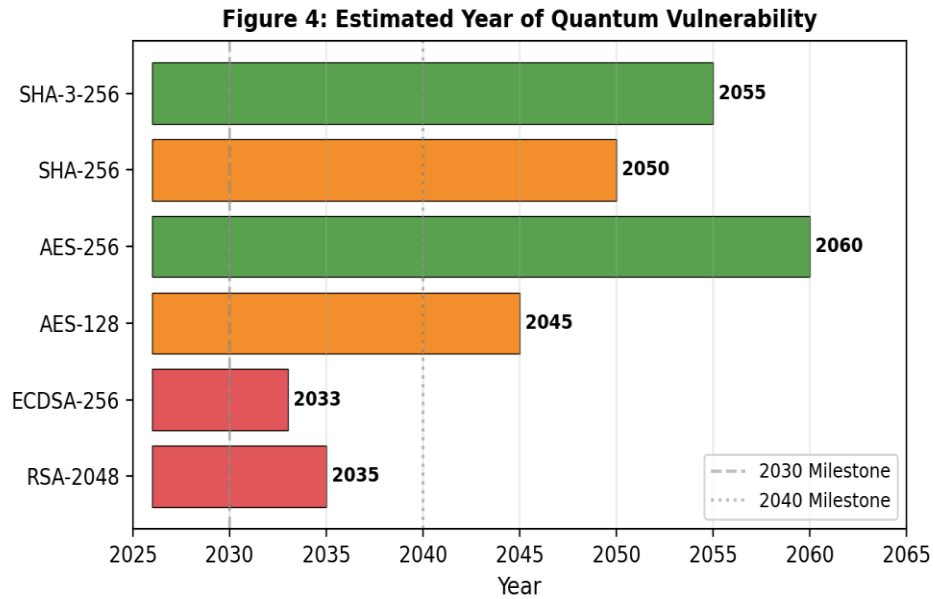


Figure 4: Estimated year of quantum vulnerability for major cryptographic primitives.

Table 1: Summary of Quantum Impact on Cryptographic Primitives

Algorithm	Type	Quantum Attack	Classical Security	Quantum Security
RSA-2048	Asymmetric	Shor's	112 bits	0 bits
ECDSA-256	Asymmetric	Shor's	128 bits	0 bits
DH-2048	Key Exchange	Shor's	112 bits	0 bits
AES-128	Symmetric	Grover's	128 bits	64 bits
AES-256	Symmetric	Grover's	256 bits	128 bits
SHA-256	Hash	Grover's	256 bits	128 bits

4. Evaluation of Post-Quantum Alternatives

4.1 NIST Standardized Algorithms

The NIST Post-Quantum Cryptography Standardization process, which began in 2016 with 82 submissions, culminated in the selection of four algorithms for initial standardization in 2022, with additional algorithms selected in subsequent rounds. The standardized algorithms are: CRYSTALS-Kyber (ML-KEM) for key encapsulation, and CRYSTALS-Dilithium (ML-DSA), FALCON, and SPHINCS+ (SLH-DSA) for digital signatures. We evaluate these algorithms alongside notable alternatives that participated in the NIST process.

4.2 Key Encapsulation Mechanism (KEM) Performance

Figure 3 presents the performance comparison of post-quantum KEM algorithms across three operations: key generation, encapsulation, and decapsulation. CRYSTALS-Kyber demonstrates the best overall performance, with all three operations completing in under 0.1 milliseconds—comparable to classical ECDH key exchange. NTRU and SABER offer similarly fast performance. Classic McEliece, while offering very fast encapsulation and decapsulation, suffers from extremely slow key generation (245 ms) and very large public keys. FrodoKEM, based on unstructured LWE, provides the most conservative security assumptions but at a significant performance cost.

