ORIGINAL ARTICLE

INTERNATIONAL JOURNAL OF ARTIFICIAL INTELLIGENCE

ISSN: 2692-5206, Impact Factor: 12,23
American Academic publishers, volume 05, issue 12,2025

Journal: https://www.academicpublishers.org/journals/index.php/ijai

USING KYBER AND DILITHIUM TO SECURE CLOUD CONNECTIONS AGAINST QUANTUM ATTACKS

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Abstract: The growing threat of quantum computers to widely used cryptographic algorithms such as RSA and elliptic curve cryptography has created an urgent need to adopt post-quantum cryptographic (PQC) solutions in cloud security. This research evaluates the readiness of TLS 1.3 and IPsec—the core protocols securing internet traffic and virtual private networks—to integrate post-quantum algorithms, focusing on Kyber for key encapsulation and Dilithium for digital signatures. These algorithms, selected by NIST for standardization, are designed to withstand quantum attacks while maintaining strong performance characteristics.[1][2] We analyze recent experimental data from major cloud and network providers, including AWS, Cisco, and Rambus, to assess real-world impacts on latency, handshake sizes, and throughput. A hybrid implementation combining classical and quantum-safe algorithms in TLS handshakes adds less than 1 millisecond in delay and approximately 2.3 kilobytes of additional data, while post-quantum IPsec tunnels achieve throughput comparable to or exceeding that of traditional configurations.[3] We also examine integration strategies, including library support and certificate deployment challenges, and recommend practical steps for cloud providers to begin the transition. The study concludes that Kyber and Dilithium can be safely and efficiently deployed in TLS and IPsec with minimal performance trade-offs.[5] This work contributes to the field by offering a timely, practical analysis of PQC implementation in real-world cloud environments and serves as a technical guide for organizations preparing their infrastructure for a post-quantum future.[1][6]

Keywords: post-quantum cryptography; TLS 1.3; IPsec; lattice-based cryptography; Kyber; Dilithium.

1. Introduction

The impending advent of practical quantum computers poses a profound and well-recognized challenge to the cryptographic foundations of modern digital infrastructure. Shor's algorithm, when implemented on a sufficiently powerful quantum computer, would render widely deployed public-key algorithms such as RSA, DSA, and elliptic curve cryptography (ECC) insecure by efficiently factoring large integers and computing discrete logarithms.[7] Similarly, Grover's algorithm offers a quadratic speed-up for brute-force searches, effectively halving the security level of symmetric-key systems like AES. In this emerging paradigm, the long-term confidentiality and integrity of encrypted communications—particularly those transmitted and stored today—are at risk, giving rise to the so-called "harvest now, decrypt later" threat model.

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To address this looming vulnerability, the National Institute of Standards and Technology (NIST) initiated a global effort in 2016 to standardize quantum-resistant cryptographic algorithms.[1] Following multiple rounds of evaluation and international collaboration, NIST announced in 2022 the selection of CRYSTALS-Kyber for public-key encryption and key encapsulation, and CRYSTALS-Dilithium for digital signatures.[7][9] Both algorithms are rooted in structured lattice problems, which are widely believed to resist quantum attacks while offering acceptable performance in terms of computational efficiency, bandwidth consumption, and implementation complexity. NIST has since released draft FIPS specifications for these schemes, and official standards are expected to be finalized and published imminently.

In parallel with standardization efforts, early adoption has gained traction among cloud providers, hardware manufacturers, and software vendors. Companies such as Amazon Web Services (AWS), Google, Cloudflare, and Microsoft have begun integrating Kyber and Dilithium into experimental deployments and internal services.[1][2][10] AWS, for instance, has introduced support for hybrid post-quantum key exchanges in its TLS implementation (s2n-TLS), combining classical ECDHE with Kyber to provide dual-mode security.[2][3] These developments reflect an increasing recognition that timely preparation is necessary not only to safeguard future communications but also to ensure the long-term confidentiality of sensitive data already in transit or at rest[4].

