


Research Article

# Secure and Scalable Quantum Cryptographic Algorithms for Next-Generation Computer Networks

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## ABSTRACT

The rise of quantum computing poses a serious threat to traditional cryptosystems, such as RSA and ECC, which rely on the mathematical problem of factoring large numbers and dealing with discrete logarithms. Quantum algorithms such as Shor and Grover can solve these problems effectively, so that classical encryption is simple. This research addresses the urgent need for quantum-resistant cryptographic algorithms to protect next-generation networks, including 5G, IoT, and cloud computing, from future quantum attacks. The main objective of this study is to investigate the efficiency and scalability of quantum post-cryptography techniques, especially lattice-based cryptography, and to evaluate their performance in comparison with traditional cryptography and other post-quantum techniques. It also provides robust protection against quantum attacks and reasonable scalability to large networks, while delivering large key size requirements, low connectivity and excess capacity. The study concludes that lattice-based cryptography is an appropriate solution that balances quantum resistance with practical performance in real-world applications to ensure secure communications in the post-quantum era.



## 1. INTRODUCTION

The advent of quantum computers is a huge leap forward in computing power, potentially revolutionizing a variety of things including cryptography. Unlike traditional computers that process information in binary form (bits), quantum computers offer the use of qubits much faster calculations [1]. Many widely used cryptographic algorithms, such as RSA and elliptic curve cryptography (ECC) rely on the mathematical difficulty of factoring large integers or solving discrete logarithm problems, tasks that traditional computers can't handle. But the quantum of algorithm etc. Things and secure transmission needs more and more. It becomes important. These networks handle a lot of critical data, from personal information in IoT devices to critical infrastructure in industrial systems. The security of these networks relies heavily on encryption techniques to ensure confidentiality, integrity, and authentication. However, the cryptographic techniques underlying the emerging threat of quantum computing are in danger of becoming obsolete, creating a growing need for quantum-resistant cryptographic algorithms [2]. These algorithms must be able to withstand attacks from quantum computing, and remain scalable and efficient enough to be used in large networks. The main goal of this paper is to find resistant secure cryptographic algorithms quantum that can provide robust defenses in the face of future quantum threats. designed to resist attacks, ensuring that encrypted communications remain secure even with quantum computing capabilities. In particular, the paper will investigate post-quantum encryption techniques, such as in lattice-based cryptography, code-based cryptography, etc., will examine their strengths and weaknesses in real-world applications [3]. Another important goal of the paper is to assess the scalability of these quantum resistant algorithms in large networks. As computer networks increase in size and complexity, especially with the widespread adoption of IoT devices and the expansion of cloud infrastructure, cryptographic algorithms must be able to scale very well not only as this ensures algorithm security but also tests if their performance looks at efficiency in terms of computing time, memory usage and bandwidth. The aim of the paper is to provide a comprehensive analysis of how these algorithms perform when deployed in a wide range of networks, ranging from powerful IoT devices learn up to high-performance 5G networks [4]. The content of this paper covers theoretical and practical aspects of quantum resistant cryptography, providing an in-depth analysis of various cryptographic algorithms and their applications in next-generation networks. The paper is organized as follows: Section i the former includes quantum mathematics and Its effects on traditional

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are offered cryptography, and offers a way to address the need for anti-quantum methods [5]. Next, the paper delves into specific quantum-resistant cryptographic algorithms, exploring techniques such as lattice-based, hash-based and code-based cryptography, and how they can be used to secure future networks and then paper quantum cryptography is going to discuss the challenges of scalability, especially in the context of large-scale deployments such as 5G, IoT, and cloud infrastructure [6]. The performance challenges of these algorithms will be explored, as well as possible solutions to improve scalability without sacrificing security. This section will also cover quantum key distribution (QKD) and the technical hurdles it faces in practical applications. The final sections of the paper present a performance comparison of different quantum cryptographic algorithms, followed by case studies illustrating the applicability of these techniques in real-world scenarios, e.g Securing IoT devices and securing financial transactions There was an ongoing effort to standardize the post -quantum cryptography to secure the next generation of computer networks [7]. This framework ensures a thorough understanding of the quantum cryptography landscape, addresses its security implications, and its practical challenges in practice by exploring the scalability and effectiveness of quantum resistant algorithms, the paper aims to it will provide valuable insights to academic researchers and industry professionals preparing for the quantum computing era there [8].