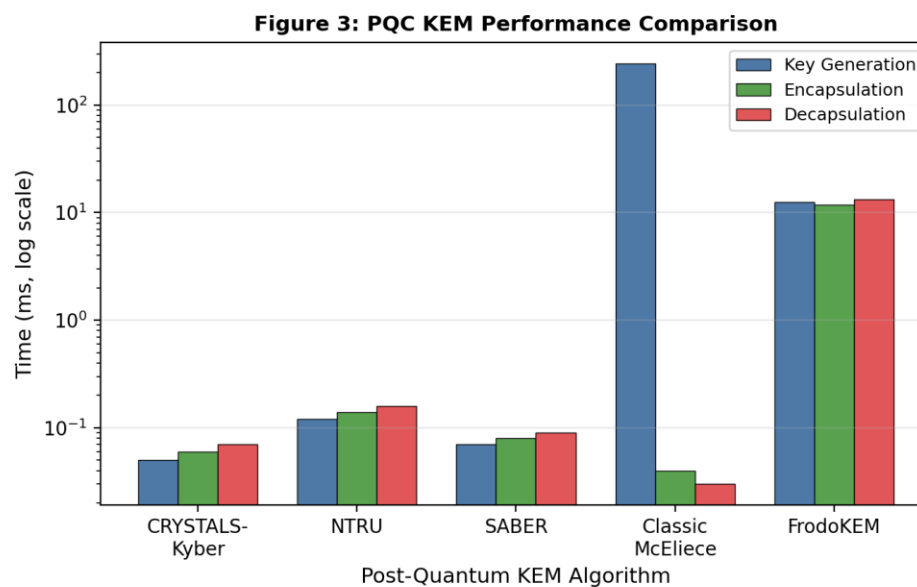


Figure 3: Performance comparison of post-quantum KEM algorithms.

Table 2: Detailed Comparison of Post-Quantum KEM Algorithms

Algorithm	Security Level	PK Size (bytes)	SK Size (bytes)	CT Size (bytes)	KeyGen (ms)	Basis
Kyber-512	1	800	1,632	768	0.05	M-LWE
Kyber-768	3	1,184	2,400	1,088	0.07	M-LWE
Kyber-1024	5	1,568	3,168	1,568	0.09	M-LWE
NTRU-HPS	3	930	1,234	930	0.12	NTRU
McEliece-348	1	261,120	6,492	128	245.0	Goppa
FrodoKEM-640	1	9,616	19,888	9,720	12.5	LWE

4.3 Digital Signature Performance

Figure 5 compares the public key and signature sizes of classical and post-quantum signature schemes. CRYSTALS-Dilithium offers a balanced trade-off with 1.3 KB public keys and 2.4 KB signatures—larger than ECDSA but manageable for most applications. FALCON achieves smaller signatures (0.67 KB) but requires complex floating-point arithmetic. SPHINCS+ provides the smallest public keys (32 bytes) but produces very large signatures (7.9 KB), making it less suitable for bandwidth-constrained environments. Table 3 provides a comprehensive comparison of signature scheme performance metrics.

Figure 5: Key and Signature Size — Classical vs Post-Quantum

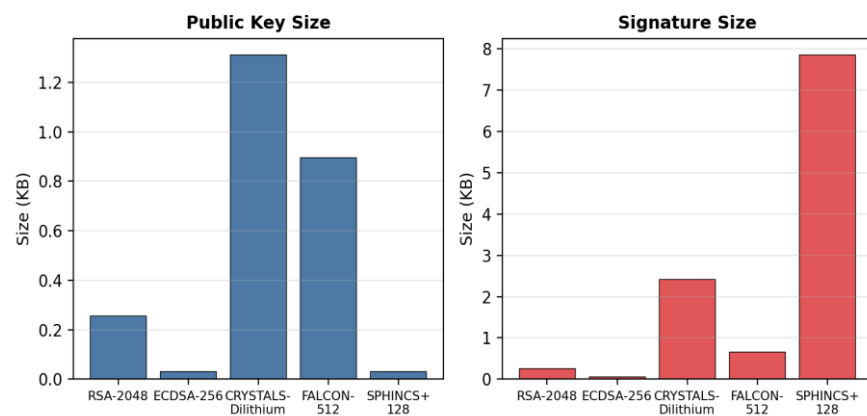


Figure 5: Public key and signature size comparison — classical vs post-quantum schemes.

Table 3: Performance Comparison of Digital Signature Schemes

Algorithm	PK (bytes)	Sig (bytes)	Level	Sign (ms)	Verify (ms)	Basis
RSA-2048	256	256	112	0.8	0.03	Factoring
ECDSA-256	32	64	128	0.2	0.5	ECDLP
Dilithium-3	1,952	3,293	3	0.4	0.15	M-LWE / M-SIS
FALCON-512	897	666	1	4.5	0.08	NTRU Lattice
SPHINCS+-128	32	7,856	1	65.0	3.2	Hash-based

4.4 Analysis and Discussion

The experimental results reveal several important insights for practical PQC deployment. First, lattice-based algorithms—particularly CRYSTALS-Kyber and CRYSTALS-Dilithium—offer

the most favorable overall performance profile. Their computational costs are within one order of magnitude of classical algorithms, while their key and signature sizes, though larger, remain practical for most network protocols. Kyber-768 at NIST Security Level 3 provides quantum security comparable to AES-192, with public keys of only 1,184 bytes and ciphertexts of 1,088 bytes—easily accommodated within standard TLS handshake messages.

