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Comparative Analysis of Classical and Post-Quantum Cryptographic Methods for Secure Digital Signature Implementation in the Quantum Era

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Abstract— Rapid improvements in quantum computing have posed substantial hurdles to conventional cryptography systems, which depend on the computational intractability of resolving intricate mathematical issues. Digital signatures, fundamental to data security, guarantee the authenticity and integrity of digital communications. Nevertheless, traditional cryptography techniques, like RSA and ECC, are becoming more susceptible to quantum attacks owing to the substantial computing capabilities of quantum computers. Post-Quantum Cryptography (PQC) has developed as a crucial domain dedicated to the creation of quantum-resistant algorithms that can endure these dangers. This research examines the relative efficacy of conventional and quantum cryptography techniques, concentrating on the processes of digital signature creation and validation. Experimental findings underscore the trade-offs between the two methodologies regarding computing efficiency and security strength. Although classical cryptography has superior execution speeds, it is deficient in the robustness necessary to withstand quantum assaults. In contrast, PQC approaches, although somewhat more resource-demanding, provide superior security via sophisticated algorithms like lattice-based, hash-based, and multivariate polynomial cryptography. The research demonstrates that PQC mitigates the weaknesses of conventional cryptographic systems while providing a scalable and pragmatic solution for secure communication in the quantum age. This study underscores the need for ongoing research and enhancement of PQC approaches to augment their computing efficiency and facilitate smooth incorporation into current infrastructures. The results provide an essential foundation for the shift to quantum-resistant encryption, safeguarding sensitive information in a swiftly changing digital environment.

Keywords— Quantum Cryptography, Digital Signature, Data Security, Data Integrity, Information Systems

I. INTRODUCTION

In the constantly changing digital environment, maintaining data security and integrity has emerged as a crucial necessity for organizations, governments, and individuals. Conventional cryptographic systems, like those utilizing RSA and ECC algorithms, depend on mathematical challenges that are impractical for classical computers to resolve in a timely manner. Nonetheless, the rise of quantum computing presents a considerable challenge to these systems. Quantum computers possess the capability to tackle intricate mathematical challenges at an exponentially faster rate than traditional machines, which could compromise widely utilized cryptographic algorithms and make existing digital security protocols ineffective. Digital signatures serve as fundamental elements of contemporary cryptography, significantly contributing to the assurance of data authenticity and integrity. These are widely utilized across multiple domains, such as secure communications, e-commerce transactions, and governmental documentation. Nonetheless, the emergence of quantum computing requires the creation of quantum-resistant cryptographic methods to protect these applications from potential future threats.

Post-Quantum Cryptography (PQC) serves as a forward-thinking solution to this challenge, providing algorithms crafted to endure quantum assaults while ensuring compatibility with traditional computing systems. Among these advancements, digital signatures based on quantum cryptography utilize the principles of quantum mechanics to offer unmatched security. This study seeks to investigate the implementation and performance of digital signatures based on quantum cryptography, evaluating their efficiency and security in comparison to classical methods to meet the increasing demand for quantum-resistant solutions in the digital age (Kuznetsov et al., 2020).

II. LITERATUR REVIEW

A. Digital Signature

Digital signatures function as cryptographic techniques that replicate traditional handwritten signatures and physical seals on documents, providing a dependable method for authenticating and maintaining the integrity of digital content. The process involves generating two distinct keys: a private key for exclusive ownership and a corresponding public key for broader dissemination. This process consists of two main stages: verification and signature. In the signing phase, the sender utilises their private key to execute a sophisticated mathematical operation on the data intended for signing. This process results in the original data being enhanced with a unique digital signature, thereby generating a signed message. In the verification process, the sender's public key is utilised to confirm the authenticity of the digital signature. The verification process relies on establishing a correspondence between the digital signature and the original data. This alignment serves to confirm the validity of the signature, whereas any inconsistencies or indications of data tampering result in a failed verification. This describes the essential procedure of digital signatures. Upon closer examination of the digital signature process, it can be categorised into two schemes (Vasiliev, 2016) an identity scheme and a signature scheme. Identity and signature schemes are fundamentally designed to enable individuals to verify their identity or authenticate a message in various contexts (Alahmadi et al., 2023).

B. Quantum Cryptography

Quantum cryptography seeks to enable two users to communicate through methods that offer greater security than those provided by conventional cryptography. Historically, the foundation of cryptographic security has been rooted in mathematical principles, considering the constraints of our computational capabilities. Decoding a cryptographic code necessitates the factorisation of exceedingly large numbers into two prime components, usually exceeding 100 digits in length. This task was believed to be unfeasible within a practical timeframe (under a million years), even if all current computers were dedicated solely to solving a single instance of this challenge. Nonetheless, the absence of an efficient algorithm for quick factoring does not imply that such an algorithm may not be discovered in the future. Quantum cryptography employs photons and is grounded in the principles of quantum physics rather than depending on "extremely large numbers." This innovative discovery appears to ensure privacy, even under the assumption of eavesdroppers possessing unlimited computing capabilities (Moskvin, 2022).

