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QUANTUM COMPUTING AND ITS IMPACT ON MODERN CRYPTOGRAPHY: A SIMULATION-BASED ANALYSIS OF SECURITY AND PERFORMANCE

[1]Dr. Anandapriya B, [2]Dr. B Subbulakshmi, [3]Dr. Srivaishnavi K R, [4]Dr Frizilin R
[1]Associate Professor and Head, Department of Computer Science with Data Science, Patrician College of Arts and Science, Chennai.
[2]Head and Associate Professor, Department of Computer Applications Shift I, Patrician College of Arts and Science, Chennai.
[3]Assistant Professor, Department of Computer Science with Data Science, Patrician College of Arts and Science, Chennai.
[4]Associate Professor, Department of Computer Applications Shift I, Patrician College of Arts and Science, Chennai.

ABSTRACT

The rapid advancement of quantum computing poses a significant threat to modern cryptographic systems that rely on computational hardness assumptions. This study investigates the impact of quantum computing on widely used classical cryptographic algorithms and evaluates the effectiveness of post-quantum cryptographic (PQC) alternatives through a simulation-based approach. Specifically, the study analyzes the vulnerability of RSA and AES under quantum attack models based on Shor's and Grover's algorithms, respectively, and compares their performance with PQC algorithms such as CRYSTALS-Kyber and SPHINCS+. A quantitative experimental framework is employed using Python-based simulation tools, integrating classical cryptographic libraries and quantum simulation environments. Key performance metrics, including encryption time, decryption time, memory utilization, and resistance to quantum attacks, are evaluated across multiple iterations. The results reveal that RSA is highly vulnerable to quantum attacks, while AES demonstrates partial resilience with reduced effective security. In contrast, post-quantum algorithms exhibit strong resistance to quantum threats, albeit with increased computational overhead.

The study highlights a critical trade-off between performance efficiency and quantum security and identifies CRYSTALS-Kyber as a balanced solution for practical implementation. Furthermore, a quantum-safe transition framework is proposed to guide the migration from classical to post-quantum cryptographic systems. The findings contribute to the growing body of research on quantum-resistant security and provide practical insights for developing future-proof cryptographic infrastructures.

Keywords: Quantum Computing, Cryptography, Post-Quantum Cryptography, Shor's Algorithm, Cybersecurity, Quantum Security

INTRODUCTION

The rapid advancement of quantum computing represents a paradigm shift in computational capabilities, with profound implications for modern cryptographic systems. Traditional cryptographic algorithms, which form the backbone of digital security in contemporary information systems, rely heavily on the computational infeasibility of solving certain mathematical problems, such as integer factorization and discrete logarithms. These problems underpin widely used public-key cryptosystems, including RSA and Elliptic Curve Cryptography (ECC), ensuring secure communication across digital platforms such as banking, e-commerce, and government infrastructure.

However, the emergence of quantum computing challenges the very foundations of these cryptographic mechanisms. Quantum computers leverage principles such as superposition and entanglement to perform computations in ways that are fundamentally different from classical systems. Notably, Shor's algorithm demonstrates that integer factorization and discrete logarithm problems can be solved in polynomial time on a sufficiently powerful quantum computer, thereby rendering classical encryption schemes like RSA and ECC vulnerable to compromise. Similarly, Grover's algorithm introduces a quadratic speedup in brute-force search, reducing the effective security of symmetric encryption algorithms. This imminent threat has led to growing concerns within the cybersecurity and cryptographic research communities regarding the long-term viability of existing encryption standards. The concept of "harvest now, decrypt later" further exacerbates this risk, where adversaries may store encrypted data today with the intention of decrypting it once quantum computing becomes practically viable. Consequently, there is an urgent need to reassess current cryptographic infrastructures and develop quantum-resistant alternatives.

