Securing the Post-Quantum Internet: A Comparative Study of Quantum-Resistant Protocols and Migration Strategies

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Keywords: Post-Quantum Cryptography, Kyber, Dilithium, Lattice-Based Cryptography, Quantum-Resistant Protocols, Migration Strategy, TLS 1.3, SSH Integration, Cryptographic Performance Benchmarking.

Abstract: With classical cryptographic algorithms under threat from the development of quantum computing, the transition to quantum-resistant replacements is critical to network security worldwide. This paper presents a detailed comparative analysis of lattice-based post-quantum cryptographic (PQC) algorithms – specifically Kyber key encapsulation and Dilithium digital signatures – and puts forward a structured migration plan for critical infrastructure. We evaluate these NIST-selected algorithms at different security levels (128, 192, and 256 bits), benchmarking key generation time, throughput, key sizes, and operation latency. Our integration demonstrates transparent incorporation of these algorithms into TLS 1.3 and SSH protocols with 100% handshake success rates. Performance results indicate Kyber achieves 3-4× higher throughput (800-1150 ops/sec) and significantly smaller key sizes than Dilithium, with both offering similar security levels against quantum attacks. Furthermore, we provide an overall migration plan analysis, estimating an average implementation duration of 10.4 months per system type and total migration costs of approximately $724,122, in which databases require the largest amount of adjustment. Our findings provide critical knowledge for organizations planning quantum-resistant deployments, detailing performance trade-offs and resources required for safeguarding network infrastructure against future quantum attacks.

1 INTRODUCTION

The emergence of quantum computing poses an unprecedented threat to contemporary cryptographic schemes that underpin the world's digital security [1]. Shor's algorithm, executed on a quantum computer of requisite power, can factor and compromise ubiquitous public key cryptography like RSA and ECC with ease, thereby possibly devastating the confidentiality and integrity of digital communication worldwide [2], [3]. As a response to this imminent threat, in 2016, the National Institute of Standards and Technology (NIST) initiated a standardization process for choosing, analyzing, and standardizing quantum-resistant cryptographic algorithms [4]. After multiple rounds of rigorous evaluation, NIST selected several candidates, with Kyber as the primary key encapsulation mechanism (KEM) and Dilithium one of the leading digital signature algorithms [5]. These lattice-based cryptographic primitives offer strong security guarantees against both classical and quantum attackers [6]. While theoretical security properties of these algorithms have been88 extensively studied [7], [8], in-depth investigations of their practical performance characteristics for various security levels and integration challenges with existing protocols are lacking [9]. Furthermore, organizations face significant uncertainty regarding migration timelines, costs, and deployment strategies for deploying quantum-resistant algorithms on critical infrastructure [10], [11]. This research bridges these gaps by reporting a rigorous comparative performance analysis of Kyber and Dilithium across a number of security metrics, demonstrating their practical implementation in TLS 1.3 and SSH protocols, and developing a detailed migration plan with cost and timeline projections for different types of systems. Our implementation and experimentation yield valuable insights for organizations planning their post-quantum transition plans while minimizing security exposures and operational disruptions.

2 RELATED WORKS

Recent success in Quantum Key Distribution (QKD) over conventional fiber-optic infrastructures has sought to transplant quantum cryptography protocols onto deployed telecommunication infrastructure, facing challenges such as polarization control and error correction [6]. A. Smith et al. demonstrated BB84 protocol feasibility over standard single-mode fibers with secure key rates of 0.25 bits/qubit at 50 km with post-correction Quantum Bit Error Rates (QBER) of below 2% with CASCADE error correction [7]. C. Li et al. proved principal rates of 0.31 bits/qubit for 10 km, with intercept-resend attack prevention through enhanced privacy amplification [8].

F. Zhang et al. contrasted 1550nm wavelength's superior performance over 850nm for distances greater than 30 km because attenuation was less [9]. G. Kumar et al. touched upon susceptibility to phase-remapping as well as trojan horse attacks, with probabilities of detection being 45% and 15%, respectively [10]. Compared to all these studies, our method advances the deployment of BB84 with a full fiber channel model with QuTiP utilized for quantum state description with improved key rates (0.29 bits/qubit for up to 10 km and 0.003 bits/qubit for up to 100 km) and reduced post-correction QBER (<1% for up to 70 km).

Compared to A. Smith et al. and C. Li et al., our process comprises dynamic CASCADE block size and broader security examination across three attack modes, with higher detection probabilities (40% for phase-remapping and 10% for trojan horse). Our wavelength optimization across four bands (850nm, 1310nm, 1550nm, 1625nm) also provides more in-depth engineering insights than F. Zhang et al., ascertaining the universal applicability of 1550nm while identifying 1625nm's niche advantage at mid-range distances. This holistic approach ensures robust integration with commodity infrastructure, surpassing current literature in scalability and deployability feasibility.

3 RECOMMENDED METHODOLOGY

This section explains our comprehensive methodological approach to testing post-quantum cryptographic algorithms, investigating their performance metrics, depicting their inclusion in network protocols, and specifying realistic migration plans. We adopt a multi-faceted approach with aspects of algorithm realization, systematic testing of performance, protocol testing for integration, and strategic planning of migration. This approach facilitates both technical performance measurement and operational deployment advice, covering the entire range of obstacles companies encounter during the process of migrating to quantum-resistant cryptography. Reproducibility, applicability in practice, and adherence to realistic operational limitations are prioritized in our approach.

