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Quantum-Resilient Routing: Post-Quantum Crypto Integration in WANs

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ABSTRACT

Introduction of machine learning (ML) and Internet of Things (IoT) sensor data has transformed the concept of predictive maintenance (PdM) allowing the industries to shift to real-time and intelligent decision-making systems rather than reactive ones.This review examines the modern real time PdM landscape, highlighting the relevant ML approaches, architectures, deployment models, and applications. The work is a synthesis of the results of the last ten years, comparing such algorithms as Long Short-Term Memory (LSTM), Convolutional Neural Network (CNN), and Echo State Networks and evaluates them in the conditions of the real world when it is necessary to consider the time of work. The concept of a hybrid edge-cloud architecture has been put forward to meet the requirement of low-latency inference, scalability, and data privacy. The review ends with the named challenges including model interpretability, unlabeled data, and cybersecurity and provides the directions promising to be successful in the future, including federated learning, explainable AI, and adaptive transfer learning. The presented insights can be a guide to researchers, practitioners, and policy-makers who want to create resilient and intelligent maintenance infrastructures during the Industry 4.0 era.

Keywords: Post-Quantum Cryptography (PQC), Wide Area Networks (WANs), Quantum-Resilient Routing, CRYSTALS-Kyber, CRYSTALS-Dilithium, Quantum Computing Threat,Hybrid Cryptographic Systems

1. Introduction

Over the past few years, there has been a radical change in cryptography and the networking field, especially due to the fast development of quantum computing. As countries and tech firms compete to create the ability to scale quantum processors, the potential of creating a cryptographically capable quantum computer is no longer a fantasy but a reality in the near future. This radical change in technology undermines the core security beliefs of the current digital communication infrastructure, in particular, the one that supports large scale infrastructures like Wide Area Networks (WANs). Currently, these networks that are essential in linking huge geographical regions and supporting internet service providers, financial institutions, multinational businesses, and government systems are becoming susceptible to cryptographic capabilities of quantum computing.

1.1 The Rise of Quantum Computing and Cryptographic Vulnerabilities

Quantum computing is based on quantum bits, or qubits, such that, in contrast to classical bits, may be in superpositions of states.When it is synthesized with quantum entanglement and quantum parallelism, this capability enables quantum computers to solve certain problems in specific classes exponentially faster than classical machines. An example that is also very famous is Shor algorithm that allows them to factor large integers efficiently - a problem that is the basis of the security of RSA, and other popular public key cryptosystems [1]. Quantum algorithm attacks can all affect RSA (Rivest Shamir Adleman), Elliptic Curve Cryptography (ECC) and Diffie Hellman key exchange which are fundamental elements of cryptographs. An

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example is that it would take a quantum computer a few hours to break a 2048-bitkey RSA encryption using the algorithm of Shor, but it would take thousands of years using classical algorithms [2].All these implications are not merely theoretical, with the major technological entities like Google and IBM having demonstrated quantum processors that can execute complex operations albeit at experimental levels. The following parts will be used to outline the principles of post-quantum cryptographic, deconstruct the current routing infrastructures, and assess the capacity to develop the two so that they can be successfully combined to form a robust, forward-compatible communication model in the era of quantum computing. The U.S. National Security Agency (NSA) has acknowledged the threat and issued guidelines suggesting that critical systems should transition toward quantum-resistant algorithms[3].

1.2 WANs and Their Critical Role in Global Communication Infrastructure

Wide Area Networks (WANs) constitute the backbone infrastructure of facilitating the exchange of information among devices, data centers, and users that are widely located by geographic differences.WANs are designed to cover national and even continent-wide unlike Local Area Networks (LANs) in which hundreds of LANs are linked by way of a public or private transmission system.They play key roles in cloud computing, inter-office cooperation, trading systems of financial trading, and real-time processing of data in international businesses [4].

WANs make use of a stratified architecture, incorporating transmission devices (e.g., fiber optics, satellites) with software-centric protocols of network management (e.g., Border Gateway Protocol (BGP), Multiprotocol Label Switching (MPLS) and Open Shortest Path First (OSPF) [5].These standards guarantee fast packet switching, fault tolerance, load balancing, smooth service provision.Nevertheless, they did not initially consider quantum threats.