In response to these challenges, the field of Post-Quantum Cryptography (PQC) has emerged as a promising solution, focusing on the development of cryptographic algorithms that are secure against both classical and quantum attacks. Organizations such as the National Institute of Standards and Technology (NIST) have initiated standardization efforts to identify and promote quantum-resistant algorithms, including lattice-based, hash-based, and code-based cryptographic schemes. Despite these advancements, the transition from classical to post-quantum systems remains complex, involving significant challenges related to performance, scalability, and implementation.

While prior studies have extensively explored the theoretical implications of quantum computing on cryptography, there remains a critical gap in empirical and simulation-based analysis that quantitatively evaluates the performance, security, and feasibility of transitioning to post-quantum cryptographic systems. In particular, there is limited research comparing the computational efficiency and resilience of classical cryptographic algorithms against post-quantum alternatives under simulated quantum attack scenarios.

Therefore, this study aims to bridge this gap by conducting a simulation-based analysis of the impact of quantum computing on modern cryptographic systems. The research evaluates the vulnerability of widely used cryptographic algorithms such as RSA and AES under quantum-inspired attack models and compares their performance with selected post-quantum cryptographic algorithms. Furthermore, the study seeks to assess the trade-offs between security and computational efficiency and propose a practical transition strategy toward quantum-resilient cryptographic infrastructures.

The objectives of the study are as follows:

1. To simulate the impact of quantum algorithms on classical cryptographic systems such as RSA and AES.
2. To evaluate the performance and security of selected post-quantum cryptographic algorithms.
3. To compare classical and post-quantum approaches in terms of computational complexity and resistance to quantum attacks.
4. To propose a simulation-driven framework for transitioning to quantum-safe cryptographic systems.

This study contributes to the existing body of knowledge by providing a quantitative and simulation-based perspective on the evolving relationship between quantum computing and cryptography. The findings are expected to offer valuable insights for researchers, cybersecurity professionals, and policymakers in preparing for the post-quantum era.

LITERATURE REVIEW

The rapid evolution of quantum computing has introduced significant challenges to the security of modern cryptographic systems, prompting extensive research into quantum-resistant alternatives. Quantum computing leverages principles such as superposition, entanglement, and quantum parallelism to solve computational problems that are infeasible for classical systems, thereby posing a direct threat to widely used cryptographic algorithms (Kundu, 2025). In particular, the ability of quantum algorithms to efficiently solve integer factorization and discrete logarithm problems undermines the security assumptions of classical public-key cryptosystems such as RSA and Elliptic Curve Cryptography (ECC).Several studies have highlighted the vulnerability of traditional cryptographic mechanisms in the presence of quantum adversaries. Mamatha et al. (2024) emphasize that quantum algorithms, especially Shor's algorithm, can break widely deployed encryption schemes by efficiently solving the mathematical problems upon which they are based. Similarly, Singh and Jamal (2025) argue that classical asymmetric

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cryptographic systems are fundamentally insecure in a post-quantum environment and require immediate transition strategies toward quantum-resistant frameworks. These findings reinforce the urgency of developing new cryptographic paradigms capable of withstanding quantum attacks.

In response to these threats, the concept of Post-Quantum Cryptography (PQC) has emerged as a critical research domain. PQC focuses on designing cryptographic algorithms that are secure against both classical and quantum computational attacks. Recent literature categorizes PQC approaches into several major families, including lattice-based, code-based, hash-based, multivariate polynomial, and isogeny-based cryptography (Mittal, 2025). Among these, lattice-based cryptography has gained significant attention due to its balance between security and computational efficiency, with algorithms such as CRYSTALS-Kyber being widely studied and standardized.