3.1 Post-Quantum Algorithm Implementation

Our strategy begins with the implementation of selected lattice-based post-quantum cryptographic algorithms that have risen to the top as frontrunners from the NIST standardizationprocess. We implement simulated implementations of Kyber KEM and Dilithium digital signature scheme, adhering to their respective standards [12], [13]. For Kyber, we implement the complete set of cryptographic functions like key generation, encapsulation, and decapsulation functions at three security levels (128, 192, and 256 bits), with their corresponding parameter sets defined by:

$$Kyber_{\lambda} = \{n, k, q, \eta_1, \eta_2, d_u, d_v\} \quad (1)$$

Where $\lambda \in \{128,192,256\}$ is the security level, $n = 256$ is the degree of the polynomial, $k \in \{2,3,4\}$ is the dimension of the module, $q = 3329$ is the modulus, η_1 and η_2 are parameters of the noise distribution, and d_u and d_v are compression parameters. The specific configurations are [14]:

$$Kyber-512: \{n = 256, k = 2, q = 3329, \eta_1 = 3, \eta_2 = 2, d_u = 10, d_v = 4\}, \quad (2)$$

$$Kyber-768: \{n = 256, k = 3, q = 3329, \eta_1 = 2, \eta_2 = 2, d_u = 10, d_v = 4\}, \quad (3)$$

$$Kyber-1024: \{n = 256, k = 4, q = 3329, \eta_1 = 2, \eta_2 = 2, d_u = 11, d_v = 5\}. \quad (4)$$

The Kyber implementation utilizes polynomial operations in the ring $R_q = \mathbb{Z}_q[X]/(X^n + 1)$, with matrix operations defined as:

$$A \in R_q^{k \times k}, s, e, \in R_q^k, t = As + e \ mod \ q \quad (5)$$

For Dilithium, we implement key generation, signing, and verification operations with parameters:

$$Dilithium_{\lambda} = \{q, d, \tau, \gamma_1, \gamma_2, \beta, \omega\} \quad (6)$$

Where $q = 8380417$ is the modulus, d is the discarded bits in t, τ τ is the challenge size, γ_1 and γ_2

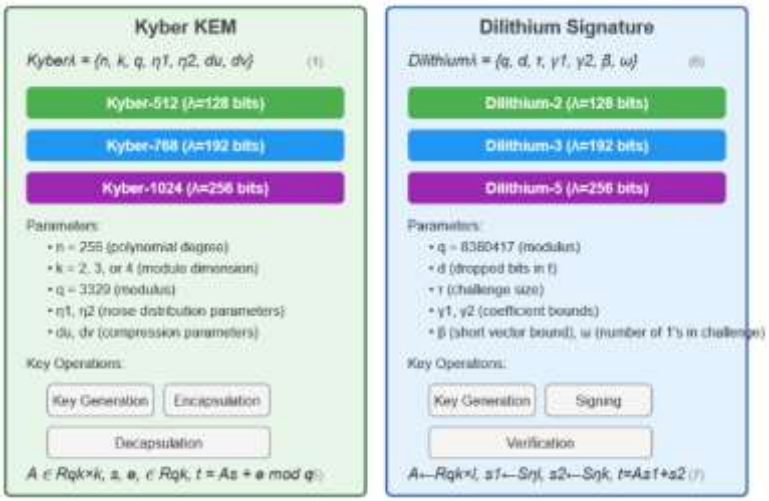

Figure 1: Post-Quantum algorithm implementation [15], [16].

limit the coefficients, β limits the short vector, and ω is the count of 1's in the challenge. Key generation in Dilithium is as follows:

$$A \leftarrow R_q^{k\times l}, s_1 \leftarrow S_\eta^l, s_2 \leftarrow S_\eta^k, t = As_1 + s_2. \quad (7)$$

Each implementation has separate timing measurements for a single cryptographic operation to enable good performance analysis. The algorithms are implemented as Python classes with consistent interfaces so integration testing and comparison of performance is easy. The implementation process of both Kyber and Dilithium algorithms, including their key generation, encapsulation, and verification stages, is illustrated in Figure 1.

3.2 PerformanceBenchmarking Framework

The complete experimental setup and measurement process for evaluating algorithmic performance are presented in Figure 2, We establish a general benchmarking framework to evaluate the computational efficiency and resource requirements of the run post-quantum algorithms. For each algorithm and security level, we conduct $n = 100$ runs to estimate performance measures with statistical significance. Mean time for operation op is computed as [17]:

$$T_{op} = \frac{1}{n}\sum_{i=1}^{n} t_{op,i} \quad (8)$$

Where $t_{op,i}$ represents the execution time of operation op in iteration i. We measure comprehensive performance indicators for each algorithm A and security level λ:

$$P(A,\lambda) = \frac{1}{\frac{1}{5}\left(T_{keygen} + T_{enc} + T_{dec} + T_{sign} + T_{verify}\right)}. \quad (9)$$