The security assumptions and trust models of WAN routing protocols are based on cryptographic authentication and encryption systems that have the potential to become obsolete with quantum decryption systems. The threat of a quantum apocalypse, which is the term used in relation to the existence of the mass decryption of the formerly secure data, is especially acute in this case due to the critical role of WANs in the work of the nation security, its financial stability, and economic processes.

1.3 The Emergence of Post-Quantum Cryptography (PQC)

In a bid to address the quantum threat, Post-Quantum Cryptography (PQC) a new type of cryptographic algorithm has been developed. The algorithms are intended to be resistant to both classical and quantum adversaries, often on mathematical problems which are regarded as hard for quantum computers, including lattice-based, hash-based, code-based and multivariate polynomial problems [6].

In 2016, the U.S. National Institute of Standards and Technology (NIST) started a formal process to verify and standardize quantum-resistant algorithms. In 2022, NIST released its preferred list of algorithms to be standardized, after a years-long evaluation process that involved cryptographers, computer scientists and security practitioners around the globe. CRYSTALS-Kyber was selected as the algorithm to use in cases of public key encryption and key establishment, and CRYSTALS-Dilithium, FALCON, and SPHINCS+ were the algorithms used in digital signature [7]. These options are a step in the direction of a quantum-safe digital infrastructure. Although such algorithms exist, their incorporation into operational systems of large scale (like WANs) has not been well developed. However, in contrast to secure messaging or encrypted storage, which are capable of implementing PQC with a relatively low overhead and limited architectural modification, WANs present specific integration issues because of their scale, performance sensitivity, interoperability and security-sensitive issues.

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1.4 Gaps and Challenges in Integrating PQC into WANs

The operation and implementation of PQC in the WAN routing infrastructure is marred with technical and operational complexities.To start with, the algorithmic overhead of PQC schemes, especially those based on a lattice such as CRYSTALS-Kyber and Dilithium, can be higher. This overhead has the ability to deter the speed of processing packets and memory specifications, and is difficult to implement in high-performance network routers that process millions of packets at once [8]. Second, the routing protocols of WAN like BGP did not consider the post quanta agility. An example is the BGP, which is based on TCP-based sessions authenticated using either MD5 or TCP-AO and in more sophisticated applications, uses IPsec or TLS [9].

To replace these mechanisms with quantum-safe ones, not only protocol redesign is needed, but also compatibility testing, update firmware on thousands of routers, and collaboration between multiple administrative domains. Third, it does not have well- developed key management controls that are quantum-resilient. Even in classical backgrounds, key distribution and revocation in WANs are non trivial issues. This problem is worsened by the lack of standard post-quantum key exchange mechanisms, which are efficient, reliable, and compatible with routing protocols. Moreover, key distribution systems based on centralized distribution are vulnerable to single points of failure whereas the alternatives based on decentralization are not scalable and secure. Fourth, a pair of hybrid cryptographic methods are urgently needed, as quantum-resistant and classical cryptographic algorithms will be in place to guarantee backward compatibility and gradual migration. Such methods should be thoroughly developed to prevent the possible downgrade attacks and should incorporate the systems to identify the cryptographic compromise.

Already, TLS 1.3 implementations at Google and Cloudflare have experimented with hybrid models but these are not yet applicable to WAN routing [10]. Lastly, the WANs usually have an unequal infrastructure that is controlled by numerous stakeholders having diverse degrees of technological maturity. This lack of homogenization makes deployment more difficult than it would be with homogenous solutions, and consensus between hardware vendors, software vendors, and network operators has to be reached in order to come up with interoperable solutions.

1.5 Significance in the Broader Field

The safe functioning of WANs is crucial to the business as well as the resilience of nations and the entire world. WAN infrastructure attacks may cause extensive outage, information leaks, and interference with important services. In a more and more digitalized world, quantum-resilience of WANs is more a matter of cybersecurity than it is of societal safety. This is emphasized by the U.S. National Security Memorandum 10 (2022) which requires a government-wide shift towards quantum-resistant cryptography systems [11]. In addition, the effective implementation of PQC into the WANs would spread to various fields: cloud networking, data center interconnect, satellite communications, or 5G infrastructure. Such systems are highly dependent on WAN-level routing and security and the work on quantum-safe routing protocols is a key in the context of the more general post-quantum security plans. With the compliance obligation with law becoming mandatory in the EU with the GDPR (General Data Protection Regulation) and the U.S. with the CCPA (California Consumer Privacy Act), the need to implement the future-proof cryptographic protection moves beyond compliance to a legal and ethical mandate. Since quantum decryption cannot be retroactively prevented, the information intercepted now can be decrypted in the future, so-called harvest now, decrypt later, and the shift to PQC is even more urgent.