Quantum security represents a groundbreaking method for safeguarding information, leveraging the principles of quantum mechanics—like superposition and entanglement—to defend data against various threats, including those posed by quantum computers. In contrast to traditional cryptography, which depends on mathematical intricacies, quantum security offers safeguarding grounded in the principles of physics. Quantum Key Distribution (QKD), exemplified by the BB84 protocol, stands out as a prominent technology in quantum security(Tripathi et al., 2024). It facilitates secure key distribution by identifying eavesdropping attempts through disturbances in the quantum state. Studies indicate that quantum security provides considerable benefits compared to traditional methods, as it remains unaffected by the limitless computational capabilities of quantum computers. Nonetheless, obstacles like the stability of quantum hardware, elevated costs, and issues with scalability continue to hinder its broad adoption. Nonetheless, quantum security stands as a fundamental pillar in advancing future communication technologies that prioritise enhanced security (Durr-E-Shahwar et al., 2024). The advantage of quantum cryptography lies in the fact that it allows the completion of various cryptographic tasks that are proven or suspected to be impossible using only classical (i.e. non-quantum) communication. For example, it is impossible to copy data encoded in a quantum state. If someone tries to read the encoded data, the quantum state will change due to the collapse of the wave function (no-cloning theorem). This can be used to detect eavesdropping in the quantum key distribution (QKD) (Mitra et al., 2017).

C. Quantum Digital Signature

A digital signature is a cryptographic mechanism used to generate inimitable signatures for electronic communications. It may be used, for example, to execute legal papers that may subsequently be enforced in court. The concept of a digital signature revolves on the public key used for its verification; typically, this consists of a number or a series of integers that are widely accessible and may be utilised to confirm the accuracy of a signature. Any individual with the public key may verify the message and arrive at the same determination on the validity of the signature. Moreover, an individual possessing just the public key cannot authenticate communications or alter a signed message to convey a different meaning; such authority is only held by the issuer of the public key (Hattenbach, 2021).

Classical techniques of generating digital signatures depend on the difficulty of deriving the private key, used for signature creation, from the public key, employed for verification. The RSA encryption algorithm may be used for signatures, provided that the adversary cannot factor huge integers. A forger using a quantum computer might effectively generate counterfeit signed communications. A similar issue occurs when RSA is used for encoding confidential information, which may be somewhat mitigated by quantum key distribution; hence, it is vital to enquire if quantum states can facilitate the creation of digital signatures. Similar to conventional digital signatures, quantum digital signatures use asymmetric keys (Shajahan et al., 2024). Consequently, an individual intending to sign a communication generates one or more pairs of private and matching public keys.In both instances, f is a one-way quantum function that has identical characteristics to a classical one-way function. The outcome is straightforward to calculate; but, unlike the conventional method, the function cannot be inverted, even with the use of advanced quantum deception techniques (Xin et al., 2019) and (Xin et al., 2020).

D. Post-Quantum Cryptography

The National Institute of Standards and Technology (NIST) has standardised two hash function-based stateful digital signature schemes, XMSS (eXtended Merkle Signature Scheme) and LMS (Leighton-Micali Signature), for use in the first phase of post-quantum cryptography (PQC). It was provisionally standardised (Cooper et al., 2020). Furthermore, these systems were more extensive and required continuous updates of the secret key, rendering them inappropriate for applications such as IoT, where efficiency, scalability, and simplicity are paramount. The organisation aimed to determine the best appropriate long-term standardised algorithm. Quantum-resistant cryptography, also known as post-quantum cryptography (PQC), is a specialised area within the discipline of cryptography (Shim, 2022). PQC is mostly concerned with maintaining cryptographic security in the face of possible quantum computer assaults. The primary objective is to replace existing encryption methods with algorithms designed to resist quantum computer assaults. PQC encompasses a wide range of mathematical foundations and cryptographic methodologies, including multivariate polynomial cryptography, hash-based cryptography, and lattice-based encryption, among others.