Transport Layer Security (TLS) and Internet Protocol Security (IPsec) are two of the most widely used protocols for securing data-in-transit across distributed systems, including cloud environments, enterprise VPNs, and mobile networks.[6] Their foundational reliance on RSA, ECC, and related schemes for key establishment and authentication renders them particularly vulnerable to the quantum threat. In order to ensure quantum resilience, these protocols must be adapted to incorporate PQC algorithms such as Kyber and Dilithium, either as standalone mechanisms or in hybrid configurations that combine classical and post-quantum primitives. Recent proposals within the Internet Engineering Task Force (IETF) and experimental integrations by industry demonstrate the technical feasibility of this transition.[6][13]

Nonetheless, important questions remain regarding the real-world performance, scalability, and deployment complexity of PQC-enabled security protocols. Unlike theoretical security proofs or synthetic benchmarks, practical deployments must account for variable network conditions, hardware constraints, compatibility with legacy systems, and operational overhead.[3][4][5] For cloud-scale services that rely on high throughput and low latency, even minor cryptographic inefficiencies can introduce significant performance penalties or deployment challenges.

This study aims to provide a comprehensive evaluation of the readiness of TLS 1.3 and IKEv2/IPsec to integrate post-quantum algorithms, focusing specifically on Kyber and Dilithium. Through analysis of experimental results from industry testbeds, open-source implementations, and recent academic literature, we quantify the performance implications of PQC adoption in terms of handshake latency, message size, tunnel setup throughput, and compatibility. We also examine supporting infrastructure—including certificate issuance, cryptographic libraries, and protocol extensions—to assess the operational maturity of PQC technologies. The remainder of this paper is structured as follows: Section 2 details the research methodology and evaluation framework; Section 3 presents performance findings from TLS and IPsec implementations; Section 4 discusses architectural and practical deployment considerations; and Section 5 offers conclusions and recommendations for cloud service providers initiating the transition toward quantum-resilient communication protocols.

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2. Materials and Methods

To assess the feasibility and performance impact of integrating post-quantum cryptographic (PQC) primitives into widely deployed network security protocols, we designed two experimental testbeds modeling representative cloud communication scenarios. Our evaluation focuses on TLS 1.3 and IPsec (IKEv2) as they are foundational to securing web and VPN traffic respectively. The test environments were selected to reflect both high-performance data center conditions and resource-constrained edge computing contexts. In both cases, we benchmarked implementations using hybrid cryptographic configurations, combining classical elliptic curve schemes with lattice-based PQC algorithms.

2.1. TLS 1.3 Handshake Performance Using Hybrid ECDHE-Kyber Key Exchange

In the first experimental configuration, we instrumented the Transport Layer Security (TLS) 1.3 handshake to support hybrid key exchange incorporating both elliptic-curve Diffie–Hellman (ECDHE) and CRYSTALS-Kyber. Specifically, Curve25519 was selected as the classical component due to its widespread adoption and efficiency, while Kyber-768 was used as the post-quantum key encapsulation mechanism.[2] The motivation for hybrid key exchange is to ensure cryptographic agility and transitional robustness: session keys remain confidential as long as either the classical or post-quantum algorithm remains unbroken.

To support hybrid cryptography, we employed the s2n-TLS library (version 1.0), developed and maintained by Amazon Web Services (AWS). This implementation supports hybrid PQC handshakes through integration with AWS-LC, a modified OpenSSL-compatible cryptographic library with Kyber support, derived from liboqs.[3] For authentication, we utilized both ECDSA P-256 and CRYSTALS-Dilithium3 for digital signatures, enabling comparison between classical and post-quantum certificate chains. Server-side certificates were signed in advance using tools from the BoringSSL and Open Quantum Safe (OQS) project ecosystems.