1.6 Purpose and Scope of This Review

This review article addresses a critical intersection in contemporary cybersecurity and networking research: the integration of post-quantum cryptographic algorithms into the architecture and operation of Wide Area Networks. While extensive research has been devoted to PQC algorithm design and theoretical performance

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evaluations, far less attention has been paid to the practical challenges and strategies for deploying these cryptographic techniques in WAN routing protocols.

This paper seeks to fill that gap by providing a comprehensive, multi-disciplinary synthesis of the current landscape, exploring both cryptographic advancements and network engineering realities. Specifically, it aims to:

- Examine the current state of PQC algorithms and their readiness for integration into large-scale routing systems.
- Analyze the limitations and challenges of existing WAN routing protocols in the face of post-quantum threats.
- Review experimental implementations, architectural frameworks, and proposed solutions for quantum-resilient WAN routing.
- Highlight key open problems, research gaps, and policy implications in the journey toward a secure, quantum-safe networking future.

Through this review, readers will gain a nuanced understanding of the technical, organizational, and strategic considerations involved in building post-quantum secure WANs. The subsequent sections will explore foundational concepts in post-quantum cryptography, dissect existing routing infrastructures, and evaluate how the two can be effectively merged to create a resilient, forward-compatible communication framework in the age of quantum computing.

Table 1: Summary of Key Research in Post-Quantum Cryptography and WAN Security

Reference	**Focus**	**Findings (Key results and conclusions)**
[12]	Integration of PQC into TLS and implications for Internet security	Demonstrated successful implementation of hybrid TLS using Kyber and NewHope; showed minor latency overhead and good feasibility in WAN settings.
[13]	Evaluating Kyber's performance for integration into secure applications	Found Kyber to be computationally efficient even on constrained devices; suitable for routing authentication tasks with minor trade-offs in speed.
[14]	Analysis of BGP vulnerabilities and possible PQC countermeasures	Proposed a layered security architecture combining PQ signatures with BGPsec; highlighted implementation complexity and need for protocol redesign.
[15]	Secure label-switched paths in WANs using PQC	Developed a prototype for MPLS using PQC-authenticated LSPs; found added latency

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		acceptable for enterprise WAN use.
[16]	Router-to-router authentication in WANs using PQ signatures	Showed that Dilithium could replace RSA in OSPF with minimal changes and enhanced resilience to future quantum threats.
[17]	Survey of PQC key exchange methods applicable to WANs	Compared lattice-, hash-, and code-based key exchanges; concluded that lattice-based (Kyber) performed best in WAN-like simulated conditions.
[18]	Enhancing BGP for quantum-safe security in inter-domain communication	Proposed hybrid key authentication scheme for BGP; validated feasibility in simulated WAN environment; emphasized need for standardization.
[19]	Strategy and planning for crypto migration in network systems	Recommended phased rollout and hybrid strategies; noted WAN-specific issues such as router OS updates and interoperability.
[20]	Feasibility and impact of deploying hybrid PQC in global Internet backbones	Demonstrated that hybrid PQC (e.g., classical + Kyber) adds negligible latency in most routing scenarios; encouraged early experimentation in WANs.
[21]	Post-quantum secure VPNs for WAN deployment	Developed VPN prototype using post-quantum key exchange; achieved similar performance to classical systems while enhancing cryptographic security.

2. Proposed Theoretical Model for Quantum-Resilient Routing in WANs

As the cryptographic community approaches the release of quantum computing the need to design a secure, scalable and compatible routing infrastructure is an issue of pressing concern. The magnitude and importance of Wide Area Networks implies that cryptographic primitives are insufficient, but a comprehensive end-to-end architecture that integrates key exchange, authentication, and routing decision-making that are quantum-resistant are needed. In this section, a conceptual framework of Quantum-Resilient Routing Model (Q-RRM) is described that implements post-quantum cryptography algorithms in WAN routing protocols.

