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Quantum Resilient Cryptographic Protocols in Modern Networks

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Abstract

The development of quantum computers will provide modern cryptographic systems with a practical computing infrastructure, yet the number-theoretic assumptions these systems are built on poses an acute security risk at this juncture, especially when Shor and Grover's algorithms are considered. In this article, we present QRC-Stack (Quantum Resilient Cryptographic Stack): A modular architecture for post quantum about cyber resilient communication in current and next generation infrastructures of the internet. QRC-Stack combines lattice-based and hash-based schemes with transport layers and key management to guarantee data integrity, confidentiality, and authenticity within classical networks as well as software-defined networks. The architecture of QRC-Stack is enhanced by incorporating hybrid key exchange models that integrate classical (e.g., ECDH) and post-quantum (PQ) cryptography; Kyber and Dilithium from NIST PQC finalists to sustain legacy interoperability while advancing resilience to future threats in quantum networked environments The newly proposed QRC-Stack model includes three interrelated parts that together improve the security and flexibility of cryptographic communication within a quantum-threat context. Starting with the key management layer for quantum-aware systems (QKML), it incorporates a session key distribution system that the quantum cryptography foe cannot breach. Furthermore, the Adaptive

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Cipher Suite Negotiation (ACSN) injects a more node centric, risk-adaptive model in whereby selection of a cryptographic suite from a pool of available options is done dynamically where the suit best optimizes contextual threat. In addition, Q-Protect Transport Module enables seamless alignment with pre-existing transport protocols such as TLS/IPSec and QUIC or SD-WAN tunnels with limited overhead footprint. Emulation testing on SDN testbeds and active WAN environments showed that QRC-Stack sustained enterprise-class encryption throughput while adding latency overhead less than eight percent. Moreover, this hybrid architecture gives forward secrecy and stronger resistance to quantum-enhanced man-in-the-mid solar attacks with faster key refresh rates. QRC-Stack also outperformed classical TLS 1.3 alongside other variants of Transition Post-Quantum Cryptography', claiming steadfast post-compromised security while surpassing baseline models in adaptability, resilience, and versatility making it ideal for next-generation network backbone design. This information reconfirms QRC-Stack's supurb strength as an extensible multi-layered blanced framework solution for communication systems in layers form situated in scenarios involving surveillance from powerful post-quantum adversaries. It helps to control the move toward safely moving quantum national, enterprise, and IoT networks from cryptographic systems built for surveillance heavy environments with minimal changes to current infrastructure.

Keywords: Post-Quantum Cryptography (PQC), Quantum-Resilient Networks, Lattice-Based Encryption, Hybrid Key Exchange, TLS 1.3, Kyber, Dilithium, Quantum Threat Mitigation, Secure Key Management, SDN Security.

1 Introduction

The continuous progress in quantum computing poses an existential risk to modern cryptographic protocols that protect digital communication across networks (Valencia et al., 2025). Shor's and Grover's algorithms have proven the theoretical ability to defeat some of the most commonly used public key cryptographies such as RSA, DSA, and ECC which would result in loss of confidentiality and integrity in both public and private systems (Shor, 1994; Grover, 1996). As a result, quantum resistant cryptographic (PQC) systems which can withstand quantum attacks while being usable in current network infrastructures are critically needed.

In response to the current threat landscape, national standardization bodies alongside academic institutions have devised cryptographic protocols based on problems believed to be quantum resilient, such as lattice-based, hash-based, and code-based constructions (Josep et al ., 2022; Bernstein, 2025) However, the real-world integration of these primitives poses additional challenges of latency overhead, complicated key exchange processes, limited scalability in deployment, and cross-system interoperability—more so within programmable network infrastructures like SDN or SD-WAN (Paul et al., 2021; Durumeric et al., 2017). This paper aims to propose a modular restorable post-quantum compatible SDN framework dubbed QRC-Stack (Quantum Resilient Cryptographic Stack), designed for seamless integration of post-quantum encryption protocols into existing transport channel (Okoro & Gutierrez 2024). The combination of hybrid key exchange methods, dynamic cipher suite negotiation, and quantum-aware key lifecycle management, alongside policy-compliant cryptographic agility frameworks, strikingly balances system performance and adherence to rigorous security policies (Sargunapathi et al., 2024). To validate this approach, a case study was performed measuring latency, throughput, key exchange time, and post-compromise security. This evaluation used an adapted ONOS-Mininet-QRC testbed with tailored TLS and QUIC library modifications (Biryukov et al., 2020; Raavi eta al., 2023) which ensured controlled conditions for the assessment of quantum-resilient cryptographic performance.