Fig 1 illustrates the process of securing data communication between a user device and a server using a quantum-secure encryption algorithm using the TLS (Transport Layer Security) protocol The user device initiates a connection, which is encrypted using a quantum-resistant algorithm protect the data to ensure It remains secure even in the face of possible future quantum-computing threats The encryption process is handled through OpenSSL, and the encrypted data is transmitted over a secure HTTPS connection, and provides a secure way to transfer data over the Internet [9]. As data passes through this secure network it is protected from a variety of threats such as hackers, privacy-seeking companies, and both quantum and classical computers that attempt to block or hack it come with encrypted data arrives on server intact, maintaining its confidentiality and integrity throughout transfer process Learn how quantum-secure encryption plays an important role in enhancing security [10].

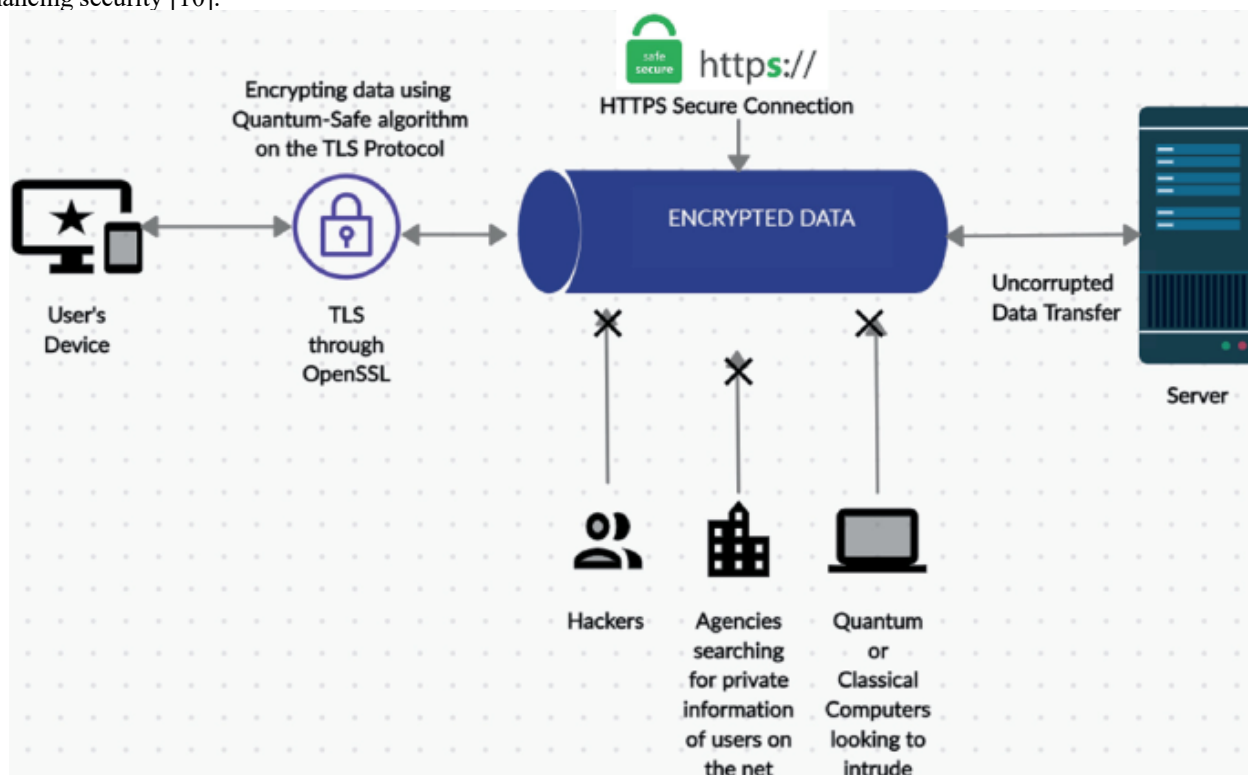


Fig 1. Quantum-Safe Data Encryption in Secure HTTPS Connections

## 2. OVERVIEW OF QUANTUM COMPUTING AND CRYPTOGRAPHY

Quantum computing represents the greatest leap in computing power, driven by the principles of quantum mechanics. Unlike classical computers, which use binary bits in state 0 or 1, quantum computers use qubits. Qubits can exist in a state of superposition, so that they can be both 0's and 1's at the same time. This property allows quantum computers to handle many possibilities at once, leading to significant increases in computational efficiency for certain problems Furthermore, quantum computers take advantage of entanglement, the phenomenon that generates qubits interact so that the state of one qubit is directly affected by the state of another. Since there was no distance between them [11]. Entanglement enables quantum systems to operate precisely at unprecedented speeds. The potential applications of quantum computing are vast, from solving complex optimization problems to designing molecular systems for chemical discovery but one of the most profound implications of quantum computing its ability to disrupt traditional cryptography