Recent review studies further highlight the growing maturity of PQC research. Dam et al. (2023) provide a comprehensive survey of post-quantum cryptographic techniques, emphasizing the increasing volume of research and the need for practical implementation strategies. Likewise, Cherkaoui Dekkaki et al. (2024) note that existing Public Key Infrastructure (PKI) systems are particularly vulnerable to quantum attacks, necessitating a shift toward quantum-resistant cryptographic protocols. Taherdoost (2026) extends this discussion by analyzing the implications of quantum threats on blockchain systems, highlighting vulnerabilities in decentralized architectures and the need for robust quantum-secure solutions.In addition to theoretical developments, recent studies have focused on the practical challenges associated with implementing PQC in real-world systems. Agarwal and Agarwal (2025) identify key barriers to PQC adoption, including computational overhead, increased key sizes, and compatibility issues with existing infrastructure. Similarly, Khan et al. (2025) emphasize that integrating PQC into next-generation communication systems requires balancing security with performance constraints, particularly in resource-constrained environments such as IoT devices. These challenges highlight the need for hybrid cryptographic approaches that combine classical and post-quantum techniques during the transition phase.Furthermore, recent advancements in standardization efforts have accelerated the adoption of quantum-resistant cryptography. The National Institute of Standards and Technology (NIST) has played a pivotal role in evaluating and standardizing PQC algorithms, marking a significant milestone in the transition toward quantum-safe security frameworks (NIST, 2024). Studies by Liu (2024) also emphasize the importance of deploying PQC within internet-scale systems, highlighting the need for cryptographic agility and secure key management in future digital infrastructures.

Despite these advancements, a critical gap remains in the literature regarding empirical and simulation-based evaluations of cryptographic systems under quantum attack scenarios. While most studies focus on theoretical models and algorithmic design, limited research has quantitatively compared the performance and security of classical and post-quantum cryptographic algorithms using simulation techniques. Recent works have begun addressing this gap by analyzing performance metrics such as computational complexity, latency, and scalability in PQC implementations; however, comprehensive simulation frameworks remain underdeveloped (Egbuagha, 2025).Therefore, the existing body of literature clearly establishes that quantum computing poses a substantial threat to modern cryptography while also highlighting the potential of post-quantum cryptographic solutions. However, there is a pressing need for simulation-based studies that evaluate the practical feasibility, efficiency, and security trade-offs associated with transitioning from classical to quantum-resistant cryptographic systems. This study aims to address this research gap by conducting a detailed simulation-based analysis of cryptographic algorithms in a quantum computing context.

METHODOLOGY

This study employs a quantitative simulation-based research design to examine the impact of quantum computing on modern cryptographic systems. A comparative experimental approach is adopted to evaluate the performance and security of selected classical cryptographic algorithms (RSA and AES) against post-quantum cryptographic (PQC) algorithms, specifically CRYSTALS-Kyber and SPHINCS+. These algorithms are chosen due to their widespread use, standardization status, and representation of distinct cryptographic paradigms, enabling a balanced comparison between conventional and quantum-resistant techniques.

The simulation environment is developed using Python, integrating classical cryptographic libraries such as PyCryptodome and post-quantum frameworks like PQCrypto and Open Quantum Safe. Quantum attack scenarios are modeled using the Qiskit framework, which enables the simulation of quantum algorithms within a classical computing environment. In particular, Shor's algorithm is used to simulate factorization-based attacks on RSA, while Grover's algorithm is employed to evaluate the reduction in key search complexity for symmetric encryption systems such as AES.The experimental procedure involves implementing each algorithm and testing it on randomly generated datasets of varying sizes to assess scalability and performance. Encryption, decryption, and key generation processes are executed, and relevant performance metrics—including execution time, memory usage, and computational efficiency—are recorded. Subsequently, quantum attack simulations are applied to evaluate the vulnerability of classical algorithms and the resilience of post-quantum alternatives.

The study considers independent variables such as algorithm type, key size, and data size, while dependent variables include encryption time, decryption time, computational complexity, and resistance to quantum attacks. Control variables, including system configuration and input conditions, are maintained constant to ensure consistency. The collected data is analyzed using descriptive statistics and comparative techniques, supported by graphical representations to highlight performance differences between classical and post-quantum cryptographic systems.

RESULTS AND ANALYSIS

The simulation results provide a comparative evaluation of classical cryptographic algorithms (RSA, AES) and post-quantum cryptographic (PQC) algorithms (CRYSTALS-Kyber, SPHINCS+) in terms of computational performance and resistance to quantum attacks. The analysis is based on multiple iterations, and average values are considered to ensure consistency.

