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Original Article

The Role of Quantum-Safe Cryptography in Next-Generation Security

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ABSTRACT

Quantum computing offers major computational advances but threatens modern public-key cryptography. Classical algorithms such as RSA, Diffie–Hellman (DH), and Elliptic Curve Cryptography (ECC) are vulnerable to quantum attacks, particularly Shor's algorithm. As large-scale quantum capabilities emerge, post-quantum cryptography (PQC) has become essential to ensure future data confidentiality, integrity, and authentication. This paper discusses the need to replace classical cryptography, explores quantum-safe solutions, and examines challenges in large-scale migration. PQC is critical across government, critical infrastructure, finance, healthcare, telecommunications, IoT, autonomous vehicles, and 6G networks. A key concern is "harvest-now, decrypt-later" attacks, where encrypted data is stored today for future quantum decryption. The study analyzes classical cryptographic vulnerabilities and reviews major PQC families: lattice-based, hash-based, code-based, multivariate-based, and isogeny-based schemes, highlighting the ongoing NIST standardization efforts. It proposes a migration framework including quantum-readiness assessment, algorithm selection, hybrid implementation, and performance evaluation. Results show that although PQC introduces higher computational complexity, optimized implementations can support real-time applications with reasonable overhead. Among PQC approaches, lattice-based schemes appear most mature and balanced in terms of security and key size. The paper concludes that quantum-safe cryptography is a necessary evolution requiring continuous monitoring, adaptable systems, and alignment with emerging standards.

KEYWORDS

Post-Quantum Cryptography (PQC), Quantum-Safe Security, Lattice-Based Cryptography, NIST PQC, Shor's Algorithm, Next-Generation Security, Hybrid Cryptography, Cybersecurity, Quantum Computing Threats.

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1. INTRODUCTION

1.1. Background

Secure communication in the modern and more digital world is underpinned by cryptography which is currently used to defend sensitive information, financial business operations, and personal data in numerous sectors. RSA, Elliptic Curve Cryptography (ECC) and Diffie-Hellman (DH) are traditional-grade public-key cryptographic algorithms that have served to track the decades in guaranteeing the desired confidentiality, integrity and authentication. These are algorithms based on the mathematical problem that is hard to compute such as integer factorization and discrete logarithms to ensure the unauthorized access, it is the key to internet security, e-commerce, and verification of digital identity. The appearance of quantum computing, however, is a huge and unprecedented threat to this landscape. These problems in the foundations of mathematics can be solved quantumly, in the same way, exponentially faster than classical algorithms, via quantum algorithms (and specifically, using Shor's algorithm). An example is the algorithm of Shor, which can be efficiently run on a powerful enough quantum computer, can factor large integers and carry out discrete logarithms, and hence will make many common cryptosystems, such as RSA and ECC, ineffective. The possible implications of such a breakthrough are extensive as encrypted priorities, computer signatures, and sensitive information stored on computers might be retrospectively undermined, which will destroy the assurance in computer-based systems and reveal important data to the enemy. This threat has caused the cryptography community to research and design algorithms that are resistant to quantum attacks, together being referred to as post-quantum cryptography (PQC). PQC is also focused on ensuring that the security is a strong promise even in the facility of quantum adversaries in order to ensure that the digital messages are safe in the quantum world. Knowing this background is critically important in how to design future-resistant cryptography, what research strategies should be pursued, and what implementation strategies should preferably be pursued, and why migrating to quantum-safe cryptography is urgently called for.