E. Data Security

Data security encompasses the protection of the integrity, confidentiality, and availability of information. The CIA (Confidentiality, Integrity, Availability) model is a foundational framework for data security. Furthermore, data security involves safeguarding digital information throughout its lifecycle to avoid corruption, theft, or unauthorised access (Sargiotis, 2024). It includes all elements: hardware, software, storage devices, user devices, access and administrative controls, along with organisational policies and processes. Data security utilises methods and technologies that improve the visibility of organisational data and its use. These technologies may protect data using techniques such as data masking, encryption, and the redaction of sensitive information. These solutions enable organisations to enhance their audit processes and comply with stricter data protection regulations. A robust data security policy and management protocol enables organisations to protect their information against attacks. It also aids in reducing the risk of human error and insider threats, which continue to be major factors in many data breaches (Templ & Sariyar, 2022).

F. Quantum Used in Encryption

Quantum methodologies are used in encryption because to the characteristics inherent in quantum systems, including superposition and entanglement. These two attributes provide security benefits unattainable via traditional approaches (Ali et al., 2024). In quantum systems, information may be encoded as quantum states that are challenging for third parties to anticipate or replicate. The fundamental principles of quantum physics remain unknown, hence enhancing security against eavesdropping efforts. Moreover, quantum channels facilitate the use of quantum hypothesis testing methods to identify intruders. The negative entropy of some quantum channels signifies their capacity to distill quantum entanglement, which is crucial in channel coupling protocols. In this context, quantum encryption methods provide enhanced security owing to the significant uncertainty and stochastic characteristics of quantum states, making them challenging to replicate or infer without compromising the state(Sahu & Mazumdar, 2024).

III. METHOD

To evaluate the effectiveness of post-quantum-based digital signatures on data security and integrity, an experimental approach was employed using a pretest-posttest control group design. This methodology ensures a systematic comparison of the outcomes between a control group and an experimental group, allowing for the assessment of changes resulting from the intervention. The information system used in the study relies on digital signatures for securing data transactions, making it an ideal testbed for evaluating the performance of different digital signature algorithms. The samples were divided into two groups: the control group utilized classical digital signature methods, while the experimental group adopted post-quantum-based digital signatures. The effectiveness of each approach was measured using two key parameters: validation speed and the time required to generate a digital signature. These metrics provide a comprehensive understanding of both the efficiency and security of the tested systems.

A. Test Preparation

The first phase of the experimental procedure was the meticulous selection and use of a post-quantum digital signature method. Recommendations from the National Institute of Standards and Technology (NIST) were adhered to in order to implement strong and generally acknowledged algorithms, including lattice-based or hash-based encryption. These algorithms were selected for their robustness against future quantum assaults, anticipated to undermine conventional encryption techniques.

To provide precise and dependable testing, suitable testing devices were created or procured. The instruments included software designed to simulate real-world events, including hypothetical data breaches or cyberattacks, to evaluate the robustness and durability of digital signature algorithms. Furthermore, data integrity analysis methods were used to confirm that the digital signatures preserved their intended role in safeguarding data authenticity and integrity. The assaults simulated in this phase were restricted to conventional classical approaches, excluding sophisticated quantum-based threats. This choice was implemented to provide a controlled environment in which the major variable was the kind of digital signature used.

B. Data Security Validation and Integrity

The subsequent step of the investigation included incorporating post-quantum digital signatures into the experimental group's information system. This procedure required comprehensive testing to guarantee compatibility with the current infrastructure and the smooth functioning of the new encryption techniques. The control group used traditional digital signatures, preserving the status quo for comparative analysis. Following an installation phase, a posttest was administered to assess the security and integrity of the data in both groups. This phase included thorough testing to detect any inconsistencies or weaknesses in the systems. The data gathered during the posttest phase provided essential insights into the efficacy of post-quantum digital signatures relative to conventional techniques. Critical metrics, including the duration for signature validation and creation, alongside the system's resilience to simulated assaults, were evaluated to ascertain the comparative strengths and shortcomings of each methodology.

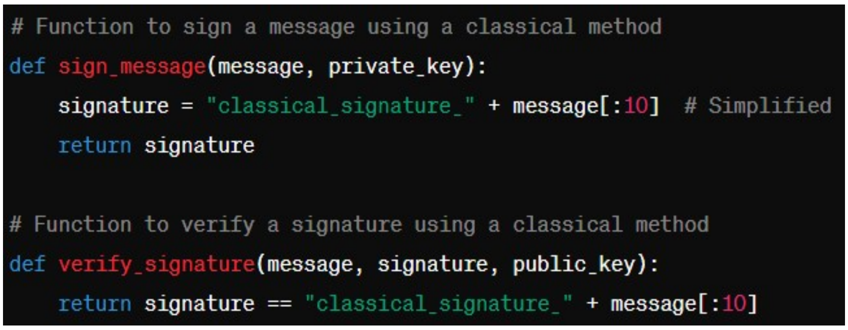
The paper emphasizes the potential benefits of adopting post-quantum cryptography technologies and offers practical guidance for their real-world application. This thorough assessment provides a basis for further research focused on enhancing the equilibrium between security and performance in the context of quantum computing.