Second, the choice of PQC algorithm depends heavily on the application context. For bandwidth-constrained IoT environments, FALCON's compact signatures may be preferable despite its implementation complexity. For applications requiring conservative, well-understood security assumptions, FrodoKEM's reliance on unstructured LWE provides additional confidence at the cost of larger parameters. Classic McEliece's enormous public keys (261 KB) make it unsuitable for most interactive protocols but viable for scenarios where keys can be pre-distributed.

Third, the performance overhead of PQC is not uniformly distributed. Key generation and signing operations for some algorithms (FALCON, SPHINCS+) are significantly slower than their classical counterparts, which may impact applications requiring frequent key rotation or high-throughput signature generation.

5. Quantum-Resistant Migration Framework

Transitioning existing cryptographic infrastructure to quantum-resistant algorithms presents operational, compatibility, and performance challenges that require a structured approach. We propose a four-phase migration framework based on industry best practices and our experimental findings.

5.1 Phase 1: Cryptographic Inventory and Risk Assessment

The first phase involves conducting a comprehensive inventory of all cryptographic algorithms, key sizes, and protocols deployed across the organization. Each cryptographic asset is classified by its quantum vulnerability (asymmetric algorithms are critical; symmetric algorithms with 128-bit keys are elevated; 256-bit symmetric algorithms are low risk) and the confidentiality horizon of the data it protects. Assets protecting data with confidentiality requirements extending beyond 2035 are prioritized for immediate migration.

5.2 Phase 2: Hybrid Deployment

The second phase deploys hybrid cryptographic schemes that combine classical and post-quantum algorithms. Hybrid key exchange concatenates a classical ECDH shared secret with a Kyber encapsulation, ensuring security even if one component is compromised. Hybrid signatures include both an ECDSA and a Dilithium signature, providing backward compatibility while adding quantum resistance. This approach follows the principle that the combined scheme is at least as secure as the stronger component.

5.3 Phase 3: Full PQC Transition

Once hybrid deployments have been validated in production and PQC standards have matured, organizations transition to purely post-quantum algorithms. This phase includes updating all TLS/SSL configurations, PKI certificates, VPN tunnels, S/MIME email encryption, and code signing infrastructure. Performance testing at scale is essential, as PQC algorithms' larger key and signature sizes impact bandwidth, storage, and handshake latency.

5.4 Phase 4: Cryptographic Agility

The final phase establishes cryptographic agility—the ability to rapidly swap algorithms in response to new attacks or standards updates. This requires abstracting cryptographic operations behind well-defined interfaces, maintaining centralized algorithm configuration, and implementing automated compliance monitoring. Cryptographic agility is particularly important given the relative youth of PQC algorithms; future cryptanalytic advances may require algorithm replacements.

Table 4: Recommended Migration Timeline

Phase	Timeline	Key Actions	Priority Systems
1. Inventory	2024–2025	Audit all crypto assets	All systems
2. Hybrid	2025–2028	Deploy hybrid schemes	TLS, VPN, PKI
3. Full PQC	2028–2032	Replace classical algorithms	All public-key systems
4. Agility	2030+	Enable algorithm swaps	Enterprise-wide

6. Conclusion

This paper has presented a comprehensive investigation into the impact of quantum computing on cryptographic algorithms. Our analysis demonstrates that quantum computers executing Shor's algorithm will render all currently deployed public-key cryptosystems—RSA, ECC, and Diffie-Hellman—completely insecure, with conservative estimates placing this threat within the 2033–2035 timeframe. Symmetric algorithms and hash functions are less severely affected, with Grover's algorithm providing only a quadratic speedup that can be mitigated by doubling key sizes.

Our experimental evaluation of NIST-standardized post-quantum algorithms reveals that lattice-based schemes, particularly CRYSTALS-Kyber for key encapsulation and CRYSTALS-Dilithium for digital signatures, offer the most practical balance of security, performance, and implementation complexity. These algorithms achieve computational speeds within one order of magnitude of classical counterparts, with key and signature sizes that are manageable for most network protocols and applications.

The phased migration framework we propose provides a structured approach for transitioning existing cryptographic infrastructure to quantum-resistant alternatives. Beginning with a cryptographic inventory and risk assessment, progressing through hybrid deployments, and culminating in full PQC adoption with cryptographic agility, this framework addresses the practical challenges of large-scale cryptographic transitions.

Future work should focus on three areas: (1) optimizing PQC implementations for resource-constrained devices such as IoT sensors and embedded systems; (2) developing standardized benchmarking methodologies for PQC algorithm comparison across diverse hardware platforms; and (3) investigating the security of PQC algorithms under side-channel attacks, fault injection, and other physical attack vectors that become critical in real-world deployments.

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