1.2. Role of Quantum-Safe Cryptography

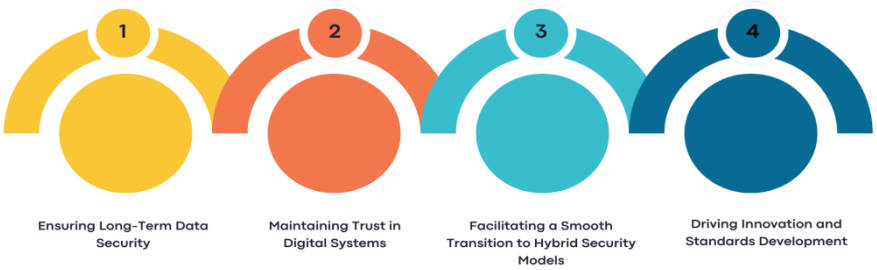

Fig 1 - Role of Quantum-Safe Cryptography

1.2.1. Ensuring Long-Term Data Security

Post quantum cryptography (PQC) or quantum-safe cryptography is central in securing sensitive information in the face of the imminent danger of quantum computing. In contrast to classical encryption algorithms brown down, like RSA and ECC, which are susceptible to an algorithm by Shor, quantum-safe encryption schemes are defined by mathematical problems that are thought to be immune to quantum attacks, metrics lattice problems, hash-based constructions, code-based problems, and multiple-variate polynomials equations. With these quantum-resistant algorithms, organizations will guarantee that confidential information, among other things, financial

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statements, and personal discussions are safe today and in the future, despite the development of quantum computational capabilities.

1.2.2. Maintaining Trust in Digital Systems

Modern digital ecosystems are based on trust. All the online banking and even software downloads rely on digital signatures, and secure key exchange and encrypted communications. The burial of classical cryptography in a post-quantum environment may destroy this confidence and allow the opponents to create fake signature, intercept confidential data or alter important information. Quantum-safe cryptography addresses such risks by giving safe security guarantees that are resistant to quantum attackers. This means that the organizations can keep their systems intact, ensure regulatory and compliance with the laws and regulations and continue to win the trust of the users in the process of transitioning to quantum-enabled world.

1.2.3. Facilitating a Smooth Transition to Hybrid Security Models

Hybrid security models, in which classical and quantum-resistant algorithms coexist in a gradual migration, can also be designed based on quantum-safe cryptography. Hybrid deployments offer the defense-in-depth property, whereby an attacker must compromise classical and post-quantum elements to be successful, and this eliminates the risk throughout the transition time. By operating in this way, the system guarantees compatibility with the current infrastructure as it implements quantum-resistant strategies in gradual phases, causing the minimum amount of disturbance to the operations and serving as a viable transition toward a system capable of entirely withstanding quantum attacks.

1.2.4. Driving Innovation and Standards Development

Lastly, quantum-safe cryptography introduces a new wave of cryptography design, standardization and implementation practices. Secure algorithm selection and evaluation is directed by the NIST PQC standardization project, and performance optimization, hardware acceleration, and hybrid protocols are researched to ensure that these new cryptographic schemes are practical and scalable to implementation.

1.3. Quantum-Safe Cryptography in Next-Generation Security

Quantum-safe cryptography or post-quantum cryptography (PQC) is on the verge of becoming one of the foundations of the future in digital security, offering a new level of protection against the new attacks brought about by quantum computing. With the growing exposure of conventional cryptographic algorithms like RSA, Elliptic Curve Cryptography (ECC), and Ditellmann–Hellman to quantum attacks, there had emerged a crisis in the requirement of cryptographic schemes that can withstand quantum attack in the future. Quantum-safe cryptography will be based upon mathematical problems that are thought to be immune to quantum computation, which include lattice-based problems, code-based constructions, multivariate polynomial systems, hash-based constructions, and isogeny-based problems using the elliptic curve. These strategies lie as the foundation of the algorithms being developed and currently standardized through programs like the NIST Post-Quantum Cryptography one. PQC has several crucial roles in the next-generation security. First, it guarantees long-term secretive state and durability of delicate information, securing messages, monetary exchanges, online identities, and essential computer infrastructure mechanisms against present and prospective foes. Second, it allows implementing hybrid cryptographic frameworks, with classical and quantum-safe algorithms running simultaneously, which offers defense-in-depth and a gradual, practical transition will not interfere with existing infrastructures. Third, PQC contributes to the emerging technologies that require a high level of security, such as

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blockchain networks, cloud computing environments, Internet of Things (IoT) systems, and cryptographically-driven systems that heavily rely on cryptography primitives to ensure data integrity, authentication, and secure communication. Furthermore, quantum safe cryptography integration into the next generation systems is a source of research and development on the algorithm design, optimization, and standardization. It promotes creating hardware-accelerated approaches to high-performance settings, dynamic protocols to deploy hybrids, and holistic security frameworks capable of countering both traditional and quantum attacks. Organizations can prevent quantum-computing progress by being quantum-safe in the present so that, in the future, they can secure their security infrastructure, assure their reliance on digital ecosystems, and address the threats of an inevitable quantum computing threat. By doing so, quantum-safe cryptography will be at the core of robust, future-oriented security measures in the next generation of quantum-based technologies.