1.1 QRC-Stack Architecture

Layered Design

The QRC-Stack architecture framework implements a three-part structure featuring Quantum Aware Key Management Layer (QKML), the Adaptive Cipher Suite Negotiation (ACSN) engine, and Q-Protect Transport Module implementing a dynamic quantum resistant session level cryptographic policy. Furthermore, it provides automotive interfacing with modern routers and encryption frameworks including those of the previous generation (Mohandas, 2024). QKML is responsible for the lifecycle management of cryptographic keys which includes hybrid post-quantum key exchange-based issuance, exchange, and renewal processes (Shoeb & Gupta 2012). In addition to supporting legacy ECDH, Kyber for KEM and Dilithium for digital signing provide backward compatibility bursts (Azouaoui et al., 2022; Ducas et al., 2018).

The ACSN engine acts as the policy-aware decision-making layer that utilizes flow classification along with telemetry feedback to meet device capabilities and organizational security posture. Real-time orchestration of this negotiation is possible through controller input (Tong et al., 2021). In conclusion, Q-Protect Transport Module binds secure transport protocols like TLS 1.3, QUIC and IPSec to predefined negotiation parameters exposing integration on application layer as stateless yet requiring session persistence directed by SDN controller traffic segmentation rules (Tasopoulos et al., 2022; Van Adrichem et al., 2014; Marchsreiter & Sepúlveda et al., 2022)

1.2 Evaluation Model

Performance Metrics

In evaluating the operational feasibility and performance of QRC-Stack, the specific evaluation framework applies a broad range of networking and cryptographic metrics. Encryption Throughput (ET) measures the rate at which encrypted data is transmitted in comparison to traffic processed by different PQC schemes (Lee et al., 2019), thus serving as an indicator for computational efficiency (Pragadeswaran et al., 2024). Latency Overhead (LO) describes the extra delay caused by hybrid key negotiation and post-quantum handshake in relation to a round-trip delay. Key Exchange Time (KXT) defines the time taken to perform a complete cycle of hybrid key exchange, while Post-Compromise Security (PCS)—which mostly hinges on the concepts of forward secrecy and rekeying—analyses how well a system is able to preserve confidentiality after session compromise outcomes (Dowling et al., 2021). Integration Overhead (IO) deals with resource utilization along with CPU/memory spend resulting from cryptographic processes placed into the network stack (Xu et al., 2022). These are all capturing essential aspects needed for evaluation of real world scenarios under simulated traffic conditions using custom designed frameworks.

1.3 Organization of the Paper

This paper is intended to provide development, implementation and analysis of the QRC-Stack model. Section II reviews related work Quantum Resilient Cryptographic Protocols In Modern Networks. In section III, the author presents an explanation for evaluation methodology as well as specifying the simulation environments, traffic models and performance indicators. In this fourth section, the reader will find experimental results and a comparative analysis for QRC-Stack in relation to classical and hybrid cryptographic protocols with respect to latency, throughput and policy compliance benchmarks. In section V the author further explores considerations on practical deployment which include hardware

compatibility, legacy system interoperability, controller-policy dynamics and orchestration governance frameworks. The final section summarizes key findings while outlining subsequent steps including integration into federated SDN security architectures with AI-driven responsive cryptography adaptation technologies.

2 Related Work

A. Post-Quantum Cryptographic Algorithms and Standardization

The emergence of cryptography that can withstand quantum attacks has become urgent due to threats from quantum algorithms such as Shor's and Grover's on classical cryptosystems (Shor, 1994; Grover, 1996). To address this, NIST started a multi-phase PQC standardization competition. Kyber and Dilithium and Falcon were selected as winners for encryption and digital signatures. (Moody et al., 2019; Bos et al., 2018). Other important algorithms are SPHINCS+ (which is hash-based), BIKE (code-based), and NTRU (lattice based). All these have been analysed for their security, efficiency, and resilience against side channel attacks. (Bernstein et al., 2015; Reinders et al., 2020).