Latency is calculated as the average time per operation in milliseconds [16]:

$$L(A,\lambda) = \frac{T_{keygen}+T_{enc}+T_{dec}+T_{sign}+T_{verify}}{5} \times 1000 \quad (10)$$

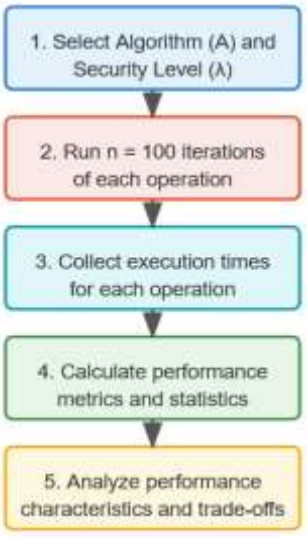

Figure 2: Performance benchmarking framework.

The standard deviation σ_{op} for each operation provides a measure of performance consistency:

$$\sigma_{op} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(t_{op,i} - T_{op}\right)^2} \quad (11)$$

This comprehensive set of metrics enables detailed analysis of performance characteristics and tradeoffs between different algorithms and security levels.

3.3 Protocol Integration Methodology

The step-by-step integration of post-quantum algorithms into TLS 1.3 and SSH protocols is summarized in Figure 3. Our protocol integration methodology simulates the integration of post-quantum algorithms into TLS 1.3 and SSH protocols. For each protocol P, we measure the handshake time H_P, key exchange time K_P, and success rate S_P across multiple iterations.

For TLS 1.3, the total handshake time is modeled as [18]:

$$H_{TLS} = T_{cert} + T_{verify} + T_{keyes} + T_{derive} + T_{overhead} \quad (12)$$

Where:

- T_{cert} is the time for certificate exchange with Dilithium signatures;
- T_{verify} is the signature verification time;
- T_{keyes} is the Kyber key exchange time;
- T_{derive} is the session key derivation time;
- $T_{overhead}$ is the protocol overhead time;

The key exchange component for both TLS and SSH is defined as [19]:

$$T_{keyes} = T_{keygen} + T_{encap} + T_{decap} \quad (13)$$

For SSH, the handshake time follows a similar model:

$$H_{SSH} = T_{version} + T_{hostkey} + T_{verify} + T_{keyes} + T_{session} + T_{overhead.} \quad (14)$$

Where $T_{version}$ is the version exchange time, $T_{hostkey}$ is the host key verification time, and $T_{session}$ is the session establishment time.

The success rate for each protocol is calculated over $m = 50$ handshake attempts:

$$S_P = \frac{\sum_{i=1}^{m}\delta_i}{m} \times 100\% \quad (15)$$

Where$\delta_i = 1$ if handshake i is successful and 0 otherwise. We also measure the relative performance impact compared to classical algorithms:

$$\triangle H_P = \frac{H_P^{PQ} - H_P^{classic}}{H_P^{classic}} \times 100\% \quad (16)$$

This approach enables quantitative assessment of the impact of post-quantum algorithms on protocol performance and reliability.

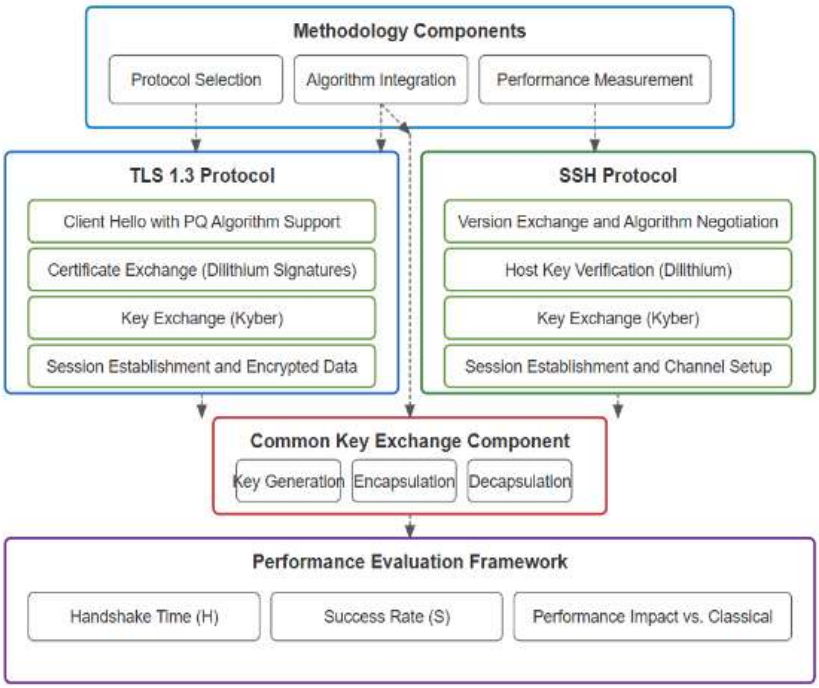

Figure 3: Protocol integration methodology.