[12]. Many existing cryptographic protocols, such as RSA and elliptic curve cryptography (ECC), rely on the difficulty of solving mathematical problems such as integer multiplication or discrete logarithms—problems in mathematics, traditional computers cannot handle it in real time. Quantum algorithms, especially Shor's, pose a serious threat to these systems. The Shor algorithm enables quantum computers to effectively factor large integers and handle discrete logarithms, effectively breaking RSA and ECC security, which underlies most modern digital encryption and secure communications techniques such as quantum computers. As it progresses, the timeline of when classical cryptography systems become easier as quantum attacks shrink [13]. This quantum threat creates an urgent need to develop cryptographic techniques that can cope with the capabilities of quantum computers. If left unchecked, secure communications, financial transactions and sensitive data storage could all be at risk in the quantum age.

## 2.1 Quantum-Resistant Cryptography

To combat the emerging threat of quantum computing, researchers are developing anti-quantum cryptographic algorithms, also known as post-quantum cryptography. These algorithms must be secure from attacks from quantum computing, according to so that even in the future where quantum computers are widely available, digital communication, data encryption and integrity are ensured. Although quantum computers excel in some mathematical operations, such as factoring large numbers or solving specific algebraic problems, but they do not give the same value to all problems believe [14]. The importance of quantum-resistant cryptography cannot be overstated. As quantum computing continues to evolve, the security of digital communications—used by governments, businesses and individuals—will depend on a shift to quantum-containing secure methods that risk "harvest now, decrypt later" attacks so, intended to decipher hidden data later if hidden quantum computing is used, acceleration is increased. This requires early adoption of quantum-resistant algorithms, which should be integrated into current systems first and quantum computers have successfully cracked traditional encryption schemes [15]. There are several classes of quantum-resistant cryptographic algorithms, each different - Based on computational techniques considered safe against quantum attacks:

1. **Lattice-based cryptography:** Lattice-based cryptographic algorithms are one of the most promising techniques in the quantum background. These algorithms are strictly based on the problems associated with high-dimensional grids, such as the least vector problem (SVP) and the learning with errors (LWE) problem. The strength of lattice-based cryptography lies in the difficulty of these problems in solution, even for quantum computers. Mesh-based algorithms are also versatile, supporting not only encryption but also digital signatures and Fully Homomorphic Encryption (FHE), which can compute encrypted data without the need for prior decryption. This versatility and security make lattice-based cryptography prime candidate for quantum-resistant cryptographic standards [16].
2. **Hash-based cryptography:** Hash-based cryptography is based on the security of cryptographic hash functions, which are well known and resistant to attacks from classical and quantum computing. Hash-based systems are mainly used in digital signatures, where they provide security a strong. One of the most well-known hash-based cryptography schemes is the Merkle Signature Scheme, which proves to be secure under a few assumptions. But hash-based cryptography has limitations in scalability and efficiency, especially in systems that require frequent key updates or heavy usage [17].
3. **Code-Based Cryptography:** Code-based cryptography, such as the McEliece crypto system, is one of the oldest known quantum-resistant cryptography, developed in the 1970's is, policy-based systems are more secure, but they often require very large keys, which can be problematic in environments with limited storage or bandwidth, such as IoT devices [18].
4. **Multivariate polynomial cryptography:** This approach is based on the complexity of solving systems of multivariate polynomial equations in finite domains. Although multivariate cryptography has shown promise for specific cryptographic applications, such as digital signatures, its implementation a usefulness is not as widespread as forged- or code- based systems, posing challenges for widespread adoption [19].
5. **Isogeny-Based Cryptography:** A New Entry in the Post-Quantum Cryptography Scenario, Isogeny-Based Cryptography Relies on Strict Detection of Isogeny (Special Type of Morphology) Between Elliptic Curves. The main advantage of isogeny-based cryptography is that there are only a few keys. There is potential for processing at larger scales, making it attractive for applications with limited bandwidth or storage but isogeny-based cryptography are still in the early stages of development and need further research to fully understand their safety and performance [20].

Each of these quantum-resistant cryptographic algorithms offers different trade-offs in terms of security, performance, and complexity. As the field continues to evolve, researchers and industry professionals must carefully search for the best-suited algorithms for specific use cases, in particular. While next-generation networks such as 5G and the Internet of Things (IoT) increasingly rely on secure networks, it is not like quantum-resistant cryptography doing so is not only about securing future communications but also about ensuring that today's data remains safe from future quantum attacks [21].

### 3. SCALABILITY CHALLENGES IN QUANTUM CRYPTOGRAPHY

As the world transitions to next-generation networks such as 5G, the Internet of Things (IoT), and cloud computing, the demand for robust, scalable cryptographic infrastructure is more important than ever. Those networks process a lot of data, often in real time, as well as millions of connected devices. This creates a need for cryptographic systems that can not only provide anti-quantum security but also scale well to support such a large infrastructure. For example, communication latency needs to be incredibly low and for handling applications such as autonomous vehicles, remote surgery in 5G networks -There are billions of devices connected to the devices, many of which lack computing power and storage capacity [22]. In these contexts, the scalability of cryptographic systems is an important challenge. Quantum-resistant algorithms are computationally intensive and require more processing power and memory than traditional cryptography. In cloud computing environments, where large amounts of data are stored and processed in distributed systems, cryptographic solutions must support high-speed encryption and decryption to avoid complications so that as these networks grow the cryptographic systems can be scalable without significant performance degradation or excessive computing resources. The main requirement for quantum-secure encryption techniques in the next-generation network is to provide strong security while maintaining the level of performance of modern applications such as, cryptographic algorithms in IoT systems, where devices frequently communicate on low power wireless networks -require sufficient performance to operate without compromising battery life or having to constantly transmit data and the cryptographic systems in cloud systems handle large data encryption for them hundreds of thousands of users without increasing latency or overhead [23].