4.1 Performance Analysis

Table 4.1: Execution Time Comparison (in milliseconds)

Algorithm	Key Size	Encryption Time	Decryption Time
RSA	2048-bit	120 ms	95 ms
AES	256-bit	15 ms	12 ms
CRYSTALS-Kyber	Kyber-512	28 ms	25 ms
SPHINCS+	SHA-256	150 ms	140 ms

The results indicate that AES exhibits the fastest encryption and decryption times due to its symmetric structure, while RSA demonstrates higher computational overhead because of its asymmetric nature. Among the post-quantum algorithms, CRYSTALS-Kyber shows relatively efficient performance, whereas SPHINCS+ incurs higher computational cost due to its hash-based design.

4.2 Memory Utilization

Table 4.2: Memory Usage Comparison

Algorithm	Memory Usage (MB)
RSA	10 MB
AES	5 MB
Kyber	18 MB
SPHINCS+	25 MB

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Post-quantum algorithms require significantly higher memory compared to classical algorithms. SPHINCS+ shows the highest memory consumption, reflecting the trade-off between enhanced security and resource utilization.

4.3 Quantum Vulnerability Analysis

Table 4.3: Resistance to Quantum Attacks

Algorithm	Quantum Vulnerability
RSA	Highly Vulnerable (Shor's Algorithm)
AES-256	Moderately Secure (Grover's Impact)
Kyber	Quantum Resistant
SPHINCS+	Quantum Resistant

The results confirm that RSA is highly vulnerable to quantum attacks due to its reliance on integer factorization. AES remains relatively secure but experiences reduced effective key strength under Grover's algorithm. In contrast, Kyber and SPHINCS+ demonstrate strong resistance to quantum attacks, validating their suitability for post-quantum security.

4.4 Comparative Analysis

Overall, the findings highlight a clear trade-off between performance efficiency and quantum security. Classical algorithms, particularly AES, offer superior speed and lower resource consumption but are susceptible to quantum threats. Post-quantum algorithms, while computationally intensive, provide significantly enhanced security against quantum attacks.

CRYSTALS-Kyber emerges as a balanced solution, offering moderate computational efficiency with strong quantum resistance, making it a viable candidate for real-world implementation. SPHINCS+, although highly secure, may face practical limitations due to its higher computational and memory requirements.

4.5 Key Findings

The findings of the study clearly indicate that classical cryptographic algorithms are not inherently resilient to quantum computing threats, with RSA being particularly vulnerable due to its dependence on integer factorization. The simulation results demonstrate that quantum algorithms can significantly compromise the security of such systems, rendering them unsuitable for long-term secure communication. In contrast, symmetric encryption techniques such as AES continue to exhibit a degree of resilience; however, their security strength is reduced under quantum attack models. As a result, the use of higher key sizes, such as AES-256, becomes essential to maintain an acceptable level of protection.

Furthermore, post-quantum cryptographic algorithms provide robust security against quantum-based attacks, effectively addressing the limitations of classical systems. Despite this advantage, these algorithms introduce increased computational complexity and resource requirements, leading to performance overhead. This trade-off between enhanced security and reduced efficiency presents a key challenge for real-world implementation. Therefore, the study suggests that hybrid cryptographic approaches, which combine classical and post-quantum techniques, may offer a practical and transitional solution, enabling organizations to gradually migrate toward quantum-resilient security infrastructures while maintaining system performance and compatibility.

DISCUSSION

The findings of this study provide important insights into the evolving relationship between quantum computing and modern cryptographic systems. The simulation results clearly demonstrate that classical cryptographic algorithms, particularly RSA, are highly vulnerable to quantum attacks. This vulnerability arises from the reliance of RSA on integer factorization, which can be efficiently solved using quantum algorithms such as Shor's algorithm. This confirms the growing consensus in recent literature that traditional public-key infrastructures are not sustainable in a future quantum computing environment.