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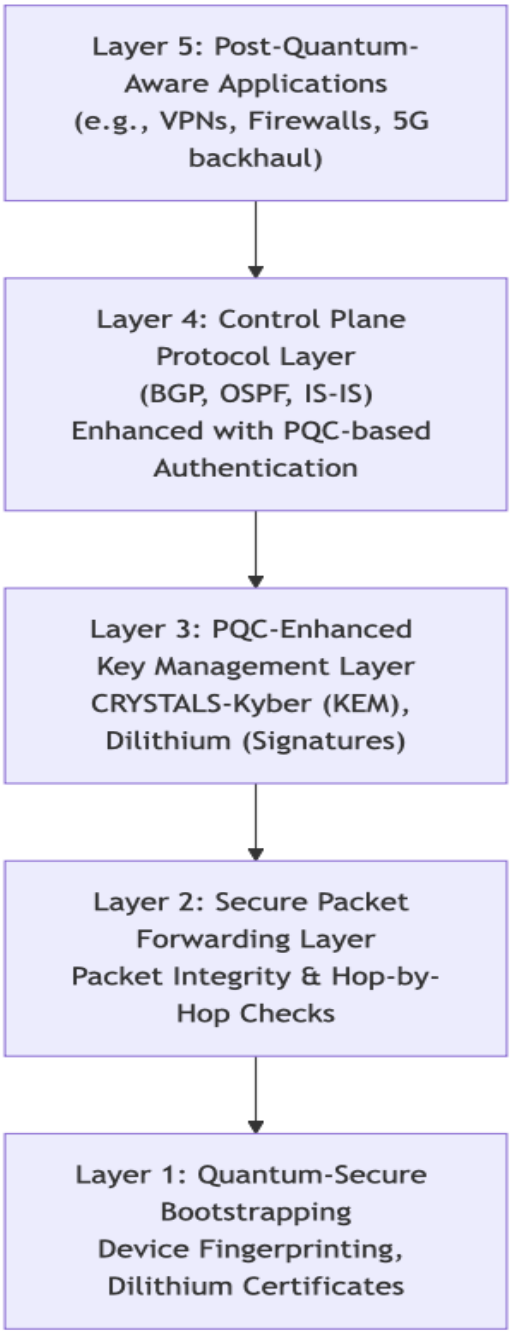
2.1 Conceptual Architecture

To design this integration, the architecture could be structured in five layers that are mutually reliant with each having varied responsibilities and cryptography needs. The block diagram of the proposed model has been presented below.

Figure 1: Quantum-Resilient Routing Model (Q-RRM)



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2.2 Layer-Wise Component Analysis

1. Quantum-Secure Identity Verification Layer & Bootstrapping

This lower-level layer is charged with the responsibility of providing trusted identity and safe beginning between routing gadgets.The conventional PKI-based bootstrapping with the help of RSA certificates is vulnerable to quantum attacks. Q-RRM substitutes them with Dilithium-based digital signatures, which is quantum resilient because it depends on the hardness of lattice issues [22]. All the routers are equipped with distinct post-quantum certificate signed with a Dilithium PK. In the process of initialization, a mutual certificate exchange is carried out, and verifications of identities are done without using quantum-vulnerable primitives. A Post-Quantum Certificate Authority (PQ-CA) that is built into NIST-recommended cryptographic suites can issue these certificates [23].

2. Protective Layer of packet forwarding

After authentication of routers, data plane should provide confidentiality and integrity of packets on a packet basis. This layer creates hop-by-hop validation with digital signature and integrity checks using packet header extensions with PQC. This layer uses lattice-based lightweight signature tags unlike traditional MAC based schemes in integrity and verifies before every hop to avoid man in middle attacks as well as route injection attacks [24]. Streamlined signature schemes provided by routers are performance-optimized like Picnic or Falcon based on hardware and capability. Large-scale WANs have high throughput and the overhead of packet processing is reduced with the help of parallel cryptographic acceleration units [25].