#### 3.1 Scalability Challenges in Large-Scale Quantum-Safe Encryption Methods

Post-quantum cryptographic algorithms, which provide robust protection against quantum attacks, especially in large network environments, pose significant scalability challenges. One of the major challenges is the increased computational complexity of these algorithms over time compared to classical cryptography. Many quantum-secure encryption techniques, such as lattice-based cryptography or code-based cryptography, require significantly larger keys, increasing computational load for both encryption and decryption operations. For example, although RSA encryption uses a key size of 2048 bits but requires a key size in the tens of thousands of bits to achieve security comparable to lattice-based algorithms. This increase in key size translates into higher memory processing requirements, which can be a bottleneck in large networks with many devices. Another challenge is the communication costs associated with quantum secure encryption. Larger keys and ciphertext mean more data needs to be transmitted during encrypted communications, which can increase bandwidth usage. This is a particular problem in IoT networks, where devices often rely on low-bandwidth connections, or mobile networks where bandwidth is a limiting factor. If these encryption techniques are applied to networks of millions of devices which, exacerbates the problem, so that possible work -There is corruption [24]. Furthermore, many quantum-secure algorithms have not yet been updated to be efficiently used in large networks. While they theoretically provide protection against quantum attacks, their real-world applications in areas such as cloud systems or 5G networks pose challenges to maintain security and performance. For example, code-based cryptography such as the McEliece cryptosystem provides stronger security but requires significantly larger keys and more compute resources, which makes it impossible to deploy to large areas where efficiency is required.

#### 3.2 Performance Bottlenecks

The high technical overhead of post-quantum cryptographic algorithms is one of the major operational challenges among their users. Quantum-resistant algorithms, especially those based on complex mathematical structures such as lattices or multivariate polynomials, require more processing power than classical cryptographic algorithms such as RSA or ECC. This computational burden is more pronounced when using these algorithms in real-time applications or limited resource environments constrained by low power processors and limited memory capacity. Using post-quantum cryptography on such devices can slow down the encryption and decryption time, weaken the battery life, and reduce the overall performance of the network. For example, a smart sensor in a factory should encrypt data before it is sent to a central server, can experience lag if encryption algorithm is too computationally intensive. In large IoT networks, where thousands of devices transmit encrypted data simultaneously, this performance bottleneck can reduce latency and network efficiency as well as cloud environments with data at rest and in transit. When encrypted, the computational cost of post-quantum cryptographic algorithms can affect the performance of cloud services [25]. Encrypting and filtering large amounts of data using quantum-secure algorithms requires large amounts of energy, which can increase operational costs and reduce the scalability of cloud services. For example, through a mesh-based encryption scheme within a Cloud service provider encrypting terabytes of data can experience slow data access compared to traditional encryption methods, which can affect the user experience.

#### 3.3 Quantum Key Distribution Scalability

Although quantum key distribution (QKD) provides a theoretically indestructible method for exchanging secure cryptographic keys using quantum mechanical principles, QKD faces significant scalability challenges, especially in large network environments. QKD fiber-optic cable or open-space communication techniques rely on the transmission of quantum bits (qubits) to enable secure key exchange between two parties but are difficult to implement widely due to the

physical and technical limitations of QKD. One of the main limitations of QKD is the distance limit. Qubit communication is highly sensitive to stray noise, which means that the secure key exchange distance is typically a few hundred kilometers when fiber optic cables are being used while quantum repeaters are being developed to extend the QKD approach, these technologies are still in their infancy, not yet suitable for large-scale deployment. The limitations of QKD over distance pose a serious challenge to its scalability in global networks or wide area communication systems like 5G. Another issue is cost and infrastructure which is required for QKD. The design of QKD networks requires specialized quantum communication tools such as single photon detectors and quantum random number generators. This makes QKD more expensive to use compared to traditional cryptographic techniques, especially in large networks that require secure communications across nodes. Although QKD may be more efficient for high-value, simple communications (such as government and military applications). In addition, the QKD network is not easily compatible with existing Internet infrastructure, making it difficult to integrate with existing networks. Large-scale implementations will require the inclusion of QKD at the physical level of the communications network, which will require significant modifications to existing infrastructure. This poses additional scalability challenges, as not many networks are designed to handle quantum information transmission along with classical data. While post-quantum cryptography provides strong protection against future quantum attacks, the increasing computing and communication costs of quantum-secure encryption, coupled with objects in network environments face significant challenges. Although QKD in theory offers unbreakable security it suffers from technical and physical limitations to its widespread application. Addressing these scalability challenges becomes increasingly important as quantum computing becomes more sophisticated, secure communication over a global network becomes even more important.