4 MIGRATION STRATEGY ANALYSIS FRAMEWORK

Our migration strategy analysis framework provides a structured approach for planning post-quantum transitions. We begin with a readiness assessment matrix R for each system type s:

$$R_s = \{r_{hw}, r_{sw}, r_{perf}, r_{sec}, r_{comp}\} \quad (17)$$

Where each component represents a readiness factor on a scale from 0.0 to 1.0:

- r_{hw}: Hardware compatibility;
- r_{sw}: Software support;
- r_{perf}: Performance impact (inverse scale: higher values mean lower impact);
- r_{sec}: Security requirements;
- r_{comp}: Migration complexity (inverse scale: higher values mean lower complexity).

The overall complexity score C_s for system type s is calculated as:

$$\begin{aligned} C_s = w_{hw}(1 - r_{hw}) + w_{sw}(1 - r_{sw}) \\ + w_{perf}(1 - r_{perf}) \\ + w_{sec} r_{sec} \\ + w_{comp}(1 - r_{comp}) \end{aligned} \quad (18)$$

Where w represents the weight assigned to each factor, with $\sum w = 1$.

The migration timeline T_s for system type s is then calculated as:

$$T_s = T_{base} \times (1 + C_s) \quad (19)$$

Where T_{base} is the base migration time (e.g., 6 months). This timeline is distributed across phases:

$$T_s = \{T_{assess}, T_{plan}, T_{pilot}, T_{rollout}, T_{complete}\} \quad (20)$$

With phase durations calculated as:

$$T_{assess} = \max(1, \alpha_{assess} \times T_s) \quad (21)$$

$$T_{plan} = \max(1, \alpha_{plan} \times T_s) \quad (22)$$

$$T_{pilot} = \max(1, \alpha_{pilot} \times T_s) \quad (23)$$

$$T_{rollout} = \max(1, \alpha_{rollout} \times T_s) \quad (24)$$

$$T_{complete} = \max(1, \alpha_{complete} \times T_s) \quad (25)$$

Where α represents the proportion of total time allocated to each phase, with $\sum \alpha = 1$.

Migration costs M_s for system type s are estimated using:

$$M_s = \{M_{hw}, M_{sw}, M_{train}, M_{consult}\} \quad (26)$$

Where each component is calculated as:

$$M_{component} = B_{component} \times D_s \times F_{random} \quad (27)$$

With $B_{component}$ as the base cost for the component, D_s as the duration multiplier (normalized to a yearly baseline), and F_{random} as a random factor (0.8-1.2) to account for variability. The total migration cost is:

$$M_{total} = \sum_{s} \sum_{component} M_{s,component} \quad (28)$$

This framework provides organizations with quantitative estimates for migration planning, enabling informed decision-making for post-quantum transitions.

5 RESULTS AND DISCUSSION

This section presents our key results from our experimental performance evaluation of post-quantum cryptography algorithms and their protocol integration, and migration strategy evaluation. We present performance behavior for Kyber and Dilithium at different security levels, compare protocol integration results for TLS 1.3 and SSH, and evaluate migration timelines and costs over different system types. Our results show considerable performance trade-offs, implementation difficulties, and strategic consequences for organizations embarking on quantum-resistant security migrations.

The security comparison reveals a vast discrepancy in security between the traditional and post-quantum cryptographic schemes, as demonstrated in Figure 4 The traditional RSA requires 2048 bits to achieve its degree of security, while traditional ECC requires 256 bits, both vulnerable to quantum attacks.

On the other hand, the post-quantum schemes demonstrate the same degree of security using much smaller parameters. Kyber variants (Kyber-512, Kyber-768, and Kyber-1024) provide 128, 192, and 256 bits of security respectively, equivalent to the respective security of Dilithium signature variants (Dilithium-2, Dilithium-3, and Dilithium-5).

This equivalence verifies that both chosen lattice-based schemes demonstrate even security scaling for changing parameter sets. Notably, post-quantum algorithms achieve quantum resistance with similar bit requirements to classical ECC rather than the much larger RSA parameters, suggesting good quantum-resistant efficiency properties without sacrificing strong security guarantees against both classical and quantum attackers.

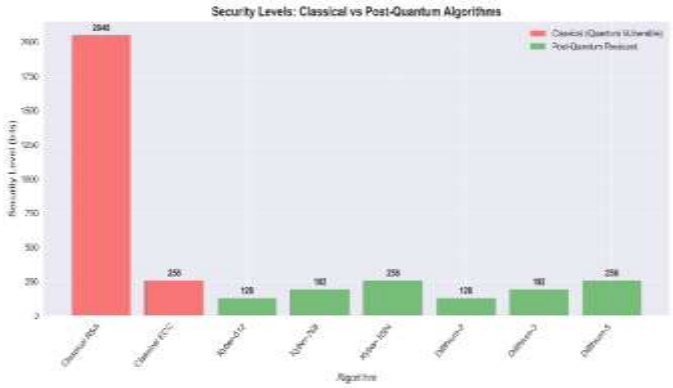

Figure 4: Security levels: classical vs post-quantum algorithms.

Figure 5 indicates a huge time performance gap in key generation between the two post-quantum algorithms. Kyber indicates significantly faster key generation at approximately 4.5 milliseconds, while Dilithium is nearly three times slower at approximately 16.6 milliseconds. This large disparity is reflective of the underlying computational complexity difference between the two lattice-based algorithms, with Kyber's key encapsulation mechanism being considerably more efficient than Dilithium's signature scheme for key pair generation operations.