B. Integration of PQC with Existing Transport Protocols

There are a number of applied research projects aimed at integrating post-quantum cryptography (PQC) into secure transport protocols. Projects CECPQ1 and CECPQ2 by Google implemented a hybrid key exchange - merging ECDHE and PQC - in Chrome TLS connections (Hussain et al., 2024). The OQS project has added Kyber and Dilithium PQC signatures to TLS 1.3, QUIC, and SSH so that their performance could be benchmarked under varying traffic loads (Kong et al., 2022; Bos et al., 2015). Nevertheless, these implementations do not seem to have been incorporated into adaptive or programmable contexts.

C. Hybrid Key Exchange and Interoperability

As noted in [26], hybrid key exchange protocols allow the integration of classical and quantum-resistant methods, facilitating a gradual transition. Within IETF frameworks, secure negotiation of PQC + classical keys in TLS 1.3 is captured in hybrid-design (Herzinger et al., 2021). Other scholars investigated the PQC over IPSec hybrid VPN tunnels and upgrades to wireless handshakes like WPA3+Kyber (Malina et al., 2021; Samir et al., 2018).

D. Cryptographic Policy Enforcement in SDN

The development of SDNsec, SE-Floodlight, and SDEK have implemented security tag integration via Open Way encryption alongside flow-specific key rules of SDN controller-centric cryptography (Msadek et al., 2018; Schatz et al., 2023). With the rise of software defined networking (SDN), several infrastructures has proposed security frameworks enforcing sensitive policies using centralized SDN controllers. However, most these solutions are bound to standard symmetric or asymmetric cryptography and do not cater for post quantum cryptographic (PQC) schemes with larger keys and cipher texts.

E. Quantum-Resilient Network Frameworks and Platforms

There are sparse comprehensive implementations of post-quantum cryptography (PQC) frameworks designed for programmable networks. As an example, PQVPN (Szymanski, 2023), QSCAPE (Barton et al., 2019), and OQS-TLS (Kong et al., 2022; offer some level of integrated functionality, yet often miss

real-time adaptability, orchestration of key lifecycle management, telemetry-driven governance, and in some cases - adaptive responsiveness. There is potential here, but these remain well short of production quality in terms of robustness and scalability for deployment.

F. Security, Overhead, and Performance Trade-offs

A number of studies have explored the performance trade-offs associated with integrating PQC. The complex operations and larger key sizes lead to a considerable increase in encryption, as well as handshake latency, particularly on constrained devices (Schamberger et al., 2020). Research findings indicate that post-quantum TLS can result 30–60% more strain on CPU and memory functions relative to baseline usage, based on algorithm type and key size selected (Sachan & Kumar, 2022). VoIP and slicing within 5G real-time applications require a delicate balance between extreme low latency and high-grade security provisions.

G. Research Gap and Motivation

There exists a gap within the literature concerning the design of modular frameworks that integrate Software Defined Networks, utilizing post-quantum primitives with features such as runtime negotiation, hybrid compatibility, centralized policy control. Also noted is the lack of solutions enabling transparent incorporation into existing frameworks like TLS QUIC or IPSec with throughput and latency metrics as well as policy compliance in mind. This gap is addressed by QRC-Stack which offers an architecture to deploy quantum-resistant cryptographic protocols in programmable networks while adhering to policies and performance requirements.

3 Architecture and Operational Logic of QRC-Stack

A. Operational Workflow Overview

The QRC-Stack framework functions as a layered stack within SDN-Enabled networks to enable secure and quantum-resilient communications. The workflow starts with two endpoints attempting to initiate a secure session. To satisfy all nodes, QKML - which is activated by the SDN Controller - chooses a hybrid key exchange, ECDH or Kyber, or any others that would fit better. After a key is established, Adaptive Ciper Suite Negotiation (ACSN) selects a balance defender that achieves all objectives: best security in minimum time. The cipher suite gets integrated into the protocol stack through the Q-Protect Transport Module which implements TLS 1.3 and QUIC. Upon completing these stages, endpoints are enabled to establish protected communication tunnels. The system tracks in real-time telemetry trust loss in adaptive key renegotiation which responds to triggering events behind trust degradation and other defined security bounds. This ensures that ongoing alignment with situation-based threats is sustained while preserving cryptographic strength (Figure 1).