2. LITERATURE SURVEY

2.1. Early Studies on Quantum Threats

The first papers on quantum threats derived the basic knowledge on quantum computation that can interfere with classical cryptographic security. The algorithm of Shor in 1994 proved that a strong enough quantum computer can break RSA, compute discrete logarithms, and factor large integers in a time dependent on its power, in other words breaking also the DiffieHellman and genus-based cryptosystem. Soon afterwards, the algorithm of Grover (1996) demonstrated that quantum methods of search could accelerate by quadratically the brute-force attack on symmetric encryptions and hash functions, and this necessitated the doubling of key sizes in classical systems. On the basis of these alarms, the following researchers started studying mathematical constructions which are likely to be resistant to quantum adversaries, including lattice-based constructions, code-based constructions and multivariate constructions. The works of these foundations formalized the quantum threat landscape and gave the foundations to the rise of post-quantum cryptography.

2.2. Families of Post-Quantum Algorithms

The term post-quantum cryptography (PQC) is used to refer to a number of families of quantum computer resistant cryptographic primitives with each family based on specific hard mathematical problems. Lattice-based cryptography, which is based on the hardness of Learning With Errors (LWE) and Ring-LWE, provides a good tradeoff between efficiency and security, and has generated numerous of the most promising NIST finalists, but with a moderate to large key size. The code-based construction systems, based on the problem of correcting code errors (e.g., the McEliece scheme), offer decades of analytical security, but have very large public keys that are of a size that makes their use not feasible in some applications. Hash-based signatures are conceptually easy to understand and are quite secure but generally small in the number of signatures that can be constructed with each key pair. Multivariate schemes involve systems of multivariate polynomials and may be very fast but their security has also been variable because of periodically cryptanalytic breakthroughs. Isogeny-based cryptography was the focus of attention due to the ability to use very small key sizes, whereas the breakdown of the SIKE protocol in 2022 showed the immaturity of this field in comparison with more conventional cryptographic families. Combined, these categories demonstrate the generality of the contemporary methods of PQC and the trade-offs that can be applied to each of them.

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2.3. NIST PQC Competition Findings

In 2016, the NIST Post-Quantum Cryptography Standardization Project initiated a first round of selection with a conclusion being reached in 20222023 after a worldwide selection process of candidate algorithms. To achieve key encapsulation, NIST chose CRYSTALLS-Kyber which is a lattice based scheme characterized by high efficiency, sound security proofs and ability to be used on various hardware platforms. In the case of digital signature NIST selected CRYSTALS-Dilithium another lattice-based construction with balanced performance and strong implementation properties, and FALCON a smaller, more complex lattice-based signature scheme with smaller signature size requirements. A stateless hash-based signature scheme SPHINCS+ was chosen to include a non-lattice variant with conservative and clearly understood security properties. These choices are the state-of-the-art in PQC and it will specify the algorithms comprising future generations of global cryptography standards.

2.4. Global Adoption Trends

The use of post-quantum cryptography across the globe has ramped up with governments and industries establishing the reality of the need to experience the dreads of massive quantum computers. The United States Executive Order 14028 requires the federal agencies to modernize the cybersecurity, including the migration process to quantum-resistant algorithms. The National Cryptography Law of China highlights the intention of the country in enhancing cryptography control, as well as the local research on PQC. Smaller-scale self-combustion processes have also been advocated, like in the EU Quantum Flagship in Europe: engaging in massive-scale quantum innovation as well as in the coordinated design of secured communication infrastructures. In every industry, researchers are always focused on the implementation of hybrid cryptographic solutions based on a classical and PQC cryptographic algorithm, in order to achieve interoperability and keep the systems safe throughout the transitional period. This is a worldwide trend as the alarm is being sounded that the implementation of PQC is not just some technical upgrade but a long-term digital security necessity.