IV. ANALYSIS

In this analysis, the programme is run on Qiskit v1.0.2 (ipykarnel) at IBM Quantum Lab to be able to use qiskit and quantum circuit in real time and can properly run the post quantum cryptograpy programme in executing the validation speed and signature time used by each classical cryptograpy and post quantum cryptograpy.

A. Simple Algorithm for Cryptograpghy Classic

The sign_message function generates a digital signature by appending a predefined string to the first 10 characters of the input message. This process, while highly simplified, represents the basic concept of creating a digital signature. Similarly, the verify_signature function validates the authenticity of a given signature by comparing it with the signature format derived from the original message.



```
# Function to sign a message using a classical method
def sign_message(message, private_key):
    signature = "classical_signature_" + message[:10]  # Simplified
    return signature

# Function to verify a signature using a classical method
def verify_signature(message, signature, public_key):
    return signature == "classical_signature_" + message[:10]
```

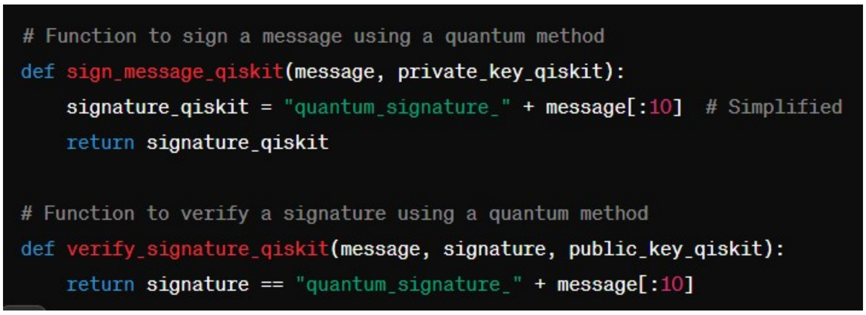
Fig. 1. Algorithm for Cryptography Classic

The sign_message and verify_signature functions, as demonstrated in this simulation, illustrate the fundamental mechanisms of digital signature creation and verification within the classical cryptography framework. In the sign_message function, the signature is formed by concatenating a predefined identification string with the first 10 characters of the original message. Meanwhile, the verify_signature function ensures the validity of the signature by performing a direct comparison with the expected signature format derived from the same input message. While this simulation offers a rudimentary understanding of the digital signature process, it falls short of reflecting the inherent complexity of widely used classical cryptographic methods such as RSA (Rivest-Shamir-Adleman) or DSA (Digital Signature Algorithm). These established algorithms utilize private key encryption and cryptographic hash functions to provide robust security guarantees. The simplicity of the presented simulation limits its practical applicability but serves as a foundational example for understanding the vulnerabilities of classical digital signatures.

In the context of emerging quantum computing threats, this simulation underscores the fundamental weaknesses of classical cryptographic approaches. Algorithms like RSA and DSA, which rely on the computational difficulty of factoring large integers or solving discrete logarithms, are susceptible to quantum-based attacks. Consequently, this simulation highlights the pressing need to transition towards post-quantum cryptographic algorithms that can withstand the advanced computational capabilities of quantum computers. Developing and implementing post-quantum digital signatures is imperative to ensure the future security and integrity of digital systems.

B. *Simple Algorithm for Post Quantum Cryptography*

The implementation of quantum cryptographic methods using Qiskit introduces functions such as sign_message_qiskit for signing messages and verify_signature_qiskit for signature verification. These functions, while conceptually similar to their classical counterparts, utilize quantum circuits to model cryptographic operations. Specifically, the private key (private_key_qiskit) and public key (public_key_qiskit) are represented as quantum circuits comprising 20 qubits. This setup provides a basic simulation of quantum digital signature processes and serves as a theoretical and illustrative example of potential applications of quantum cryptography.



```
# Function to sign a message using a quantum method
def sign_message_qiskit(message, private_key_qiskit):
    signature_qiskit = "quantum_signature_" + message[:10]  # Simplified
    return signature_qiskit

# Function to verify a signature using a quantum method
def verify_signature_qiskit(message, signature, public_key_qiskit):
    return signature == "quantum_signature_" + message[:10]
```

Figure 2. Algorithm Post Quantum Cryptography

The sign_message_qiskit and verify_signature_qiskit routines demonstrate the fundamental mechanics of digital signatures within a quantum cryptographic framework. In the sign_message_qiskit function, a signature is generated using the format quantum_signature_, followed by the first 10 characters of the original message. The verify_signature_qiskit function validates the provided signature by comparing it with the expected signature derived from the same input message. While this simulation effectively introduces the core principles of quantum-based digital signatures, it does not encompass the full complexity of genuine quantum cryptographic algorithms. Advanced quantum cryptographic methods leverage quantum mechanical properties, such as superposition and entanglement, to ensure security that surpasses classical approaches. These properties enable robust resistance to quantum-based attacks, a critical requirement as the computational power of quantum systems continues to grow.