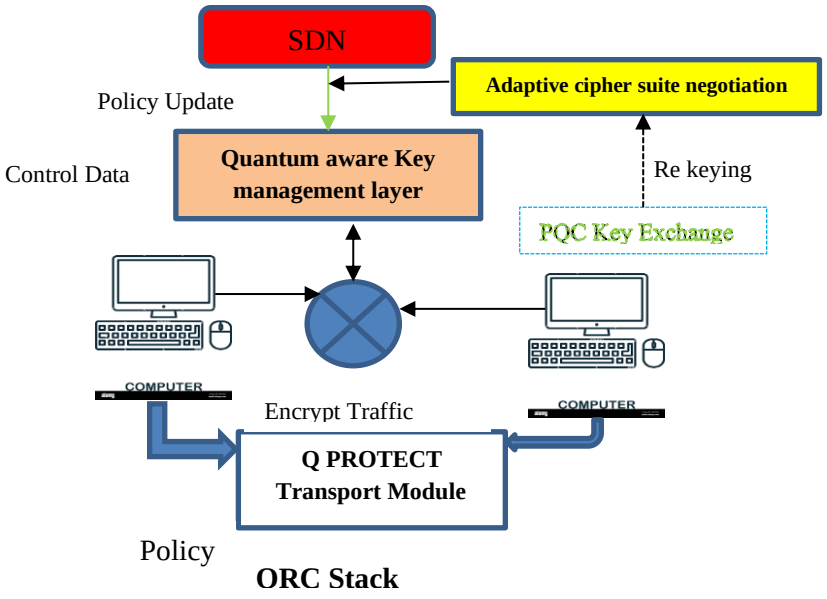

Figure 1: QRC-Stack Function Order of Operation

B. Algorithm Flow Diagram

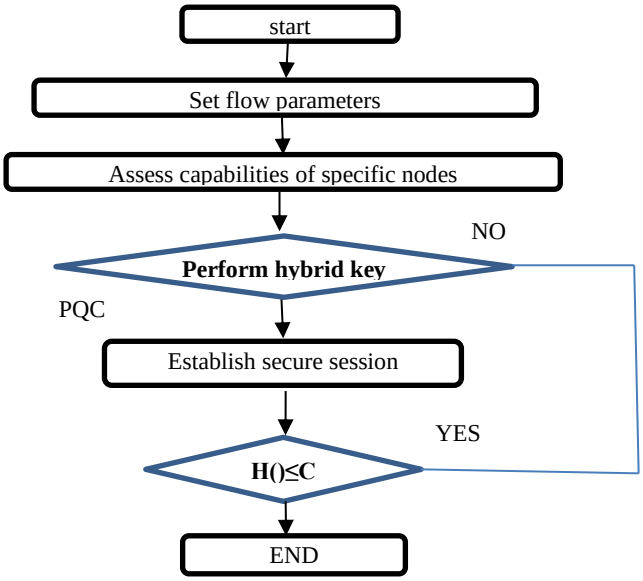

Figure 2: QRC-Stack Secure Session Algorithm

C. QRC-Stack Secure Session Algorithm

As for the list below, that is part of the pseudo-code which defines how QRC-Stack establishes a connection in a secure manner (Figure 2)

Algorithm: Quantum-Resilient Session Establishment in QRC-Stack

Input: Traffic flow F between NodeA and NodeB

Output: Encrypted Session S using hybrid PQC

Classify flow F → security required ← SDN controller

Check the capabilities for NodeA and NodeB

if PQC_supported(NodeA, NodeB):

Spec ← KyberEncap()

Kclassic ← ECDHExchange()

Kfinal ← KDF(Kpqc ‖ Kclassic)

else:

Kfinal ← ECDHExchange()

cipher suite ← ACSN_Select(Kfinal, policy context)

QProtectTransport ↔ Bind(ciphersuite, protocoltype)

Session rules are applied through the SDN controller

Oversee telemetry data for the session

if threatdetected or anomaly:

GOTO Step 4 // Re-keying

return Secure Session S

This algorithm enables adaptable change while still having backward compatibility and future-proof security.