3. METHODOLOGY

3.1. PQC Migration Flowchart

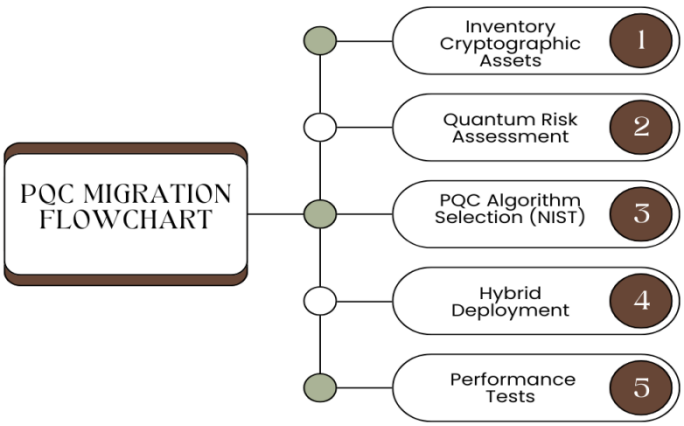

Fig 2 - PQC Migration Flowchart

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3.1.1. Step 1: Inventory Cryptographic Assets

PQC migration is first done by mustering a complete list of all the cryptographic resources in an organization. This involves the determination of the spots of encryption, digital signatures, key exchanges, certificates, and cryptographic libraries in systems, applications, devices, and communication channels. This is aimed at developing an elaborate map of cryptographic dependencies to ensure organizations have an idea of what needs to be upgraded or changed during the transition to post-quantum solutions.

3.1.2. Step 2: Quantum Risk Assessment

After identification of cryptographic assets, organizations consider the risks that may occur in terms of quantum characteristics of every component. The factors that it evaluates include the sensitivity and lifetime of data that is protected, the risk of harvest now, decrypt later attacks, as well as the risk that quantum processing capabilities may break some specific algorithms. Organizations can make a difference in their PQC migration efforts by prioritizing them to work on areas where they are significant by classifying their assets in terms of exposure and impact.

3.1.3. Step 3: PQC Algorithm Selection

The next step is to choose appropriate post-quantum algorithms based on a comparison of risks, usually based on NIST PQC standardization process guidelines. This includes the selection of recommended algorithms like CRYSTALS-Kyber to encapsulate keys or Dilithium and FALCON to encapsulate digital signatures. The properties of the algorithm, which are determined (performance, level of security, and level of implementation complexity) are matched to the system requirements of specific organizations to maintain quantum resistance on a long term basis.

3.1.4. Step 4: Hybrid Deployment

Since the shift towards PQC has to be gradual and compatible with the backwards compatibility, the organizations implement hybrid cryptography architects with a combination of classical algorithms and PQC algorithms. This two-way strategy will guarantee into the future of interoperability with the current systems as well as providing quantum-resistant guard layers. Hybrid deployment enables the organizations to continue operations through the migration time as the infrastructure gets ready to the entirely post-quantum condition.

3.1.5. Step 5: Performance Tests

The last is that of performing performance and interoperability testing in order to make sure that PQC algorithms can be efficient even in the current architectures. Tests are used to determine a factor such as latency, computational overhead, memory usage and compatibility with hardware accelerators or network protocols. Such assessments aid companies in confirming that security improvements will not interfere with system functionality and eventually allowing post quantum cryptography to be embraced easily and safely.

3.2. Algorithmic Complexity Analysis

The realisticity and the security of post-quantum cryptographic systems cannot be assessed without the help of algorithmic complexity analysis since these algorithms need to strike a balance between quantum resistance and efficiency. Key size is also one of the most important parameters since most PQC schemes (especially lattice based and code based) have larger public and private keys than the usual RSA or ECC. Such larger key sizes may have an impact on storage, certificate format, and the bandwidth used in the network. The size of ciphertext is also critical as it stipulates the size of information exchanged during encryption or key encapsulation. Bigger ciphers can impose some