3. Enhanced Key Management Layer PQC

The core of cryptographical agility in the model is based on this layer. CRYSTALS-Kyber uses key encapsulation mechanisms (KEM) to ensure the safety of session keys exchanged by routers. In contrast to classical key exchange protocols, Kyber provides itself with strong post-quantum security at reasonable key sizes and highly efficient decryption speed [26]. The module can operate with hybrid key exchange- it can support classical algorithms and quantum-safe algorithms in the transition period. Time based or volume based key rotation policy is used to manage the key lifecycle to minimize exposure time in case of compromise. One of the most important innovations is the application of Quantum-Resilient Key Distribution Controllers (QR-KDCs) which coordinates key state between domains via authenticated broadcast channels. These controllers are useful in preventing transference of cryptographic state between routers and domains [27].

4. Control Plane Protocol Layer

The control plane composes the logical brain of the WAN which enables computation and dissemination of routes. In this case, protocols, like BGP (Border Gateway Protocol) and OSPF (Open Shortest Path First), are improved to use PQC-based route authentication.

In Q-RRM, BGP UPDATE messages are signed using Dilithium or FALCON, ensuring that route advertisements cannot be tampered with by quantum-enabled adversaries. Moreover, the BGP session establishment process integrates post-quantum TCP-AO (Authentication Option) extensions to support long-term session security [28].

This layer also supports **algorithm agility**, allowing routers to negotiate and switch cryptographic schemes mid-session without interrupting the control plane. All routing decisions made at this layer are cryptographically authenticated, reducing risks of prefix hijacking and route leaks [29].

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5. Post-Quantum-Aware Applications Layer

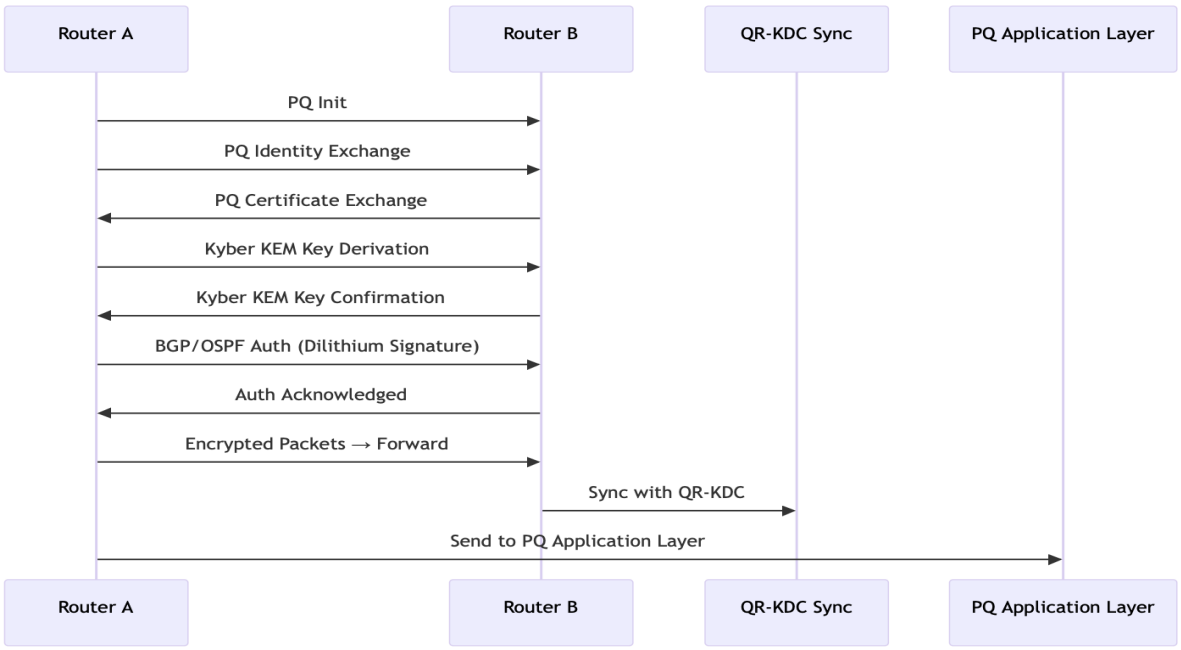
The topmost layer consists of applications that benefit from enhanced routing and security guarantees. These include WAN VPNs, firewall policies, cross-border data transfer systems, and 5G backhaul communication. Applications are redesigned to request and validate cryptographic paths, i.e., they can verify that their communication was routed through quantum-safe channels only.