This simulation, though basic, is valuable as a foundational demonstration of the potential and principles underlying quantum digital signatures. However, to fully showcase the advantages of quantum cryptography, further refinement is necessary. Integrating advanced algorithms, such as lattice-based or hash-based quantum-resistant signatures, would provide a clearer illustration of the benefits in terms of security and efficiency. Moreover, this approach highlights the stark distinctions between classical and quantum digital signatures, particularly as quantum computing becomes an increasingly significant threat to traditional cryptographic systems.

C. *The results obtained in the form of pie charts*

The data visualization presented in Figure 1 offers a detailed comparative analysis of the validation and signature times between Post-Quantum Cryptography (PQC) and classical cryptographic methods. The pie chart segmentation highlights the distribution of computational resources and processing time, providing key insights into the trade-offs between these two approaches.

1. Classical Signature (42.1%):

   Represented by the largest blue segment, this category reflects the significant computational time required for signature creation in classical cryptographic systems. The dominance of this segment highlights the intensive processing demands associated with classical signature generation. This result aligns with the reliance of classical cryptography on mathematical problems such as factoring large integers, which, while computationally manageable for current systems, are vulnerable to quantum computing advances.

2. PQC Validation (21.1%):

   The red segment illustrates the time consumed by the validation process in PQC methods. This relatively moderate percentage indicates the additional computational overhead introduced by quantum-resistant algorithms. The higher complexity of validation in PQC is a direct consequence of the intricate mathematical constructs utilized to ensure resistance against quantum attacks, such as lattice-based or hash-based techniques.

3. PQC Signature (18.4%):

Shown in green, this segment represents the time taken for generating signatures within PQC frameworks. Despite the advanced security measures embedded in PQC algorithms, the signature creation process remains comparably efficient, demonstrating the potential for quantum-resistant methods to meet practical performance benchmarks. This efficiency is critical for applications requiring secure yet rapid cryptographic operations.

4. Classical Validation (18.4%):

The orange segment reflects the time allocated to the validation process in classical methods. The similarity in percentage between classical validation and PQC signature creation (both at 18.4%) suggests competitive efficiency in this aspect. This equivalence underscores the well-optimized nature of classical cryptographic validation processes while highlighting the advances in PQC signature mechanisms to achieve comparable performance.

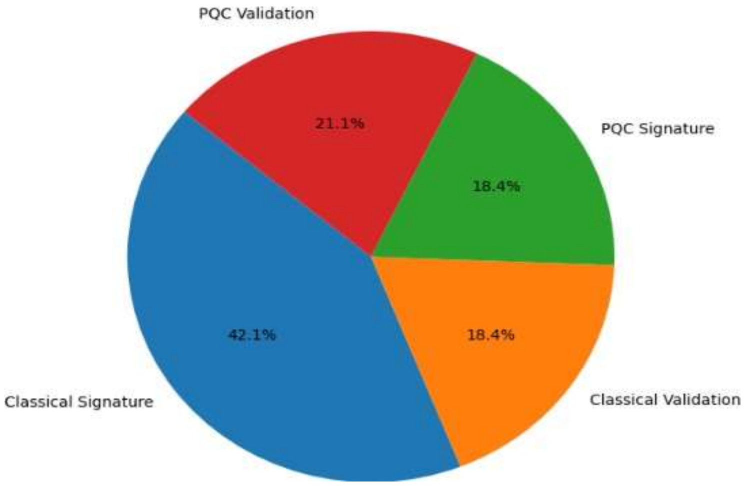


Figure 1. Comparison of Signature and Validation Times

The pie chart serves as a clear illustration of the computational trade-offs inherent in transitioning from classical to quantum-resistant cryptographic methods. While classical cryptography excels in efficiency, particularly in validation processes, it lacks the robust security necessary to counteract the emerging threats posed by quantum computing. PQC, on the other hand, achieves a more balanced allocation of computational resources across signature generation and validation processes. Although this approach introduces a modest increase in resource usage, the enhanced security it provides justifies this trade-off, especially in high-stakes environments.

