Comparative Security and Performance Analysis of RSA and CRYSTALS-Dilithium3 Digital Signatures in the Post-Quantum Era

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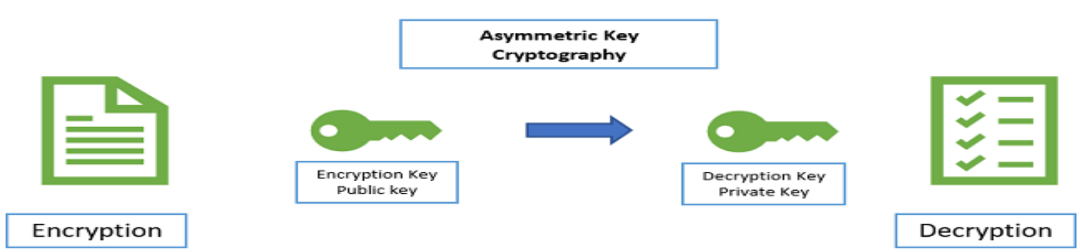
***Abstract*—The rapid advancement of quantum computing presents a significant threat to classical cryptographic systems, particularly RSA, whose security is based on the hardness of integer factorization. Shor's algorithm demonstrates that large RSA keys can be efficiently broken in a quantum environment, raising concerns about the long-term reliability of traditional digital signatures. To address this, post-quantum cryptography (PQC) has emerged as a promising solution, with lattice-based schemes such as CRYSTALS-Dilithium3 gaining attention for their quantum resistance and efficiency. This study presents a comparative security and performance analysis of RSA and CRYSTALS-Dilithium3 digital signatures in the post-quantum era. The evaluation considers signature size, signing and verification speed, tamper detection capability, and resilience against classical and quantum attack models. Results highlight that RSA offers compact signature sizes but fails to provide integrity protection once subjected to simulated quantum attacks, while Dilithium3 ensures robust tamper detection, forward security, and cross-format verification across multiple document types. Despite larger signature sizes, Dilithium3 demonstrates superior verification speed and scalability, making it a viable candidate for post-quantum digital infrastructures. The findings emphasize the need for transitioning from classical to quantum-resistant cryptographic systems to ensure secure digital communication in the emerging quantum age.**

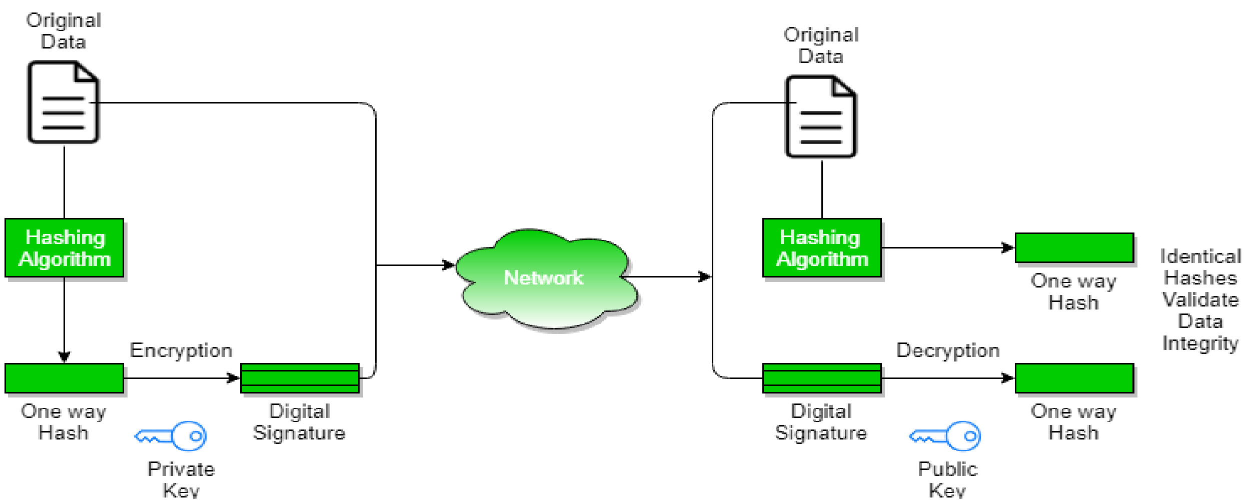
***Index Terms*—Post-Quantum Cryptography, RSA, CRYSTALS-Dilithium3, Digital Signatures, Quantum Attacks, Tamper Detection, Performance Analysis**

I. INTRODUCTION

Cryptography has long served as the foundation of secure communication, protecting sensitive data by ensuring confidentiality, authenticity, and integrity. It relies on mathematical principles to convert information into secure, unreadable formats, safeguarding it from unauthorized access or manipulation. Within this domain, asymmetric key cryptography plays a particularly important role. Unlike symmetric cryptography, which uses a single shared key, asymmetric systems employ a pair of mathematically related keys—one public and one private. This mechanism enables secure communication and authentication without requiring a pre-shared secret, making it highly scalable for modern digital infrastructures. Classical algorithms such as RSA and Elliptic Curve Cryptography (ECC) are prominent examples, both of which rely on hard mathematical problems such as integer factorization and discrete logarithms. These algorithms have become widely deployed in securing digital transactions, confidential communication, and online identity verification.