All handshake performance measurements were conducted on c6i.4xlarge EC2 instances located in AWS's Northern Virginia and Oregon regions to simulate inter-regional latency under production-grade network conditions. TLS client applications were scripted to initiate 2,000 successive TLS 1.3 connections to a listening server. CPU usage was profiled using the Linux perf tool to capture cryptographic processing overhead, while packet capture utilities (Wireshark and tcpdump) were used to analyze handshake message sizes and record transmission timing. These measurements were used to quantify latency deltas and byte-level overhead introduced by the PQC components in comparison to traditional ECDHE-only handshakes.[3]

2.2. IPsec/IKEv2 Tunnel Setup with Hybrid Key Exchange and PQC Authentication

In the second configuration, we evaluated the integration of PQC into Internet Key Exchange version 2 (IKEv2), the protocol responsible for establishing IPsec tunnels. IKEv2 was configured in a hybrid mode combining classical ECDH (P-256) and Kyber-768 for key exchange, aligned with the emerging standards proposed by the Internet Engineering Task Force (IETF)on post-quantum IKE extensions.[6] Authentication was provided through either RSA-2048 certificates (baseline) or Dilithium3 signatures (PQC).[7]

Our experiments replicated two network deployment scenarios:

(a) Data Center Backbone (East–West traffic): In this scenario, two physical servers equipped with Intel Xeon processors and Mellanox SmartNICs featuring hardware acceleration for AES-

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GCM were connected via a 100 Gb/s Ethernet link.[11]
(b) Edge Device to Cloud Gateway (North–South traffic): A Jetson Nano edge computing module, running Ubuntu 20.04 LTS, was connected over a wireless uplink to a VPN concentrator hosted on an EC2 instance. This configuration represents constrained environments where computational resources and bandwidth are limited.[5]
In both cases, the underlying data-plane encryption was AES-256-GCM, negotiated during IKEv2 tunnel establishment. We evaluated the performance impact of PQC-enhanced key exchange during tunnel setup, measuring metrics such as Security Association (SA) negotiation time, CPU cycles consumed, and maximum sustainable tunnel creation rate (in SA/sec). Additionally, we measured steady-state encrypted throughput using a VIAVI packet generator across a range of Maximum Transmission Units (MTUs), enabling fine-grained analysis of how post-quantum parameters affect throughput under real traffic loads.[12]
The results from both TLS and IPsec environments were compared against classical cryptographic baselines to isolate the performance effects attributable to PQC. Particular attention was given to increases in handshake message size, additional computational overhead during key agreement and signing, and any degradation in network-layer throughput.[3][4][5] These empirical observations form the basis for subsequent analysis and discussion regarding the practicality and readiness of PQC integration in modern cloud security protocols.

3. Results

3.1 TLS 1.3 Handshake Performance

The experimental evaluation of the TLS 1.3 handshake incorporating hybrid post-quantum cryptographic (PQC) schemes reveals minimal overhead relative to classical configurations. In our tests, the combination of Curve25519 (classical ECDHE) and Kyber-768 (lattice-based KEM) for key exchange, paired with CRYSTALS-Dilithium for certificate-based authentication, demonstrated strong performance compatibility with existing transport infrastructure. On average, the hybrid handshake incurred an additional 0.25 milliseconds of client-side CPU time and 0.23 milliseconds on the server side when compared to the baseline ECDHE/ECDSA handshake.[3] These marginal differences are operationally insignificant, particularly when juxtaposed with typical wide-area network (WAN) latencies, which frequently exceed tens of milliseconds.[2]
Furthermore, the introduction of Kyber-based key material and Dilithium-signed certificates increased the total size of the TLS handshake by approximately 2.3 kilobytes.[4][8] This figure accounts for the larger public key sizes and signature payloads associated with post-quantum primitives. While this represents a considerable size increase compared to the ~32-byte public key typically associated with Curve25519, modern network stacks and buffer configurations handled the increase without any observable degradation or packet loss.[4][9] These results are consistent with performance findings reported by AWS in their TLS deployment tests using the s2n-TLS library, where hybrid PQC handshakes demonstrated production-grade stability under high-throughput workloads.[3][10]
A breakdown of cryptographic operation timings, as summarized in Table 1, further illustrates the computational efficiency of Kyber and Dilithium. At an equivalent target security level of ~192 bits, Kyber-768 key encapsulation completed in an average of 0.201 milliseconds per session, compared to 0.299 milliseconds for ECDH over P-384. Similarly, Dilithium-3 signature generation averaged 0.992 milliseconds per operation, outperforming ECDSA P-384,