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overhead on communication, potentially particularly in a limited resource state such as IoT equipment, embedded application, or high-latency network. Encryption and decryption throughput is another important measurement that is needed to measure the rate at which a system can handle cryptographic operations. Applications such as secure messaging platforms, large-scale server nodes, VPN gateways, and cloud infrastructures require high throughput because a performance bottleneck may negatively affect user experience or system uptime. In the same way, the time requirements to generate and verify signatures are essential to the authentication intensive systems, such as digital certificates, blockchain technologies and secure firmware updates. Inefficient signature operations may have the effect of deferring transactions and inefficient verification has impact on those systems where validation has to be undertaken at high numbers of signatures per second. To provide an example of the complexity of PQC, we should cite the Learning With Errors (LWE) assumption on which most lattice-based algorithms are based. LWE problem can be defined by plain language as follows: the system produces a public matrix A, multiplies this by a secret vector s, sums it with a small random noise vector e and gives an output vector b which are all calculated by a modulus q. The equation is as follows: in words: A times s + e = b, hypotom, q. The complexity of estimation of the secret vector s given the publically known values A and b, due to the noise e added to the relationships, offers the basis of the security and complexity of LWE-based cryptography.

3.3. Simulation Environment

The simulation environment is very instrumental in precise assessment of the performance of the post-quantum cryptographic (PQC) algorithms such that the findings are reproducible, consistent, and reflective of the conditions of the real world implementation. To conduct this research, all experiments were performed on a work station that has an Intel i9 processor that has more than one high-performance cores that can serve the computational needs of the current PQC schemes. The 32 GB RAM of the system is adequate memory resources to accommodate algorithms having large key size, high-dimensional lattice computations, and signature generation operations that consume a lot of memory. Operating system is Ubuntu, 22.04, which is a stable, popular Linux distro used in research settings due to its ability to work with cryptographic libraries, stable performance behavior, and with strong developer toolchain. The PQC algorithms were coded with liboqs, an open-source library managed by the Open Quantum Safe project but offers the usual interface to the key encapsulation and digital signature schemes chosen or suggested by NIST. The Liboqs is explicitly aimed at the benchmarking and testing of post-quantum algorithms and provides trustworthy implementations to test correctness and performance. In order to measure the actions of the algorithm in a quantitative manner, a number of key performance measures were taken. The number of CPU cycles was established to measure the nominal cost of raw computation of such operations like key generation, encapsulation, decapsulation, signature creation and verification. Latency was also measured, the overall time of running cryptographic functions, and it indicated the effectiveness of algorithm complexity to determine the delay experienced by users and responsiveness of a system. Finally, memory footprint (a method to analyze the amount of consumed memory) was analyzed to estimate how much memory is being consumed by each algorithm which is also a crucial measure when deploying an algorithm within an embedded system, mobile device, or IoT hardware with only limited memory resources. This combination of hardware and software and the selected measures offers an end-to-end system to assess both the performance and viability of PQC algorithms when operating in realistic conditions.

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4. RESULTS AND DISCUSSION

4.1. Performance of PQC Algorithms

Table 1: Performance of PQC Algorithms

Algorithm	Key Size (%)	Latency (%)	Security Level (%)
RSA-3072	29%	100%	20%
Kyber-512	61%	20%	40%
Dilithium-2	100%	50%	60%
SPHINCS+	300%	100%	100%