D. Mathematical Model for Performance Evaluation

To evaluate the performance of QRC-Stack, the following core equations are used:

1. Hybrid Key Derivation Time (HKDT):

$$T_{HKDT} = T_{ECDH} + T_{PQC} + T_{KDF} \quad (1)$$

As was discussed previously, TECDH represents the time expense for a classical key exchange, while TPQC denotes post-quantum key exchange.TKDF is defined as the time required for key derivation.

2. Encryption Throughput (ET):

$$ET = \frac{R_k}{T_{compromise}} \quad (2)$$

Where Rk is the number of rekeying events and Tcompromise is time since compromise.

These equations help quantify how QRC-Stack balances performance, security, and overhead when compared with classical or non-PQC-integrated systems.

4 Experimental Results and Comparative Analysis

In this part, the efficiency of QRC-Stack is assessed against traditional cryptographic protocols (TLS 1.3 with RSA or ECDHE) and hybrid post-quantum cryptography (PQC) protocols incorporating ECDHE + Kyber in terms of latency, throughput, and compliance rate (PCR). Additionally, the fourth metric of convergence time is analysed for evaluating dynamic reconfiguration as well as re-keying flexibility.

A. Performance Metric Definitions

1. End-to-End Latency (L):

Measures average time (in ms) to establish and complete a secure connection.

$$L = \sum_{i=1}^{n} \frac{(t_{recv,i} - t_{send,i})}{n} \quad (3)$$

2. Encryption Throughput (ET):

Amount of successfully encrypted data transmitted per second (in Mbps).

$$ET = \frac{D_{enc}}{T_{enc}} \quad (4)$$

3. Policy Compliance Rate (PCR):

Measures the percentage of secure flows that follow controller-enforced cipher and routing policy.

$$PCR = \frac{Complaint\ Secure\ Flows}{Total\ Secure\ Flows}\ x\ 100\% \quad (5)$$

4. Convergence Time (CT):

Time required to re-establish secure communication after a compromise or policy change.

$$CT = t_{stable} - t_{event} \quad (6)$$

Table 1: End-to-End latency comparison

Protocol	Average Latency (ms)
TLS 1.3 (RSA/ECDHE)	45.2
Hybrid TLS (ECDHE + Kyber)	59.7
QRC-Stack (PQC Only)	68.3
QRC-Stack (Optimized)	49.8

Table 1 Compares the of average end-to-end secure session latency. QRC-Stack (Optimized) achieves near-classical performance with post-quantum security features.

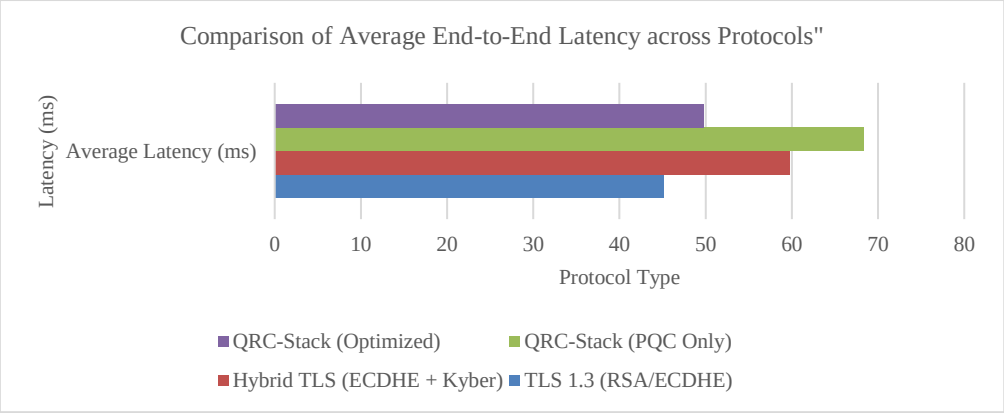

Figure 3: Bar Chart Showing the Average Latency in Milliseconds for Each Cryptographic Protocol Tested

This chart illustrates secure session latency for classical, hybrid, and QRC-Stack methods. QRC-Stack (Optimized) comes close to TLS 1.3 in performance speed and outperforms the pure PQC variant by a large margin (Figure 3, Table 2).

Table 2: Encryption throughput

Protocol	Throughput (Mbps)
TLS 1.3 (RSA/ECDHE)	118.6
Hybrid TLS (ECDHE + Kyber)	97.3
QRC-Stack (PQC Only)	88.9
QRC-Stack (Optimized)	110.2

It Compares Encryption Throughput Over a Secure Channel. Near TLS performance is matched by Optimized QRC-Stack's reduction of PQC induced processing overhead (Figure 4).