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which required 1.702 milliseconds. These performance advantages are attributable to the design of lattice-based schemes, which avoid the scalar multiplications characteristic of elliptic curve arithmetic, and instead rely on polynomial arithmetic optimized for vectorized and constant-time execution on modern CPUs.[13]
These findings support the claim that hybrid PQC configurations not only maintain compatibility with classical TLS implementations but also introduce negligible computational burden. Moreover, the slight performance gains observed in signature generation suggest potential benefits in session initialization and server-side certificate management, particularly in high-volume or latency-sensitive applications.

3.2 IPsec/IKEv2 Tunnel Throughput

The performance assessment of IPsec tunnels secured with hybrid PQC key exchanges yielded similarly favorable results. Using testbed configurations modeled after those reported by Lawo et al., we examined tunnel negotiation and data-plane throughput in two representative deployment contexts: high-throughput data centers and edge-to-cloud mobile connections.
In the data center scenario, where two physical hosts were connected over a 100 Gb/s Ethernet link with hardware offload support for AES-256-GCM, the PQC-enabled IKEv2/IPsec configuration sustained line-rate performance. For maximum transmission units (MTUs) of 1024 bytes or greater, measured throughput approached the physical link limit of 100 Gb/s. At lower MTUs (e.g., 64 bytes), throughput declined to approximately 34 Gb/s due to header overhead and increased interrupt frequency, but still remained within expected tolerances for small-packet processing. When tested with mid-size frames (MTU ≈512 bytes), throughput recovered to ~95 Gb/s. Crucially, the addition of Kyber-768 as a hybrid component in the IKEv2 key exchange did not introduce measurable degradation, indicating that the key negotiation phase did not constrain the data path.[5]
In a separate test simulating an edge computing scenario, a Jetson Nano device (quad-core ARM Cortex-A57) was used to establish an IPsec tunnel with a remote cloud gateway. Despite its limited CPU and memory resources, the device maintained a stable encrypted tunnel with sustained throughput of 0.486 Gb/s. This result confirms the viability of PQC-enhanced IPsec even in constrained environments, provided that efficient cryptographic implementations and hardware-assisted encryption (e.g., AES-GCM via ARM Crypto Extensions) are utilized.[6]

Taken together, these results affirm that post-quantum key exchanges, when deployed in hybrid configurations within TLS and IPsec, do not pose a significant barrier to performance. The symmetric encryption mechanisms (AES-GCM) remained the dominant factor in throughput performance, and the introduction of Kyber and Dilithium did not introduce latency spikes or bottlenecks in tunnel negotiation or data transfer phases

Table 1. TLS cryptographic operation times (mean) for PQC vs classical algorithms (security ~192-bit)

Operation	Algorithm	Security	Time (ms)
TLS key agreement	Kyber-768 (PQ)	192-bit	0.201
	ECDH P-384 (Classical)	192-bit	0.299
TLS signature	Dilithium-3 (PQ)	192-bit	0.992
	ECDSA P-384 (Classical)	192-bit	1.702

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The comparative results in Table 1 demonstrate that post-quantum algorithms perform at parity with—or exceed—the efficiency of established classical schemes at comparable security levels. While the differences in absolute time are modest, they become increasingly relevant in high-frequency session environments, such as load-balanced HTTPS frontends or IoT deployments.[3][4][5][10]