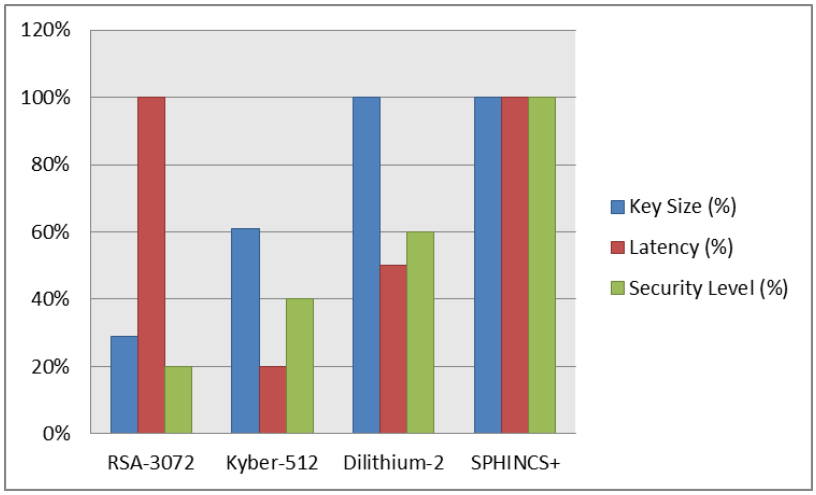

Fig 3 - Graph representing Performance of PQC Algorithms

4.1.1. RSA-3072

RSA-3072 has a key size of about 29 percent of the largest PQC key size, although with a latency of 100 percent, indicating the costliness of the classical public-key operations. Although RSA is old and well-established, it actually can only offer a classical security level of approximately 20 per cent. compared to the current PQC standards, which is the reason why it is vulnerable to future quantum attacks.

4.1.2. Kyber-512

Kyber-512 is highly efficient and with a moderate size of 61 per cent key it is very fast with very low latency of only 20 per cent, it is among the fastest PQC algorithms to encapsulate keys. It is rated at 40 percent, equivalent to NIST PQC Level 1 and is sufficient in most general-purpose applications and has much higher quantum resistance as compared to RSA.

4.1.3. Dilithium-2

Dilithium-2 has a key size of 100% which matches the size of a footprint in Kyber but still is manageable in the majority of modern systems. It has a moderate latency of 50 that indicates balanced performance in terms of signature generation and verification. Having security rating of 60, which is comparable with that of NIST Level 2, Dilithium-2 offers increased security more than Kyber without compromising the realistic performance features.

4.1.4. SPHINCS+

The key size in SPHINCS+ is quite large accepted here being 100 in value thus much larger than other PQC schemes. It is also slow with a high latency of 100 per cent because of the

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computation involved in the process of signing using hash. Nevertheless, SPHINCS+ offers the best level of security of 100% and satisfies NIST Level 5, so it can be used with very sensitive or long-lived cryptography operations although it has overhead performance.

4.2. Security Evaluation

Post-quantum cryptography security assessment concentrates on the examination of how long the algorithms withstand the most efficient quantum attacks that have been predicted in the next few decades. The quantum-safe algorithms are actually made resistant to the Shor algorithm that compromises the classical public-key cryptography (RSA, Diffie Hellmann and elliptic-curve cryptography) by facilitating an efficient computation of factorization as well as discrete logarithms. Using instead mathematical problems such as lattices, codes, hash-based constructions, PQC schemes are safe even against the full ability of Shor attacks. Alongside the algorithm by Shor, the algorithm by Grover is also a major threat to the security of quantum calculations since it enables them to accelerate the brute-force search and hash preimage assaults. Although Grover approach has no direct compromise on the public-key systems, it essentially reduces the security margin of symmetric primitives by half. Post-quantum designs thus use larger key sizes, longer hash functions and stronger parameter space to work around resistance to a quadratic speedup of Grover. In addition to these popular threats, more recent optimizations of quantum random walks present more active techniques that can speed up some type of state-space exploration or structured search. To solve these issues, PQC algorithms have their security based on problems that are thought to be resistant to both the classical and quantum-enhanced search methods with parameters that are selected to resist the attacks of new cryptanalytic methods. Although the schemes of PQC become more mature, in order to implement the switch to quantum-safe systems, special care must be provided to the layered security. Hybridization Hybrid algorithms (i.e. mix-ups of classical algorithms with PQC algorithms) offer an important defense-in-depth technique in the transition period. When these are configured, an attacker has to compromise the system by breaking both of these components simultaneously and such configurations are really minimally risky as international infrastructure adjusts to the international post-quantum deployment. All these factors combine to ensure that the current PQC-based algorithms can offer solid protection against the threats posed by known and estimated quantum attacks that can be used in the long-term security of data in the quantum-enabled future.