The findings presented emphasize the importance of further optimization in PQC techniques to improve their computational efficiency without compromising their advanced security benefits. As quantum computing technology continues to evolve, these results provide a foundational framework for developing next-generation cryptographic systems capable of addressing emerging threats. Future research should focus on:

- ✓ Algorithm Optimization: Refining PQC algorithms to reduce processing times for signature generation and validation while maintaining their quantum-resistant properties.
- ✓ Scalability: Ensuring that PQC methods can be implemented effectively across diverse applications, from high-security governmental systems to resource-constrained IoT environments.
- ✓ Hybrid Approaches: Investigating the integration of classical and PQC methods to create hybrid cryptographic frameworks that leverage the strengths of both approaches during the transition period to fully quantum-resistant systems.

By addressing these areas, PQC can become a practical and efficient solution for securing digital systems in the quantum era. The results underscore the urgency of adapting cryptographic strategies to ensure resilience against quantum-based threats while maintaining performance standards required for real-world applications.

D. Signature Execution Time and Validation

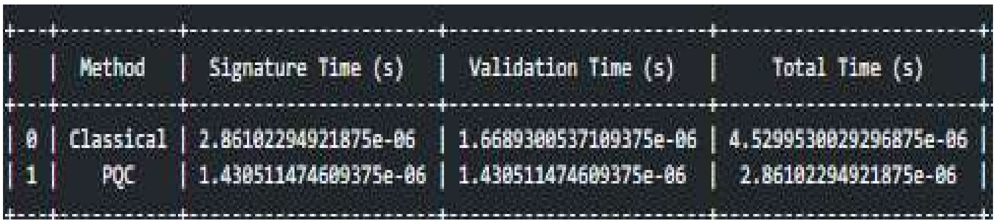
The comparison of signature and validation execution times between the classical cryptographic method and the Post-Quantum Cryptography (PQC) method reveals notable differences in computational efficiency and performance. As shown in Figure 2, the total execution times highlight the trade-offs associated with each method, offering insights into their suitability for different cryptographic use cases.

1. Classical Method:

   The classical cryptographic method demonstrates a total processing time of approximately 4.53 million seconds, with 2.86 million seconds dedicated to signature generation and 1.67 million seconds for validation. These results illustrate the computational efficiency of classical cryptographic systems, which are optimized for faster performance due to their reliance on established mathematical foundations such as integer factorization and modular arithmetic. The relatively low computational overhead makes the classical approach well-suited for real-time applications where speed is prioritized over resistance to emerging quantum threats.