4. Discussion

The findings of our evaluation support the viability of integrating post-quantum cryptographic algorithms—specifically Kyber and Dilithium—into existing cloud security protocols, including TLS 1.3 and IKEv2/IPsec, with minimal degradation to performance. Empirical results from both controlled and industry-grade environments demonstrate that the additional cryptographic overhead introduced by post-quantum primitives remains well within acceptable bounds for latency-sensitive and high-throughput applications. In the case of TLS, the observed handshake latency increase of approximately 0.2 to 0.3 milliseconds is negligible when considered alongside typical network round-trip times, which routinely exceed tens of milliseconds in geographically distributed systems.[13] Similarly, IPsec tunnel setup and sustained throughput remained stable across a variety of MTU settings and link capacities, confirming that PQC-enhanced key exchanges do not inhibit scalable tunnel provisioning or data-plane performance, particularly when AES-GCM encryption is hardware-accelerated.[11][12]
Nevertheless, several practical and architectural considerations must be addressed to ensure robust and secure integration of PQC in production environments:

Message Size and Memory Overhead. One of the most prominent differences between classical and post-quantum cryptographic primitives is the size of public keys and signatures. For example, Kyber-768 public keys are approximately 1,088 bytes, a substantial increase over X25519's 32 bytes.[14] Similarly, Dilithium signatures are multiple kilobytes in size, depending on the chosen security level. This enlargement increases the size of handshake messages in TLS and IKEv2, potentially impacting initial connection latency and stressing intermediate network devices. In our TLS 1.3 handshake tests, the aggregate increase of ~2.3 KB in message size required no special adjustments on modern cloud servers, but the same may not hold true for legacy appliances, middleboxes, or constrained embedded systems. Protocol implementers must verify that buffers, MTU settings, and fragmentation handling are appropriately tuned to accommodate these larger payloads.[11][12]

Hybrid Key Agreement Strategies. In all tested configurations, we employed hybrid key exchanges combining a classical scheme (e.g., ECDHE) with a post-quantum counterpart (e.g., Kyber). This dual-key strategy offers strong transitional security guarantees: as long as either cryptographic primitive remains secure, the resulting session key is protected. While hybridization increases computational load—nearly doubling key exchange computations—our tests confirm that the additive overhead remains modest and does not compromise protocol responsiveness.[3][6] Organizations such as AWS explicitly recommend this model as a practical and secure interim solution while PQC standards and support infrastructure mature.[1]

Standards Readiness and Library Support. A key factor in PQC deployment is the

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availability of standards-compliant and cryptographically sound implementations. Although TLS 1.3 and IKEv2 remain the dominant secure transport protocols, neither includes native support for PQC ciphersuites in their current standardized forms. However, active working groups within the IETF are advancing extensions to support hybrid and pure post-quantum configurations, including draft specifications for PQC-enabled TLS and IKE negotiation mechanisms.[6] On the implementation side, cryptographic libraries such as AWS's s2n-TLS, OpenSSL (via the liboqs plugin), and wolfSSL now provide experimental support for Kyber and Dilithium.[3][4] Our use of s2n-TLS benefited from low-level optimizations, including constant-time assembly routines for Kyber key encapsulation. It is essential, however, that developers remain vigilant: early implementations of PQC algorithms revealed side-channel vulnerabilities (e.g., the "KyberSlash" timing leakage), which have since been mitigated through hardened code paths.[17] Production environments should rely exclusively on formally audited, side-channel-resistant, and ideally FIPS-certified implementations to minimize risk.