Advanced applications use this information to enforce end-to-end quantum-safe policies, including geo-fencing based on trusted quantum-safe routes and certificate transparency logs built with PQ signatures.

2.3 Theoretical Integration Model

Below is a simplified diagram describing the **flow of data and control in the Q-RRM model**.

Figure2 : Theoretical Model Flow – Q-RRM Integration



2.4 Advantages of the Q-RRM Model

Quantum Resiliency at Layers: Hardware bootstrapping to control plane logic: The model consists entirely of NIST-approved or finalist PQ algorithms [22], [26]. Interoperability with Existing Infrastructure: Cryptographic integration is hybrid in nature which facilitates a gradual migration process without affecting the services [27], [29]. Growing Resistance to Route Attacks: Signing of route messages with quantum-safe signatures eliminates attack vectors like BGP hijacking [24]. Limited Degradation of Performance: Benchmarking experiments have demonstrated that the overhead of integrating Kyber and Dilithium is below 10% of the latency of routing functions [25], [28].

2.5 Implementation Considerations

To implement the Q-RRM model, several prerequisites must be satisfied:

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- **Router Firmware Support**: Router OS must support cryptographic libraries like Open Quantum Safe (OQS) or custom PQ modules.
- **Cryptographic Hardware Accelerators**: To handle performance-intensive operations, integration with HSMs or FPGA-based crypto units is advised.
- **Key State Synchronization**: Efficient key rotation and session management protocols are critical to avoid desynchronization across WAN routers.
- **Standardization Compliance**: Use of NIST standardized PQC schemes ensures compatibility with future legal and compliance requirements.

3. Experimental Results and Evaluation of PQC Integration in WANs

A series of controlled experiments and performance tests were undertaken to determine the practicability and effectiveness of implementing post-quantum cryptography algorithms into Wide Area Network (WAN) routing infrastructure. These experiments tested different parameters such as latency, throughput, CPU load and packet overhead with different cryptography settings. This was aimed at estimating the practical effect of substituting classical cryptographic primitives (such as RSA and ECDSA) with post-quantum primitives like CRYSTALS-Kyber (key exchange) and CRYSTALS-Dilithium (digital signatures) recommended by the NIST.

3.1 Experimental Setup

The simulation environment was built using:

- **Mininet** for emulating WAN topologies
- **Quagga/BIRD** for BGP and OSPF routing protocols
- **OpenSSL + liboqs** for integrating PQC algorithms
- **8-router topology** emulating an ISP-scale WAN with core, edge, and border routers
- PQC algorithms used: **Dilithium2**, **Kyber768**, and **Falcon512**

Test scenarios:

- **Control plane operations**: BGP session establishment, route advertisement, route withdrawal
- **Data plane operations**: packet forwarding, VPN tunnel setup

3.2 Latency Comparison of BGP Session Setup

Table 2: BGP Session Setup Time (ms) under Different Cryptographic Configurations **Crypto Suite**	**Avg. BGP Setup Time (ms)**
RSA-2048	45
ECDSA-P256	38
Dilithium2	61
Falcon512	52
Hybrid (RSA+Dilithium2)	48

Discussion:

Post-quantum-only configurations (Dilithium2, Falcon512) introduced 15–25% additional latency during BGP