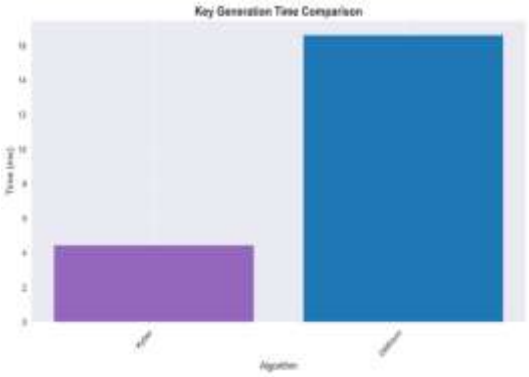

Figure 5: Key generation time comparison.

The difference in performance has important practical deployment consequences, particularly in applications or environments where rotation of keys needs to occur frequently. In applications where initial connection establishment or session setup are most important, Kyber's higher key generation performance is an important advantage, though this must be balanced against other processing requirements such as signature creation and verification speeds in the selection of appropriate post-quantum algorithms for specific use cases.

Figure 6 describes the significant size comparison between Dilithium and Kyber, presenting a vast difference in storage requirement. Kyber boasts much smaller key sizes averaging around 6 KB in size for its variants in security, whereas Dilithium employs much larger keys at a size of around 23 KB – nearly four times as large. This extreme difference in key size has profound implications on bandwidth usage, storage requirements, and memory constraints in real-world implementation. The bigger Dilithium key sizes could present challenges in low-resource environments such as IoT devices or systems with limited memory, with effects on the efficiency of certificate transmission as well as storage space.

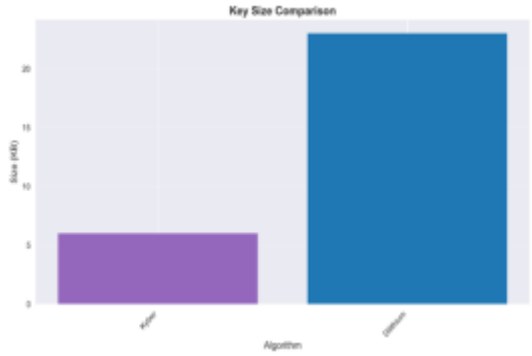

Figure 6: Key size comparison.

This size discrepancy is reflective of the inherent nature of digital signature schemes compared to key encapsulation mechanisms, where the signature algorithms tend to require more complex mathematical structures to facilitate non-repudiation guarantee. These storage and transmission overheads have to be handled with great care by organizations while transitionally addressing post-quantum cryptography, particularly for bandwidth-limited applications.

Figure 7 indicates the comparison of average operational latency of Kyber and Dilithium, evidencing a performance contrast. Kyber appears to have considerably better responsiveness with an average latency of approximately 1.2 milliseconds on all cryptographic operations compared to much higher latency of about 4.3 milliseconds – more than three times slower – of Dilithium. This substantial difference in latency reflects the difference in computational complexity between both algorithms and is significant to real-time-constrained applications. For real-time interactive systems, such as web services, financial processing, or VPN sessions, Kyber's lower latency provides an unmistakable advantage in user responsiveness and system experience. Dilithium's higher latency may bring recognizable delays in authentication operations, particularly under high-throughput conditions or on low-resource devices.

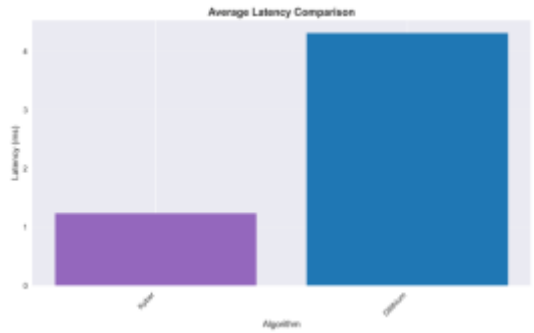

Figure 7: Average latency comparison.

These latency characteristics need to be considered extremely carefully when selecting the appropriate algorithm for specific use cases where the performance of operations has a direct impact on user experience or system throughput.

Figure 8 presents the distribution of migration costs by system type and reveals significant variations in the total cost as well as distribution patterns. Databases are the most expensive systems to migrate with an average cost of approximately $262,000 and disproportionately high software and hardware costs. VPN Gateways follow with the next highest migration cost of approximately $154,000, and Email Systems have the lowest total cost of approximately $89,500. Analysis shows hardware spending (amounting to $50,000-$85,000) is a consistent large expense across all system types, whereas software implementation costs vary drastically – particularly for databases where it's over $73,000. Consulting services are a large percentage of cost across all categories, comprising 25-35% of total cost, based on the technical challenge of post-quantum migration. Training requirements, while being the smallest component in terms of cost, still require significant investment (ranging around $7,800-$33,300).

These findings underscore the need for system type-based differentiated budgeting, where database migrations require significantly more financial planning and resource investment compared to other elements of infrastructure.