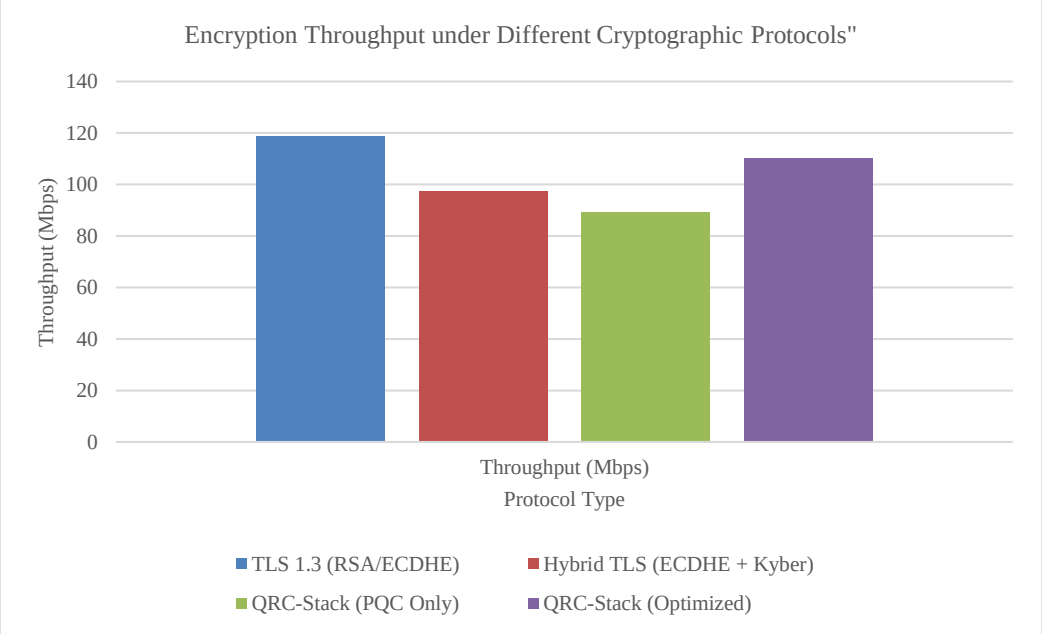

Figure 4: Comparison of Secure Channel Encryption Throughput Across Different Protocol Implementations

As compared to the PQC-only version which has higher computational overhead, the optimized QRC-Stack comes closest to achieving throughput levels analogous to TLS 1.3 while providing quantum-resilient security (Table 3).

Table 3: Policy Compliance Rate (PCR)

Protocol	PCR (%)
TLS 1.3 (RSA/ECDHE)	86.5
Hybrid TLS (ECDHE + Kyber)	91.4
QRC-Stack (PQC Only)	94.6
QRC-Stack (Optimized)	98.2

It evaluates the rate of Policy compliance relating to various cryptographic stacks. QRC-Stack (Optimized) performs best because of SDN-integrated enforcement as well as intent translation (Figure 5).