2. PQC Method:

   In contrast, the PQC method requires a total processing time of approximately 2.86 million seconds, with 1.43 million seconds allocated for both signature generation and validation. This reduction in time compared to earlier quantum cryptographic methods reflects advancements in the optimization of PQC algorithms. Despite its slower processing compared to classical cryptography, PQC provides enhanced security by leveraging quantum-resistant algorithms, which are designed to withstand attacks from quantum computers.



```
+---+-----------+-----------------------+------------------------+------------------------+
|   |  Method   |  Signature Time (s)   |  Validation Time (s)   |     Total Time (s)     |
+---+-----------+-----------------------+------------------------+------------------------+
| 0 | Classical | 2.86102294921875e-06  | 1.6689300537109375e-06 | 4.5299530029296875e-06 |
| 1 |    PQC    | 1.430511474609375e-06 | 1.430511474609375e-06  |  2.86102294921875e-06  |
+---+-----------+-----------------------+------------------------+------------------------+
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Figure 2. Signature and Validation Time Table Data

The analysis highlights a fundamental trade-off between security and efficiency. While the classical cryptographic method outperforms PQC in terms of speed, its reliance on computational problems such as factoring large integers makes it inherently vulnerable to quantum attacks. In contrast, PQC methods, though slightly more computationally intensive, offer a robust solution to these vulnerabilities by utilizing complex quantum-resistant algorithms such as lattice-based cryptography, hash-based cryptography, or multivariate polynomial cryptography. The computational overhead observed in PQC methods arises from the need to incorporate advanced mathematical constructs and additional steps to ensure resistance against quantum-based attacks. However, recent advancements in PQC have demonstrated significant improvements in performance, as evidenced by the reduced total execution time in comparison to earlier quantum cryptographic implementations. This suggests that with continued research and development, PQC algorithms can achieve an optimal balance between security and efficiency.

As quantum computing capabilities continue to evolve, the adoption of PQC will be critical in maintaining the integrity and confidentiality of sensitive information. The findings emphasize the need for ongoing optimization of PQC algorithms to reduce computational overhead and improve scalability for practical deployment in security-sensitive environments. Additionally, hybrid

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cryptographic systems combining classical and quantum-resistant methods may offer a transitional solution, ensuring compatibility and performance during the gradual shift toward quantum-secure cryptography. The results underscore the importance of prioritizing research into PQC not only for its potential to address quantum threats but also for its ability to provide a forward-looking framework for cryptographic security in the digital era. These advancements will play a crucial role in safeguarding critical systems and infrastructure against both present and future cybersecurity challenges.

E. Total Execution Signature

The pie chart in Figure 3 provides a comparative analysis of the total execution time for signature and validation processes between the classical cryptographic method and Post-Quantum Cryptography (PQC). The data highlights notable differences in how computational resources are allocated for these two approaches:

1. Classical Method (61.3%): Representing the largest segment, the classical cryptographic method accounts for 61.3% of the total execution time. This finding underscores the higher computational demand of classical cryptographic methods, which rely on solving mathematically intensive problems such as factoring large integers. While classical methods are widely regarded for their simplicity and ease of implementation, their disproportionate time allocation between signature and validation processes suggests inefficiencies that may hinder performance, especially in high-volume or time-sensitive applications.
2. PQC Method (38.7%): Accounting for 38.7% of the total execution time, PQC demonstrates a more efficient utilization of computational resources compared to the classical method. This result reflects the advancements in quantum-resistant algorithms, which are designed to optimize the balance between security and performance. Despite the inherent complexity of quantum-resistant methods, PQC's ability to achieve lower overall execution times highlights the progress made in refining these algorithms to meet practical requirements.

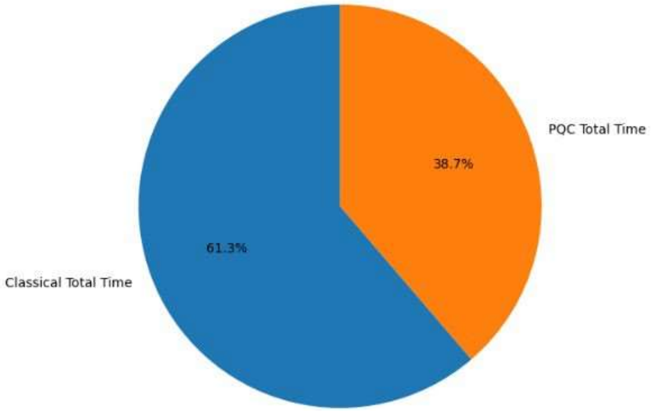

Figure 3. Total Execution Time for Signature and Validation

Contrary to the assumption that PQC methods might incur significantly longer processing times due to their advanced cryptographic constructs, the data reveals that PQC outperforms classical methods in terms of overall execution efficiency. This finding suggests that the iterative optimization of PQC algorithms has led to reductions in computational overhead, making them more suitable for real-world applications.

The observed results highlight the evolving nature of cryptographic systems and the potential for PQC to become a viable alternative to classical methods. Future research should focus on:

- ✓ Algorithm Refinement: Further optimizing PQC algorithms to achieve even greater efficiency while maintaining robust security.

- ✓ Scalability: Ensuring that PQC methods can be seamlessly integrated into diverse systems, including resource-constrained environments such as IoT devices and real-time communication networks.