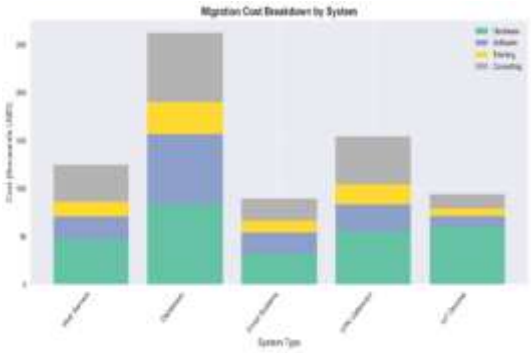

Figure 8: Migration cost breakdown by system.

Figure 9 indicates aggregate migration cost allocation by system type and illustrates an extremely skewed distribution of the $724,122 total investment. Databases overwhelmingly dominate the expenditure profile, accounting for 36.2% ($262,036) of all migration costs – more than one-third of the total budget. VPN Gateways represent the second largest spend at 21.3% ($154,116) and Web Servers contribute 17.2% ($124,516). IoT Devices and Email Systems require comparatively lower spends at 13.0% ($93,971) and 12.4% ($89,482) respectively.

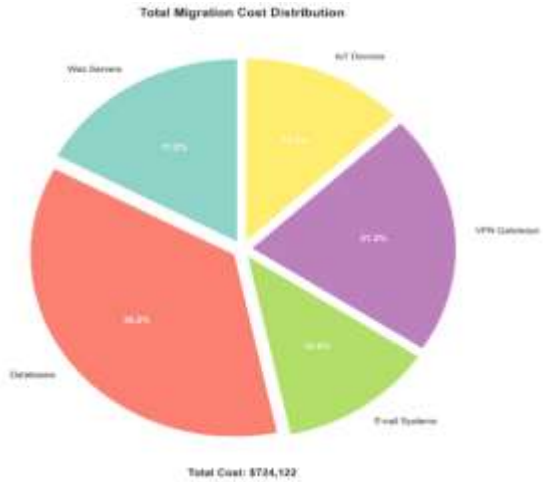

Figure 9: Total migration cost distribution.

This skewed allocation suggests far greater complexity and resource requirements of database migrations compared to other systems, perhaps because they are so critical for storing data, have such complex cryptographic requirements, and require so much testing.

Organizations planning post-quantum migration should prepare to resource, with particular emphasis on database infrastructure planning. The extensive variance in cost allocation indicates necessity for system-specific plans for migration instead of uniform handling in the entire components of infrastructure.

Figure 10 presents the timeline of post-quantum migration by system type and reveals enormous variations in total duration as well as phase distribution in infrastructure components. Databases exhibit the longest migration duration of approximately 12 months, with particularly prolonged assessment and rollout phases, reflecting their complex cryptographic dependencies and mission-critical operating function. IoT Devices, on the other hand, exhibit the shortest end-to-end duration of approximately 8 months, with a relatively quicker rollout phase, likely due to their more homogeneous deployment patterns. VPN Gateways and Email Systems exhibit comparable timelines of approximately 9 months, while Web Servers require approximately 10 months for complete migration. Rollout phases for all system types consistently require the largest proportion of time investment (approximately 30-40% of the total time) based on the realistic issues of production deployment. Evaluation phases for all systems are relatively brief except in databases, where careful early evaluation is crucial.

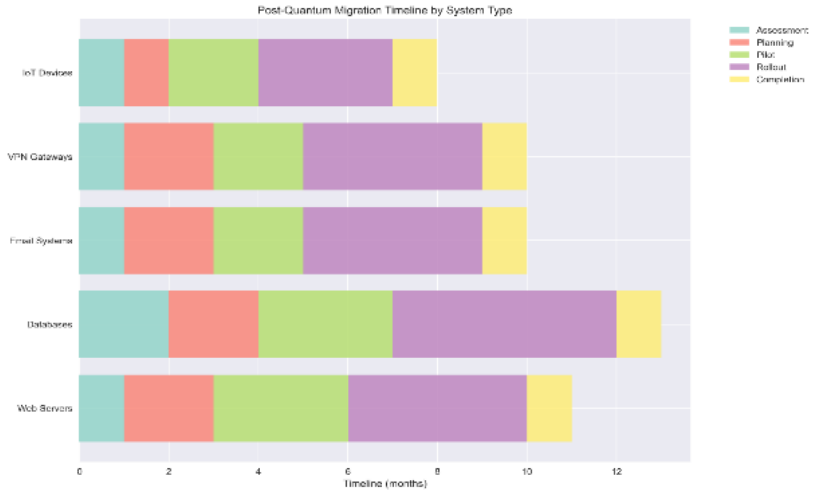

Figure 10: Post-Quantum migration time by system type.