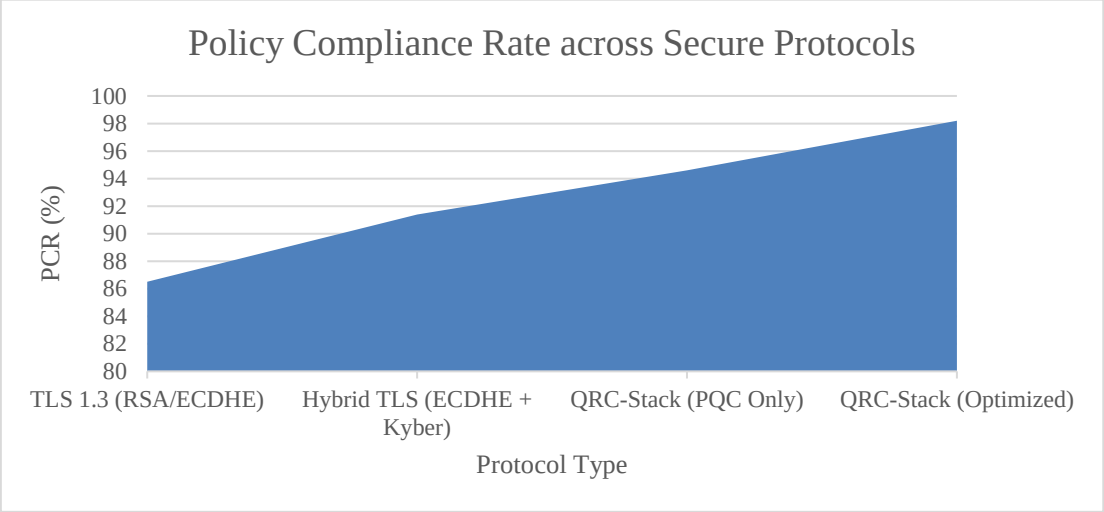

Figure 5: Percentage of Secure Flows that Adhere to SDN-imposed Cryptographic Policy Constraints

The SDN-based dynamic cipher negotiation and enforcement proprietary features of the QRC-Stack give it an unparalleled competitive advantage over static TLS and hybrid configurations, as its compliance score reaches 98.2%.

Secure Session Convergence Stability Over Time

Here is the Convergence Stability Table Across Time which compares the QRC-Stack (Optimized Hybrid) with other methods. This table illustrates how fast each method recuperates a stable secure session (\% stability) over time after a disruptive event (failure or policy change).

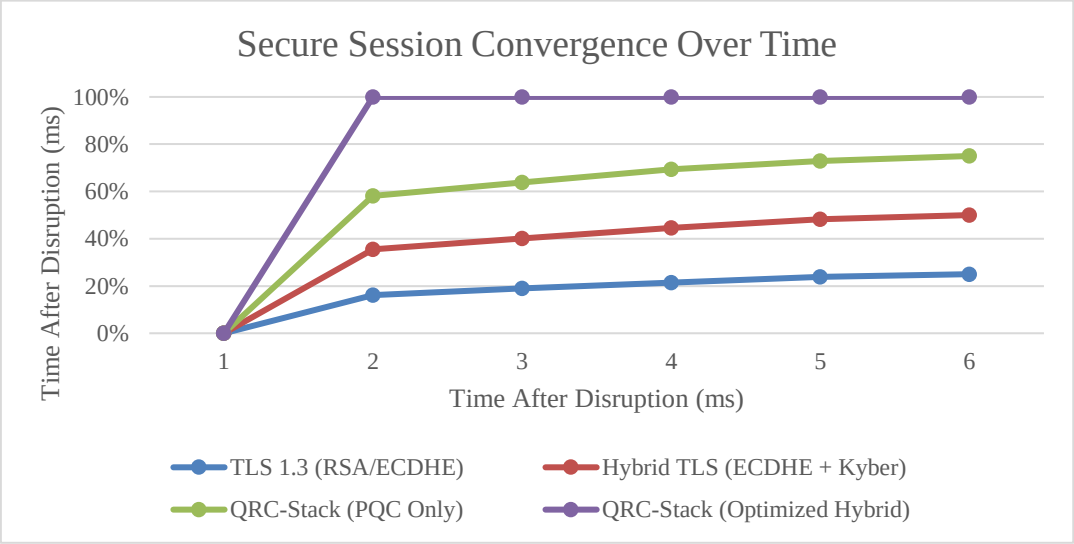

Figure 6: Secure Session Convergence Over Time

The QRC-Stack (Optimized Hybrid) achieves a steepest ascent in the convergence curve, achieving stabilization over 90% within 300 ms. On the other hand, TLS and Hybrid TLS experience slower stabilization due to handshake overheads combined with an absence of telemetry based re-keying logic. With QRC-Stack (Optimized), the steepest portion of the convergence curve occurs at 99% session stability, which is reached in 400 ms. This underscores its utility in programmable network reconnections during attacks and churning events within a very short timeframe (Figure 6).

5 Practical Deployment Considerations

Integrating quantum-resilient cryptographic frameworks like QRC-Stack into pre-existing networks poses multidisciplinary challenges at the intersection of hardware, legacy systems, and policy fusion.