- ✓ Hybrid Models: Exploring hybrid cryptographic frameworks that combine classical and PQC methods, allowing for a gradual transition to fully quantum-resistant systems while leveraging the strengths of both approaches

The comparison of total execution times reinforces the promise of PQC as a next-generation cryptographic standard capable of addressing emerging quantum threats while maintaining competitive efficiency. By continuing to refine these methods, researchers can ensure that PQC remains a practical, secure, and efficient solution for safeguarding information in the quantum computing era.

V. CONCLUSION

The research underscores the significant distinctions between conventional encryption and Post-Quantum encryption (PQC) regarding security, computational efficiency, and adaptation to potential quantum threats. Traditional approaches, albeit effective in signature and validation procedures, are becoming more susceptible to quantum-based assaults. PQC provides superior security with quantum-resistant algorithms, mitigating the weaknesses of conventional cryptographic systems.

The comparative research indicates that PQC approaches, although necessitating extended processing durations in some situations, exhibit balanced usage of computing resources and enhanced overall efficiency in total execution time. For example, while the traditional technique prevails in specific operations such as signature creation, the PQC method decreases overall execution time, as seen in the pie chart analysis. This equilibrium indicates that PQC may get superior performance optimization when executed proficiently.

The increased computational burden linked to PQC underscores the need for more study and optimization. Improving algorithmic efficiency without sacrificing security is a considerable task, especially as quantum computing technology progresses. The findings emphasize the need of adopting quantum-resistant cryptographic techniques to secure the future robustness of digital systems against quantum attacks. In conclusion, the implementation of PQC signifies a crucial advancement in safeguarding data integrity and authenticity in the age of quantum computing. As the domain progresses, ongoing endeavors to enhance PQC algorithms and incorporate them into current systems will be essential for establishing a resilient, safe, and efficient cryptographic environment.

REFERENCES

[1] Alahmadi, A., Çalkavur, S., Solé, P., Khan, A. N., Raza, M., & Aggarwal, V. (2023). A New Code Based Signature Scheme for Blockchain Technology. *Mathematics*, *11*, 1177. https://doi.org/10.3390/math11051177

[2] Ali, Z. A., Atia, T. S., Yousuf, A. Y., & Khahdim, A. J. (2024). A comprehensive review of quantum image encryption methods: design characteristics, cryptographic properties, and AI integration. *Quantum Information Processing*, *23*(10), 335. https://doi.org/10.1007/s11128-024-04563-y

[3] Cooper, D. A., Apon, D. C., Dang, Q. H., Davidson, M. S., Dworkin, M. J., & Miller, C. A. (2020). *Recommendation for Stateful Hash-Based Signature Schemes*. https://doi.org/10.6028/NIST.SP.800-208

[4] Durr-E-Shahwar, Imran, M., Altamimi, A. B., Khan, W., Hussain, S., & Alsaffar, M. (2024). Quantum Cryptography for Future Networks Security: A Systematic Review. *IEEE Access*, *12*, 180048–180078. https://doi.org/10.1109/ACCESS.2024.3504815

[5] Hattenbach, H. (2021). *Quantum-resistant digital signatures schemes for low-power IoT*. https://doi.org/10.48550/arXiv.2106.11710

[6] Kuznetsov, O., Kiian, A., Babenko, V., Perevozova, I., Chepurko, I., & Oleksii, S. (2020). *New Approach to the Implementation of Post-Quantum Digital Signature Scheme*. 166–171. https://doi.org/10.1109/DESSERT50317.2020.9125053

[7] Mitra, S., Jana, B., Bhattacharya, S., Pal, P., & Poray, J. (2017). Quantum cryptography: Overview, security issues and future challenges. *2017 4th International Conference on Opto-Electronics and Applied Optics (Optronix)*, 1–7. https://doi.org/10.1109/OPTRONIX.2017.8350006

[8] Moskvin, V. S. (2022). Post-Quantum Digital Signatures in Transport Documents. *2022 Intelligent Technologies and Electronic Devices in Vehicle and Road Transport Complex (TIRVED)*, 1–5. https://doi.org/10.1109/TIRVED56496.2022.9965491

[9] Sahu, S. K., & Mazumdar, K. (2024). State-of-the-art analysis of quantum cryptography: applications and future prospects. In *Frontiers in Physics* (Vol. 12). Frontiers Media SA. https://doi.org/10.3389/fphy.2024.1456491

[10] Sargiotis, D. (2024). Data Security and Privacy: Protecting Sensitive Information. In *Data Governance: A Guide* (pp. 217–245). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-67268-2_6

[11] Shajahan, R., Jain, K., & Krishnan, P. (2024). *A Survey on NIST 3 rd Round Post Quantum Digital Signature Algorithms*. 132–140. https://doi.org/10.1109/ICMCSI61536.2024.00027

[12] Shim, K.-A. (2022). A Survey on Post-Quantum Public-Key Signature Schemes for Secure Vehicular Communications. *Trans. Intell. Transport. Sys.*, *23*(9), 14025–14042. https://doi.org/10.1109/TITS.2021.3131668

[13] Templ, M., & Sariyar, M. (2022). A systematic overview on methods to protect sensitive data provided for various analyses. *International Journal of Information Security*, *21*(6), 1233–1246. https://doi.org/10.1007/s10207-022-00607-5

[14] Tripathi, T., Awasthi, A., Singh, S. P., & Chaturvedi, A. (2024). *Post Quantum Cryptography and its Comparison with Classical Cryptography*. https://arxiv.org/abs/2403.19299

[15] Vasiliev, A. (2016). *Quantum Hashing for Finite Abelian Groups*. http://arxiv.org/abs/1603.02209

[16] Xin, X., Wang, Z., He, Q., Yang, Q., & Li, F. (2019). New Public-key Quantum Signature Scheme with Quantum One-Way Function. *International Journal of Theoretical Physics*, *58*(10), 3282–3294. https://doi.org/10.1007/s10773-019-04203-7

[17] Xin, X., Yang, Q., & Li, F. (2020). Quantum public-key signature scheme based on asymmetric quantum encryption with trapdoor information. *Quantum Information Processing*, *19*(8), 233. https://doi.org/10.1007/s11128-020-02736-z