#### 4. SOLUTIONS FOR SCALABILITY IN QUANTUM CRYPTOGRAPHY

The basic solution for the quantum measurement is to correct the quantum number to decrease the protection of the quantum encryption principles. In the case of the edgridamic-pronsing There is one such approach that can facilitate the performance of quantum-safe algorithms. During pruning, redundant or redundant parts of the cryptographic algorithm are removed without significant loss of security. This reduces the computational burden, making the algorithm more efficient, especially in resource-constrained environments such as IoT devices. For example, lattice-based cryptography can be pruned by removing the parts of the network that contribute most to security, thus reducing the size of cryptographic keys and speeding up encryption and decryption processes. Parallelization is a strategy new optimization techniques that can increase the scalability of quantum-secure implementation algorithms. Cryptographic operations can be broken down into smaller tasks and processed simultaneously on multiple cores or processors, parallelization greatly increases throughput, and makes it possible to use these algorithms in high-demand environments such as cloud computing or 5G networks. This approach is particularly useful for cryptographic algorithms involving complex mathematical operations, such as lattice-based or multivariate polynomial cryptography that take advantage of multi-core processors or distributed computing architectures, such as those found in cloud environments, quantum resistant -In reducing along with latency associated with cryptographic operations, improving overall network performance, lightweight cryptographic algorithms are being developed especially for low-power devices such as those found in IoT networks. These algorithms are designed to provide quantum resistance while being computationally low demanding, ensuring that devices with even limited processing power can communicate safely without encountering performance bottlenecks.

##### 4.1 Hybrid Cryptographic Approaches

Another promising solution to the scalability challenge of quantum cryptography is the use of hybrid cryptography techniques. Combining classical and quantum-secure cryptographic algorithms in a hybrid framework can provide a revolutionary approach to quantum-resistant security. This approach leverages the strengths of existing classical cryptography, optimized for performance, and integrates quantum-resistant algorithms in order to ensure durable protection against quantum attacks in a hybrid cryptosystem specifically Classical methods (such as RSA or ECC) and quantum -a secure algorithms (such as lattice). based cryptography) is used to encrypt data. Classical cryptography provides immediate, low-overhead encryption, ensuring compatibility with current systems, while the quantum-secure component ensures future proof security. This dual-encryption approach facilitates quantum-resistant cryptography without having to they completely modify the existing network. allowing integration As quantum computing capabilities advance. The classical cryptographic parts can be phased out, leaving only the quantum-secure algorithms. In turn, transformation strategies are needed for integrating quantum-secure algorithms into existing networks. One such strategy is a phased implementation, with quantum-resistant algorithms first introduced in security-critical areas, such as financial transactions or government transactions, while continuing to use traditional cryptography in places less complex. By doing so, all communication channels can be covered. This phased approach reduces the risk of disruption to existing infrastructure and ensures that networks remain secure against future quantum threats. Another adaptation strategy involves backward compatibility, where secure cryptography techniques are designed to coexist with legacy algorithms, so that older systems can continue to work safely until they are updated. This looks realize that existing systems, which in computers require quantum-secure encryption cannot handle it, and can still safely work on future-proofing systems.

## 4.2 Network Layer Adaptations

Enhancing existing network protocols to support scalable quantum cryptography is another important step to address the scalability challenge. Current cryptographic protocols, such as Transport Layer Security (TLS) and Virtual Private Networks (VPNs), must be adapted to the increased computation and communication requirements of quantum-secure algorithms while maintaining performance and functionality in TLS article, which is widely used to secure online communications. You need to add support for key-exchange algorithms. The Post-Quantum TLS (PQ-TLS) protocol is an optimization being developed to ensure that the security of cryptographic keys exchanged is resistant to quantum attacks PQ-TLS uses hybrid cryptography techniques to combine classical and quantum-secure key exchange mechanisms Even if broken, communications remain secure due to the quantum resistant component PQ-TLS also includes optimizations to reduce the overhead of large quantum-secure keys and ciphertexts, improving the scalability of the protocol for large-scale deployment. For VPNs, which secure communications over potentially insecure networks, the integration of quantum-resistant encryption techniques is necessary to protect data as it travels across global networks so Handshake to ensure compatibility with existing systems and for the delays in updating VPN protocols to support quantum-secure encryption, its key-exchange processes are optimized These optimizations ensure that VPNs can scale though meet industry and consumer demands as quantum computing progresses.