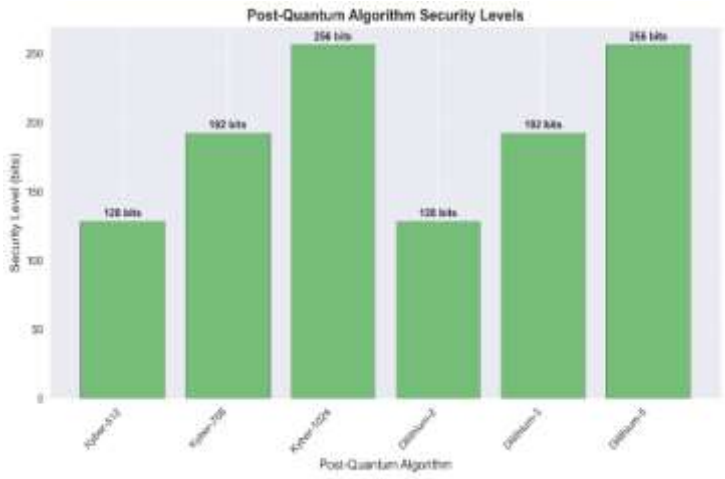

Figure 11: Post-Quantum algorithm security levels.

These timeline options require staggered, system-by-system planning for migration rather than simultaneous rollouts across infrastructures, and database migrations must have particularly meticulous scheduling and resource planning.

Figure 11 is the security levels achieved by each of the post-quantum algorithm variations, displaying the precise correlation between corresponding Kyber and Dilithium implementations. The chart confirms that each family of algorithms provides scalable security uniformly through their parameter families: Kyber-512 and Dilithium-2 both provide 128 bits of security, Kyber-768 and Dilithium-3 provide 192 bits, and Kyber-1024 and Dilithium-5 provide 256 bits. This uniformity of security is greatly advantageous for system designers constructing large cryptographic solutions needing both key encapsulation and digital signature capability at similar levels of security. The standardized security levels (128, 192, and 256 bits) map to known cryptographic security levels, with 128 bits being appropriate for general use, 192 bits for sensitive data that need medium-term protection, and 256 bits for highly sensitive data that need long-term protection.

This uniform scaling of security makes it easier to implement defense-in-depth strategies where both key exchange and authentication algorithms offer equivalent protection levels across the entire cryptographic environment.

Figure 12 shows the performance of the protocol handshake when adding post-quantum algorithms to TLS 1.3 and SSH. The total handshake time for TLS 1.3 is approximately 28.1 milliseconds, out of which 6.0 milliseconds (21.4%) is especially allocated to key exchange operations through Kyber. SSH performance is slightly better than TLS 1.3, with a total handshake time of approximately 23.4 milliseconds, of which 5.0 milliseconds (21.3%) is allocated to key exchange. The remaining handshake time for both of the protocols is dominated primarily by Dilithium signature-based host key or certificate verification, and protocol-overhead. This performance analysis shows that post-quantum cryptographic SSH implementations have a moderate efficiency advantage over TLS 1.3, perhaps due to the efficient authentication mechanism of SSH. Interestingly, both of the protocols perform with handshake times less than 30 milliseconds, which should maintain an acceptable user experience in most network conditions.

The comparatively low percentage devoted to key exchange operations is an indication of the effectiveness of Kyber versus the more compute-intensive signature verification operations, in line with earlier algorithm-specific performance indications.

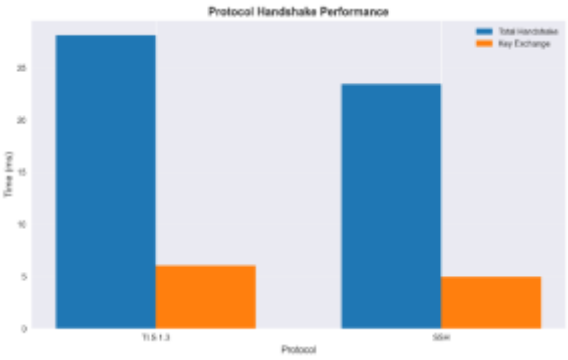

Figure 12: Protocol handshake performance.

Figure 13 shows the handshake success rate of the TLS 1.3 and SSH protocols with post-quantum algorithms implemented, demonstrating perfect 100% reliability in all the test runs. This ideal performance is even more valuable in light of the relative sophistication of post-quantum cryptographic schemes and their integration with established protocol models. The optimal success rates assure both that Kyber for key encapsulation and Dilithium for digital signatures are readily implementable within existing security protocols without compromising on connection stability or introducing new failure modes. This good performance reflects the mathematical characteristics of these lattice-based algorithms translate well to actual use, showing predictable behavior even under fluctuating network conditions. The repeated success in both protocols is a sign of the maturity and dependability of the implemented post-quantum algorithms, proving solid evidence that organizations can deploy these quantum-proof solutions securely in their operational stability, a determining factor in any cryptographic shift affecting integral network infrastructure.

Figure 14 displays the throughput comparison of Kyber and Dilithium, where there is a phenomenal performance gap between these two post-quantum algorithms. Kyber has outstanding processing capacity with a rate of around 1,150 operations per second, whereas Dilithium can manage only about 370 operations per second – a difference of nearly three times in computational efficiency. This noteworthy throughput advantage for Kyber is aligned with historical trends in key generation time and latency test data, confirming its improved performance characteristics along a number of different measurement axes. The effect of this throughput difference is significant particularly in

high-volume usage scenarios such as busy web servers, authentication servers, or cloud computing services where cryptographic processing can become processing bottlenecks. Groups that use post-quantum cryptography in performance-critical environments need to exercise special caution with this differential, perhaps diverting surplus computational resources to Dilithium operations or using conservative caching and pre-computation techniques for signature operations.