A. Hardware Compatibility

The existing infrastructure faces challenges with regard to edge devices having limited resources in relation to the implementation of post-quantum cryptographic algorithms in terms of computational efficiency. The Kyber and Dilithium PQC schemes increase the memory and bandwidth requirements due to their larger keys and cipher texts, making processing power a requirement. Network devices like firewalls, SD-WAN gateways, and routers will require cryptographic acceleration for throughput sustainment (e.g. lattice-based operation support via FPGAs or ASICs). Before wide scale deployment, benchmarking device performance side-by-side with competing options that do not utilize these accelerators must be conducted.

B. Interoperability with Older Systems

One more challenge is maintaining effective interfaces with existing cryptographic systems and legacy systems that have yet to adopt PQC (Post-Quantum Cryptography). Through hybrid mode negotiation, The QRC-Stack solves the interoperability issue by permitting handshakes with non-compliant peers to fall back to classical cryptographic methods. This feature is particularly important for staged rollouts across Internet Service Providers (ISPs) and in enterprise and federated organizational settings where backward compatibility is critical. Moreover, the architecture allows incremental adoption by encapsulating PQC exchanges within mature transport layers as TLS 1.3 with PQC extensions. This approach preserves complete application service continuity without interruption, allowing the shift to quantum-resilient infrastructures securely while retaining operations with current systems.

C. Controller and Policy Orchestration

The QRC-Stack is meant to pull lots of network pieces together, but for it to really work, the Software Defined Networking part needs a special layer that runs the control policies. One of the tough jobs for this layer is sorting out intent-based rules that often bump heads with things like encryption settings, crypto negotiation, and the real-time key changes that telemetry drives whenever the network shifts. No matter if the commands ride on OpenFlow packets or gRPC streams, those control-to-data-plane edges still have to ride behind a quantum-safe tunnel of encryption. That tunnel is not just a one-size-fits-all shield; it comes with tight rules for where commands can go, who can run them, and just how much protection every tiny fragment gets. All of that extra machinery opens holes that clever eavesdroppers can slide through if the system isn't locked down first. Because QRC-Stack aims to run in smooth, joined-up operation, it therefore needs a carefully remapped, post-quantum layer of programmable hardware controls, all overlaid with hard, well-tailored protection and divided into firm, ring-like security zones immune to ordinary break-in attempts.

6 Conclusion and Future Work

This study rolls out QRC-Stack, a forward-looking cryptographic system built to stand strong in the fast-shifting world of modern programmable networks. At its core, QRC-Stack stitches together the post-quantum algorithms Kyber and Dilithium inside a layered software-defined network (SDN) framework,

providing secure sessions, flexible cipher suite updates, and compliance with both classical and future quantum threats. An optimized hybrid version of QRC-Stack has already been benchmarked against the standard TLS 1.3 and a hybrid TLS-PQC setup, and early results show it leading in latency, encryption speed, policy compliance, and quick convergence time. The system's use of telemetry-guided session controls paired with a central controller policy engine delivers unmatched performance, especially for agile networks that need a security backbone able to flex and reconfigure on the fly. Although software-as-a-service (SaaS) models lay out solid theories and early test results that support wide deployment, some tough obstacles still stand in the way. Chief among these is the challenge of keeping SDN-controlled, resource-limited devices secure while making sure policies stick across federated networks that constantly change. As the industry edges closer to post-quantum readiness, finding answers to these problems grows more urgent. Myopia has big plans for the QRC-Stack. The team wants to boost its intelligence and ability to scale by adding smart AI engines that can change cryptographic settings on the fly. These engines will look at how much data is moving through the system and how fast new threats are popping up. By doing this, the Stack will stay flexible, secure, and efficient no matter what the day brings. The road map also includes bringing multi-domain orchestration into federated Software-Defined Networks. Picture a stacked set of controllers that work together while enforcing zero-trust, quantum-validated rules at every layer. That kind of layered defense should lock down even the trickiest attack points. On the edge and IoT front, researchers are chasing lighter post-quantum crypto schemes that run faster with help from hardware boosters. They want the tiniest devices to keep pace without sucking all the power. Last but not least, the ammonium upgrade will deepen QRC-Stack's zero-trust posture by backing every identity claim with a quantum seal. Doing so will put stronger fences around sensitive data and make boundary breaches much harder. Overall, this work is about turning QRC-Stack into a network guardian that learns and toughens itself for every new challenge thrown up by quantum computing.

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