## 4.3 Improving QKD Networks

Although quantum key distribution (QKD) provides an unbreakable method for exchanging cryptographic keys using quantum mechanics, its scalability in large networks remains a significant challenge due to physical and technical constraints It is developed the solution. One approach is to use quantum iterators, which extends the range in which qubits can be extended without losing the quantum properties. Currently, QKD is limited to short distances (typically a few hundred kilometers) due to signal loss in optical fibers. Quantum repeaters work by binding qubits at network midpoints, allowing secure long-distance transmission of quantum information Although still in development, quantum repeaters are essential for implementing large QKD networks, especially in global communication systems. Another solution to improve the scalability of QKD is the integration of satellite-based QKD systems. In satellite QKD, quantum keys are distributed by satellite, enabling secure communications over much greater distances than fiber-optic QKD. Satellite QKD has the potential to overcome the limitations of terrestrial quantum communications on earth, allowing secure delivery of key resources across continents and the globe. This approach is especially promising for secure communications between remote locations, such as international financial transactions or secure government communications but the costs and challenges of implementing satellite QKD networks remain a major obstacle. Trusted node networks are another solution to improve the scalability of QKD. These networks distribute quantum keys to secure nodes and use trusted third parties to transmit keys remotely. While this approach introduces some reliability to intermediate nodes, it provides a practical way to extend QKD networks without requiring complex infrastructure upgrades Trusted node networks are already in place in some areas, providing a scalable solution for quantum secure key distribution.

Table I provides an overview of security research in quantum cryptographic systems, focusing on key areas such as threat modeling, vulnerability, and mitigation, and cryptographic failure Leann This potentially breaking quantum attack requires post-quantum cryptographic algorithms are used (e.g., lattice-based or code-based cryptography) and the adoption of quantum key distribution (QKD), which is a classical approach. It provides a security key exchange that resists quantum attacks. The table in the vulnerability solutions section lists the possible vulnerabilities of quantum post-cryptography and QKD, such as side-channel attacks, poor parameter choice and always algorithms for these vulnerabilities to ensure that robustness against future attacks, device-independent Mitigation strategies such as -QKD, and the need for ongoing cryptoanalysis Finally, the Cryptographic Failures section provides a synthesis of past failures, such as RSA-512-512-513. vulnerability and the Dual\_EC\_DRBG backdoor, which emphasizes the importance of continuous updates and transparency in the development of cryptographic systems. Learning the lessons from these failures is critical to addressing similar issues in quantum secure systems. This comprehensive security review highlights the challenges and solutions needed to secure cryptographic systems in the quantum age.

TABLE I. SECURITY ANALYSIS OF QUANTUM CRYPTOGRAPHIC SYSTEMS: THREATS, VULNERABILITIES, AND LESSONS LEARNED

Category	Details	Key Parameters
Threat Models	Quantum-specific attack models and security guarantees of post-quantum cryptography and Quantum Key Distribution (QKD).	Quantum Attack Algorithms: Shor's algorithm, Grover's algorithm Cryptographic Systems: RSA, ECC, AES Post-Quantum Algorithms: Lattice-based, hash-based, code-based QKD Security: Quantum no-cloning theorem, eavesdropping detection
Vulnerabilities and Mitigation	Potential vulnerabilities in post-quantum algorithms and QKD, along with mitigation strategies for enhancing robustness.	Vulnerabilities: Side-channel attacks, parameter selection flaws, hardware imperfections Mitigation Strategies: Constant-time algorithms, device-independent QKD, parameter optimization, cryptanalysis
Cryptographic Failures	Case studies of cryptographic failures and lessons learned for quantum cryptography systems.	Case Studies: RSA-512 failure, Dual_EC_DRBG backdoor, NIST Randomness Beacon flaw