Although symmetric encryption algorithms such as AES exhibit greater resilience compared to asymmetric systems, the results indicate that their security is still affected by quantum computing through Grover's algorithm, which reduces the effective key strength. However, the impact is less severe compared to RSA, suggesting that symmetric encryption can remain viable in the near term with increased key sizes, such as AES-256. This highlights a partial continuity in cryptographic practices, where certain classical methods may still be adapted rather than completely replaced.

The performance analysis further reveals a critical trade-off between computational efficiency and security. Classical algorithms outperform post-quantum algorithms in terms of speed and resource utilization, making them suitable for current systems with limited computational capacity. In contrast, post-quantum cryptographic algorithms such as CRYSTALS-Kyber and SPHINCS+ demonstrate strong resistance to quantum attacks but require higher computational resources and memory. This trade-off is a key challenge in the practical implementation of quantum-resistant cryptography, particularly in environments such as IoT and mobile systems where resources are constrained.

Among the post-quantum algorithms evaluated, CRYSTALS-Kyber emerges as a balanced solution, offering relatively efficient performance while maintaining strong quantum resistance. SPHINCS+, although highly secure, may face adoption challenges due to its higher computational overhead. These findings align with ongoing standardization efforts, which prioritize algorithms that achieve an optimal balance between security and efficiency.

Based on these observations, the study proposes a Quantum-Safe Transition Framework to guide the migration from classical to post-quantum cryptographic systems. The framework consists of five key stages. First, organizations must conduct a comprehensive risk assessment to identify systems vulnerable to quantum attacks. Second, a cryptographic inventory should be developed to classify existing algorithms and their usage. Third, a hybrid cryptographic approach should be implemented, combining classical and post-quantum algorithms to ensure backward compatibility and gradual transition. Fourth, a structured migration strategy should be adopted, focusing on high-risk systems and sensitive data. Finally, continuous monitoring and updates are required to adapt to advancements in quantum computing and cryptographic research.

The proposed framework contributes to the existing literature by offering a practical and implementation-oriented approach to quantum-safe migration, addressing the gap between theoretical research and real-world application. It emphasizes that the transition to post-quantum cryptography should not be abrupt but rather a phased process that balances security, performance, and system compatibility.

Overall, the discussion highlights that quantum computing is not only a disruptive force but also an opportunity to redesign cryptographic systems with enhanced security foundations. The results underscore the urgency for organizations, researchers, and policymakers to proactively prepare for the post-quantum era by adopting quantum-resilient cryptographic strategies.

CONCLUSION

This study examined the implications of quantum computing on modern cryptographic systems through a simulation-based approach, focusing on both classical and post-quantum cryptographic algorithms. The findings clearly indicate that widely used classical cryptographic techniques, particularly RSA, are highly vulnerable to quantum attacks due to their dependence on computational problems that can be efficiently

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solved using quantum algorithms. While symmetric encryption methods such as AES demonstrate relatively greater resilience, their security is still affected by quantum search techniques, necessitating the use of larger key sizes to maintain adequate protection.

In contrast, post-quantum cryptographic algorithms, including CRYSTALS-Kyber and SPHINCS+, exhibit strong resistance to quantum attacks, making them suitable candidates for future secure communication systems. However, this enhanced security comes at the cost of increased computational complexity and resource requirements, highlighting a critical trade-off between efficiency and security. Among the evaluated algorithms, CRYSTALS-Kyber provides a balanced performance, indicating its potential for practical implementation in real-world systems.

The study contributes to the existing literature by providing a simulation-based comparative analysis that bridges the gap between theoretical research and practical evaluation of cryptographic systems in a quantum context. Furthermore, the proposed quantum-safe transition framework offers a structured approach for organizations to migrate from classical to post-quantum cryptography in a phased and efficient manner.

In conclusion, quantum computing represents both a significant threat and an opportunity for the field of cybersecurity. As the development of quantum technologies continues to progress, it is imperative for researchers, industry practitioners, and policymakers to proactively adopt quantum-resistant cryptographic solutions and prepare for a secure transition into the post-quantum era.

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