4.3. Implementation Challenges

The use of post-quantum cryptographic (PQC) algorithms present a number of viable challenges that organizations should be keen on overcoming in order to make their deployment safe and effective. The significantly larger size of keys of many PQC schemes, especially lattice-based, code-based, and hash-based algorithms, is also one of the major problems. Both of these expand the bandwidth utilization of networks, and directly contribute to an augmented overhead of transmission, prolonged handshake duration, and decreased performance in resource-limited or latency-intensive settings. This is particularly objectionable to mobile networks, IoT ecosystems and real-time applications in which the size of the packet and the efficiency of transmission is of paramount importance. In addition to network, hardware acceleration will gain significance especially to embedded devices like smart sensors, industrial controllers and low power microcontrollers. PQC algorithms commonly contain computationsally-demanding operations (such as high-dimensional matrix multiplications, arithmetic with polynomials, and handling hash-trees) that are beyond the ability of a lightweight hardware model. Some special accelerators or special instruction sets might be necessary to achieve acceptable performance, thereby adding cost and design complexity to hardware suppliers. The other major problem is the migration of legacy systems, which many have been constructed based on classical algorithms, such as RSA and ECC,

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and cannot easily support PQC primitives because of fixed protocols or hard limits of memory and long lifespan hardware. The redesign of such systems can frequently take a long time of architectural development, firmware development, or adding new or extending protocols, which may be time-intensive and unsafe, particularly in safety-critical systems like medical devices, industrial automation, or aerospace systems. Moreover, interoperability during the transition process should be handled with some care since classical and PQC elements have to co-exist in hybrid structures to be able to guarantee compatibility between heterogenous infrastructures. Combined, these issues underscore the fact that effective deployment of PQC is not an upgrade of cryptography but a complicated engineering process that mandates joint innovations in software, hardware, and system design.

5. CONCLUSION

Quantum computing is a disruptive technology, and, at the same time, it is an outright threat to the conventional form of public-key cryptography, which forms the backbone of internet-based security of digital interactions, financial infrastructures, and key infrastructure. The traditional cryptology tools like RSA and Diffie-Hellman and elliptic-curve cryptography, upon which people have trusted their entire lives, are subject to a quantum attack, the most notorious example being the Shor algorithm capable of breaking down large integers and computing discrete logarithms, which makes the traditional encryption and digital signature useless. With advancements in quantum computing power, the threat of harvest now, decrypt later attack becomes real, and the need to move to quantum-resistant cryptography must only be underscored by its urgency. This paper has discussed post-quantum cryptography (PQC) as a current and necessary solution to this new threat. Theoretically-strong practical efficiency and good performance have led to lattice-based algorithms like CRYSTALS-Kyber and CRYSTALS-Dilithium becoming particularly promising in key encapsulation and digital signature operations as well as other major PQC families. Other alternative security approaches, such as hash-based, code-based and multivariate and isogeny based algorithms, are also available with their own trade-offs that differ in key size, computation overhead, and deployment costs.

The implementation of PQC does not pass without challenges though it has the inherent security advantage. Migration involves thorough inventory of cryptographic assets, thorough quantum risk assessment and close consideration of the choice of algorithms that are able to satisfy the performance and security requirements. Big key and computation sizes require optimization of network bandwidth and hardware acceleration especially on resource-constrained devices and embedded systems. Classical deployment Hybrid deployment techniques have been shown to offer an in-between transition that preserves interoperability and enhances the resistance to quantum attacks. Performance testing - such as latency, throughput, memory footprint, signature generation times, etc. is also important so that PQC integration does not adversely impact system performance or user experience.

In the future, it can be expected that research should grow in terms of integrating PQC into new technologies. To illustrate, a joint implementation of PQC and AI-based adaptive security models may be used to support dynamic and context-rooted cryptographic protection based on changing threats. Equally, blockchain frameworks that are developed based on PQC have the ability to make distributed ledger systems more resilient to future quantum adversaries, which will provide long-term data integrity and trust. The unavoidable shift to quantum resistant cryptography indicates the need to adopt earlier, plan, and invest heavily in infrastructure. Through theoretical and

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practical considerations, organizations can protect digital ecosystems, ensure the trustfulness of the communication systems, and become resilient to the quantum-enabled dangers of the future. Finally, PQC is not just an upgrade to ensure the future of the digital technology, it is a requirement.

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