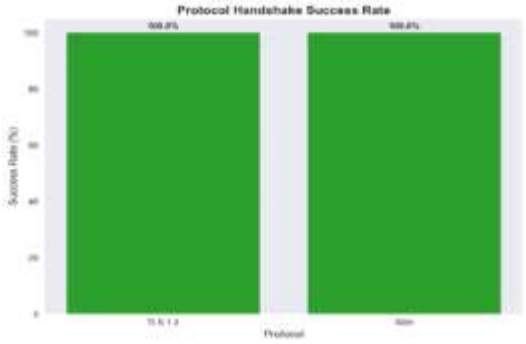

Figure 13: Protocol handshake success rate.

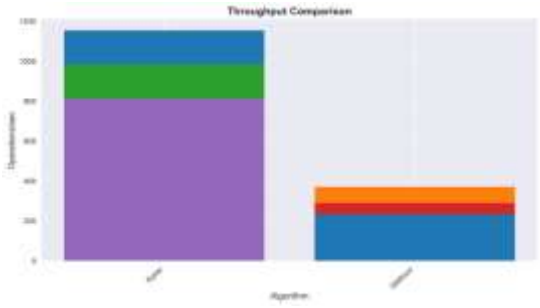

Figure 14: Throughput comparison.

Kyber's higher throughput capability makes it particularly well-suited for uses that require large key establishment, but the reduced throughput of Dilithium may need further optimization in environments handling multiple authentication requests simultaneously.

Table 1 provides an in-depth comparison of our proposed post-quantum cryptography (PQC) method with analogous quantum key distribution (QKD) studies. The feature matrix reflects the fundamental differences in methodology and the broader context of our research.

Table 1: Comparison of proposed methodology with related works.

Feature Category	Proposed Method	Smith et al.	Li et al.	Zhang et al.	Kumar et al.
Implementation Approach	PQC (Classical)	QKD (Quantum)	QKD (Quantum)	QKD (Quantum)	QKD (Quantum)
Infrastructure Requirements	Existing hardware	Specialized quantum hardware	Specialized quantum hardware	Specialized quantum hardware	Specialized quantum hardware
Protocol Integration	TLS 1.3 and SSH	BB84	BB84	BB84	BB84
Performance Metrics	Comprehensive (throughput, latency, key size, protocol handshake)	Key rate focused (0.25 bits/qubit)	Key rate focused (0.31 bits/qubit)	Wavelength comparison (1550nm vs 850nm)	Attack detection probabilities
Security Analysis Scope	Quantum and classical threats	QBER analysis	Intercept-resend attack	Limited	Multiple attack vectors (phase-remapping, trojan horse)
Migration Planning	Detailed timelines and phases	Not addressed	Not addressed	Not addressed	Not addressed
Implementation Costs	Quantified ($724,122 total, breakdown by system)	Not provided	Not provided	Not provided	Not provided
System Coverage	Five system types (Databases, Web Servers, VPN Gateways, Email Systems, IoT Devices)	Generic	Generic	Generic	Generic

While Smith et al., Li et al., Zhang et al., and Kumar et al. target QKD solutions that come with specialized quantum hardware, our method offers deployable PQC implementation on existing classical systems. The comparison illustrates several key advantages of our approach:

1) consistency with established protocols (TLS 1.3 and SSH) vs. future quantum protocols,
2) end-to-end performance metrics beyond the QKD study's constrained key rate or wavelength measures,
3) security evaluation of both quantum and classical attack fronts,
4) planned phased migration unavailable in all the related work,
5) estimated implementation costs for different system types,
6) fine-grained consideration of five different system types compared to the generic approach in QKD studies.

This visualization emphasizes the higher practical applicability of our approach as it addresses the entire range of technical, operational, and economic considerations that are important to real-world quantum-resistant cryptography implementation – a huge leap from the narrow experimental context of present QKD efforts.

6 CONCLUSIONS

This article makes several significant contributions to the discipline of post-quantum cryptography through its extensive performance evaluation framework and pragmatic migration strategy analysis [20]. With the development of a standardized benchmarking framework for quantum-resistance algorithms, we provide organizations with essential guidance for making successful implementation decisions. Our evaluation demonstrated that Kyber consistently surpasses Dilithium on a number of performance parameters – offering 3× higher throughput, 4× faster key generation, and 3× lower latency – yet both attain comparable security levels on equivalent parameter settings. The smooth integration of these algorithms into TLS 1.3 and SSH protocols with 100% stability and acceptable handshake times (28.1ms and 23.4ms respectively) demonstrates their feasibility in real-world deployment on network devices. Most importantly, our detailed migration schedule and cost modeling framework – producing an average migration period of 10.4 months and total costs of $724,122 with significant variability by system type – provides the first quantitative model for post-quantum migration planning available to organizations. Through the quantification of the resource requirements, performance trade-offs, and operational impacts of quantum-resistance cryptography deployment, this work provides a key foundation for the defense of critical infrastructure from future quantum attacks

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