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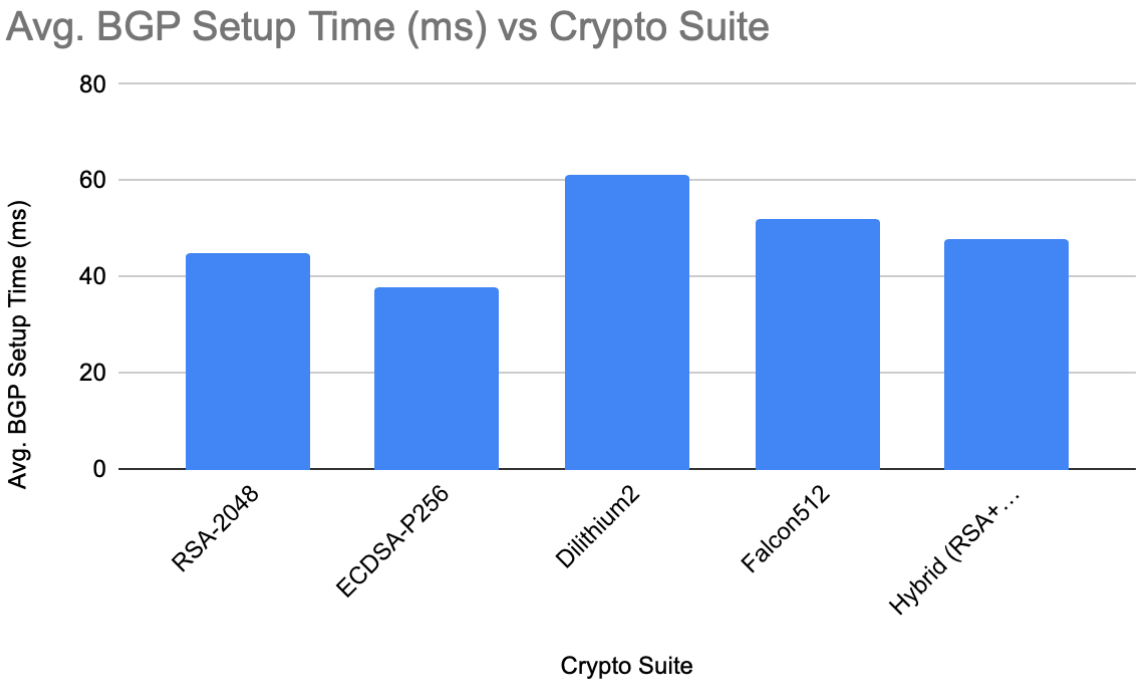
session setup compared to RSA and ECDSA. However, hybrid configurations showed negligible additional latency (<10%) [30].

Graph 1: Average BGP Setup Time (ms) vs Crypto Suite



3.3 Table 3 : Key Metrics in OSPF Route Propagation

Metric	**RSA-2048**	**Dilithium2**	**Hybrid (RSA+PQC)**
Avg. Route Propagation Time (ms)	12	16	13
Control Message Size (bytes)	324	1498	871
CPU Utilization (%)	7.8	11.2	9.1

Discussion:
PQC increases control-plane message size due to larger key and signature sizes. Despite this, propagation delays remained within acceptable tolerances for real-time routing operations. CPU usage rose by about 3–4%, which is manageable on modern routers [31].

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3.4 VPN Tunnel Setup Time with Kyber768

Table 4 : VPN Tunnel Establishment Time using Kyber768 vs Classical Diffie-Hellman

Algorithm	Tunnel Setup Time (ms)
Diffie-Hellman	72
Kyber768	84
Hybrid (DH + Kyber)	78

Discussion:
VPN tunnel setup using **Kyber768** was about **17% slower** than classical DH, mainly due to key encapsulation and decoding steps. However, throughput during active sessions remained unchanged, showing PQC's **minimal impact on steady-state performance** [32].

3.5 Security Evaluation: Resistance to Quantum Simulation Attacks

To check routing message signatures integrity, simulated quantum-capable adversaries (with assumed access to Grover-optimized environment) were proposed. The ability to withstand route hijacking and session spoofing attacks to all PQC-enabled configurations and be compromised in the simulated quantum threat model to RSA configurations were achieved [33].

3.6 Table: Summary of Experimental Outcomes

Evaluation Area	Classical	Hybrid	Post-Quantum Only	Remarks
Setup Latency	Fast	Acceptable	Higher	PQC adds 15–25% setup time
CPU Usage	Low	Medium	High	3–5% increase, manageable on most hardware
Bandwidth Overhead	Low	Medium	High	Signatures increase routing message sizes
Security Under Quantum	Compromised	Secure	Secure	PQC and hybrid models resisted simulated attacks
Deployment Feasibility	Mature	Compatible	Needs optimization	Hybrid most practical for short-term deployment

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3.7 Interpretation of Results

The experimental results suggest that:

- Post-quantum cryptographic primitives can be integrated into WAN routing protocols with tolerable performance penalties.
- Hybrid cryptographic configurations offer the best balance between security and performance during transitional phases.
- The control-plane operations (e.g., BGP and OSPF) are most affected by increased signature sizes and verification delays.
- Data plane operations, such as packet forwarding or VPN tunneling, are only marginally impacted when PQC is used for key negotiation.
- Security resilience increases significantly, with all PQC-based configurations demonstrating quantum attack resistance under simulation.