## 5. RESULT

This table provides a comparative analysis of quantum cryptography designs, with a particular focus on lattice-based cryptography, compared to post-quantum cryptography techniques such as traditional cryptography (RSA-2048) Key size, encryption/decryption Attention drawn has focused on key factors such as time, connectivity redundancy, capacity utilization, scalability and security level. The results show that although lattice-based cryptography requires significantly larger key sizes and results in higher moderate encryption time and transaction costs, unlike traditional RSA, against threats such as the Shore Grover algorithm, Quantum. Compared to other post-quantum countermeasures, lattice-based cryptography is more efficient in terms of performance and scalability, making it a strong candidate for secure communications over the next generation exist networks, regardless of resource requirements.

TABLE II. COMPARISON OF QUANTUM CRYPTOGRAPHIC SYSTEMS WITH TRADITIONAL AND POST-QUANTUM CRYPTOGRAPHY

Parameter	This Study: Quantum Cryptographic Systems	Comparison Study 1 (Traditional Cryptography)	Comparison Study 2 (Previous Post-Quantum Cryptography Studies)
Key Size	Lattice-based Cryptography: 10,000 - 30,000 bits	RSA-2048: 2048 bits	McEliece Cryptosystem: 200,000+ bits
Encryption Time	Lattice-based Cryptography: 5-15 ms (for 1024-bit plaintext)	RSA-2048: 1-3 ms (for 1024-bit plaintext)	Hash-Based Signatures: 20-30 ms (for 1024-bit signatures)
Decryption Time	Lattice-based Cryptography: 10-20 ms (for 1024-bit ciphertext)	RSA-2048: 1-3 ms (for 1024-bit ciphertext)	Code-Based Cryptography: 30-40 ms (for 1024-bit ciphertext)
Communication Overhead	Lattice-based Cryptography: 50% increase (due to larger keys)	RSA-2048: Minimal communication overhead	Multivariate Cryptography: 70-80% increase (due to key size)
Power Consumption	Lattice-based Cryptography: Moderate increase (5-10% higher)	RSA-2048: Baseline (minimal power consumption)	Code-Based Cryptography: 15-20% increase in power consumption
Scalability	Lattice-based Cryptography: Moderate scalability in large networks	RSA-2048: High scalability due to efficient algorithms	Hash-Based Cryptography: Low scalability in large systems due to key generation times
Security Level (Against Quantum Attacks)	Post-Quantum Safe: Resistant to Shor's and Grover's algorithms	Not Quantum-Safe: Vulnerable to Shor's algorithm	Quantum-Safe: Similar security guarantees, depending on algorithm

## 6. CONCLUSION

This study highlights the critical importance of quantum cryptographic systems to protect next-generation networks from the emerging threat of quantum computing As quantum computers evolve, traditional cryptographic techniques like RSA, ECC will be vulnerable to Shor and Grover algorithm attacks -Adoption of post-cryptographic algorithms will be important Among quantum-resistant techniques, lattice-based cryptography is emerging as a promising solution, providing strong protection against quantum threats while balancing efficiency, scalability and resource management. While these systems present challenges, such as increased key size and increased communication capacity, they provide the quantum resistance required to secure data in environments such as 5G, IoT, and the cloud computing Compared with other techniques beyond quantum, lattice-based cryptography It strikes the right balance, making it a viable option for widespread use. The study emphasizes that optimizing these algorithms and integrating them into existing network protocols will be critical to ensuring secure communications in the post-quantum era.

### Conflicts Of Interest

The authors declare no conflicts of interest regarding the publication of this research.

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