Certificate Ecosystem and Trust Infrastructure. While our experiments focused primarily on key exchange, full post-quantum readiness also requires the migration of the certificate infrastructure to quantum-safe signature schemes. Presently, the vast majority of X.509 certificates used in TLS and IPsec employ RSA or ECDSA signatures. Transitioning to PQC-compatible certificates—e.g., those signed using Dilithium or SPHINCS+—requires coordinated updates across certificate authorities (CAs), browser root stores, and operating system trust anchors. In the interim, hybrid certificates or cross-signed composite chains may be used to enable gradual interoperability. Notably, major providers such as AWS are prioritizing PQC key exchange in their TLS endpoints while broader certificate support continues to evolve.[6]

In sum, our results align with those published by industry and academic sources: lattice-based post-quantum schemes such as Kyber and Dilithium are not only theoretically secure but practically deployable within performance-critical cloud environments.[10] The primary barriers to widespread adoption are no longer technical, but organizational. Providers must undertake systematic cryptographic inventories, prioritize the upgrade to TLS 1.3 and modern IPsec stacks, and begin evaluating hybrid PQC deployments in staging environments. Initiatives such as NIST's Post-Quantum Cryptography Project, NSA's CNSA 2.0 suite[16], and IETF's hybrid handshake specifications provide a clear roadmap for industry alignment.

As major infrastructure operators like AWS, Google, and Cloudflare continue to integrate PQC support into public services,[1][2] it is imperative that enterprise stakeholders and government agencies proactively follow suit. Early adoption not only reduces the long-term risk of retroactive decryption but positions organizations to comply with forthcoming regulatory and compliance frameworks mandating quantum-safe encryption for national security and critical infrastructure protection.

5. Conclusion

This study has examined the integration of post-quantum cryptographic algorithms—specifically CRYSTALS-Kyber for key encapsulation and CRYSTALS-Dilithium for digital signatures—into core cloud security protocols, namely TLS 1.3 and IPsec (IKEv2). Empirical results from both simulated and real-world testbeds confirm that the adoption of these algorithms in hybrid configurations is technically feasible and imposes minimal performance overhead. In the case of TLS 1.3, the introduction of Kyber-based key exchange mechanisms

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adds only a few hundred microseconds to the handshake process and increases message size by a modest 2–3 kilobytes—well within tolerable limits for most cloud networking environments. Similarly, PQC-enhanced IPsec tunnels were shown to maintain line-rate throughput in high-capacity data centers and deliver reliable performance in constrained edge deployments.[5][11]
The findings substantiate the broader industry movement toward post-quantum readiness. Leading cloud service providers and security vendors are actively integrating Kyber and Dilithium into cryptographic libraries, transport stacks, and endpoint devices. These developments align with the recommendations of global standardization bodies, including NIST and the IETF,[6][7] and reflect a pragmatic acknowledgment of the need to future-proof secure communications infrastructure.
Nonetheless, successful deployment requires a carefully managed transition. Particular attention must be paid to the handling of increased key and signature sizes, mitigation of potential side-channel vulnerabilities, and interoperability between classical and quantum-safe systems. Hybrid key agreement schemes offer a practical and secure migration path, allowing for graceful fallback during the early phases of adoption. Moreover, the migration should be accompanied by upgrades to protocol versions (e.g., TLS 1.3 and IKEv2) and the use of rigorously vetted, side-channel-resistant implementations.[17]
Looking ahead, future research and operational validation are necessary to monitor the behavior of PQC algorithms in long-lived, production-scale deployments. Areas of interest include performance under high-load conditions, resilience to real-world network volatility, and robustness against emerging attack vectors. By initiating transition planning today and conducting staged deployments of PQC-enabled systems, cloud service providers can ensure that their platforms remain secure against both current and foreseeable cryptographic threats—including those posed by large-scale quantum computers.
In conclusion, Kyber and Dilithium present a viable and efficient foundation for post-quantum secure communications. Their integration into TLS and IPsec represents not only a technical advancement but also a critical step toward preserving confidentiality, integrity, and trust in the next era of digital infrastructure.

Acknowledgements

We would like to thank the teams at AWS, Cisco, and the Open Quantum Safe project for providing tools, code libraries, and performance data that supported our work. We also thank the developers of the s2n-TLS library and the Kyber and Dilithium implementations for making their work available to the public. Their contributions made it possible for us to test and evaluate post-quantum cryptography in real-world settings. Any mistakes or oversights in this paper are our own.

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