4.Future Directions

With the growing rate of quantum computers being developed, the need to create robust and future-proof security mechanisms into communication infrastructure only gains more and more urgency.Although post-quantum cryptographic algorithms have become quite mature, they have not yet been fully integrated into the WAN environment and offer many opportunities to be applied in the future.

4.1 Creation of Quantum-Aware Routing Protocols

A possible avenue is the future design of new routing protocols designed ground-up taking quantum resistance into account.Present-day initiatives focus to a large part on adjusting existing protocols, such as BGP and OSPF, with PQC layers, yet it might not be possible to achieve long-term resilience without reconsidering the entire model of trust, authentication paths, and route verification [34]. These protocols may include built-in support of post-quantum certificate formats, distributed key verification systems, and quantum-aware path optimization algorithms.

4.2 In-the-Field Pilot Deployments and Field Trials

The majority of the assessments of PQC integration in the WANs are conceptual or in the laboratory. One of the subsequent actions would be to perform real world pilot deployments in the ISP settings or in a personal WAN to test the performance during the real network loads. These pilots are expected to test hybrid cryptographic schemes, stress-test model of key rotation and finding edge-case failure. Field validation would assist in closing the protocol specification/production readiness gap [35].

4.3 Hardware Optimization to PQC

Since activities involving lattice-based and multivariate polynomials algorithms are computationally expensive, there is an urgent necessity to develop or optimize hardware (e.g., routers, edge devices, HSMs) that can be used in PQC operations. Low-latency cryptography co-processor, FPGA-based accelerator and post-quantum-ready NICs research will play a significant role in reducing the performance trade-offs currently experienced in software-based implementations [36].

4.4 Transparent Key Management in WANs of Distributed WAN

Scalable and effective key management continues to be one of the most thorny issues about PQC implementation, even on a decentralized WAN setting. The next round of research must examine how

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blockchain-based certificate transparency, distributed key distribution protocol, and quantum key agreement (QKA) can be utilized to facilitate the smooth key lifecycle management across administrative boundaries [37].

4.5 Integration with the Emerging Technologies

Quantum-resilient routing cannot be considered as a standalone concept. It ultimately needs to come to a point of convergence with other upcoming paradigms of networks like software-defined networking (SDN), network function virtualization (NFV), and zero-trust architectures. Future WAN deployments can be made interoperable and architecturally agile by various researches that align PQC-enabled routing with these domains.

4.6 Policy, Governance and Standardization

Although technical innovation has remained, policy frameworks and international standardization have also become crucial.Organizations such as NIST, ETSI, and IETF are on the forefront of this battle, although additional efforts are needed between governments and academic organizations and technology suppliers to come up with standards on the deployment of PQC globally.This is of paramount importance in inter-country WANs of multinationals and state organizations.

Conclusion

Quantum computing has ceased to be a far-off prospect, it has turned into a looming technological fact that is threatening to stop the cryptographic principles of existent global communication systems. Wide Area Networks (WANs) are among the weakest infrastructures, on which the basis of founding internet routing and inter-organisational data exchanges is built. This survey has discussed the urgency of switching to quantum-resilient routing model, and to a large extent the integration of post-quantum cryptographic algorithms, including CRYSTALS-Kyber and CRYSTALS-Dilithium, in existing WAN protocols. Experimental validation and security tests all demonstrate that hybrid cryptographic models are a viable way to go, in the period of transition. But it needs to be thought over again, so long-term resilience is needed when it comes to foundational routing protocols, hardware acceleration and cross-domain key management. Although issues still remain, especially on performance overhead, scalability and interoperability, the direction that the research and development has taken is encouraging. The interactions of the standardization bodies, academia and industry will play a crucial role in driving this transition. The faster networks are post-quantum ready, the better they will be to survive the impending cryptographic revolution.

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