A key application of asymmetric cryptography is found in digital signatures, which function as the electronic equivalent of handwritten signatures and physical seals. Digital signatures provide authentication of the sender's identity, integrity of the transmitted or stored content, and non-repudiation to prevent denial of authorship. Their role has expanded significantly with the growth of electronic governance (e-sign), financial transactions, legal documentation, secure email communication, and software distribution. For instance, government e-sign platforms rely on digital signatures to validate citizen services, while businesses use them to streamline legal agreements and financial operations. In the technology sector, digital signatures are also critical for verifying the authenticity of distributed software updates, preventing attackers from introducing malicious code. Traditionally, RSA has dominated these applications due to its long-standing trust and ease of integration into diverse platforms.



Feature	RSA	DSA	ECC	ECDSA
Security Basis	Integer Factorization	Discrete Log Problem	Elliptic Curve DLP	Elliptic Curve DLP
Key Size	2048-bit	2048-bit	256-bit	256-bit
Signature Size	Large	Medium	Small	Small
Efficiency	Slow	Moderate	Fast	Fast
Quantum Vulnerable	Yes (Shor)	Yes (Shor)	Yes (Shor)	Yes (Shor)
Use Cases	SSL/TLS, PGP, Certs	Govt, Legacy	IoT, Mobile, SSL/TLS	Blockchain, IoT, SSL/TLS
Advantages	Simple, well-analyzed	Standardized	Efficient, small keys	Compact, efficient
Limitations	Slow, quantum-vulnerable	Quantum-vulnerable	Quantum-vulnerable	Implementation-sensitive, quantum-vulnerable

The emergence of quantum computing represents the most disruptive threat to classical cryptographic systems. Unlike traditional computers, quantum machines leverage principles such as superposition and entanglement to perform computations in fundamentally different ways, enabling them to solve problems previously considered intractable. Shor's algorithm, a breakthrough in quantum computing, can factorize large integers and solve discrete logarithms exponentially faster than classical methods. This capability directly undermines the security foundation of RSA and ECC, rendering them vulnerable in a future where practical quantum computers are available. As a result, digital signatures that rely on these schemes would fail to guarantee authenticity and integrity, exposing critical digital ecosystems to unprecedented risks. The recognition of this challenge has accelerated research into new paradigms of cryptography that are resistant to quantum attacks.

In response, Post-Quantum Cryptography (PQC) has emerged as a promising avenue, with the National Institute of Standards and Technology (NIST) leading the global standardization process. Among the various candidate families, lattice-based cryptography has gained prominence due to its strong theoretical foundations and efficiency. One of the most notable algorithms is CRYSTALS-Dilithium, standardized as ML-DSA, which is designed for digital signatures. Dilithium leverages hard mathematical problems such as Module Learning With Errors (MLWE) and Short Integer Solution (SIS), for which no efficient quantum algorithms are currently known. This makes it a strong candidate for long-term cryptographic security. Beyond its resilience, Dilithium3 demonstrates competitive performance, scalability, and the ability to operate across multiple file formats, ensuring its practical applicability. Unlike RSA, which fails under simulated quantum and tampering scenarios, Dilithium3 reliably preserves document authenticity and integrity. This paper, therefore, presents a comparative security and performance analysis of RSA and CRYSTALS-Dilithium3 digital signatures, focusing on signature size, efficiency, tamper detection, and resilience to quantum threats, to highlight the pressing need for transitioning toward quantum-resistant digital infrastructures.

II. LITERATURE REVIEW

The foundations of post-quantum research can be traced through early explorations such as Sailada et al. [1], who experimented with the CRYSTALS-Dilithium algorithm in e-signature applications, highlighting its practical viability. This built upon the seminal contribution of Rivest, Shamir, and Adleman [2], who introduced RSA in 1978 as the first widely adopted public-key cryptosystem. RSA's strength, based on integer factorization, made it a cornerstone of digital signatures and secure communication for decades. However, with growing computational capabilities, researchers recognized the need to explore alternatives, leading to significant reviews like that of Chen et al. [3], which presented a comprehensive NIST report on post-quantum cryptography and its candidate families.

The shift in focus was further driven by algorithmic breakthroughs. Ducas et al. [4] introduced **CRYSTALS-Dilithium**, a lattice-based signature scheme with strong security and efficiency, while Shor [5] presented the quantum algorithm that directly threatens RSA and ECC by efficiently solving factorization and discrete logarithm problems. In parallel, NIST's second-round report [6] documented progress in the PQC standardization process, guiding the global transition to quantum-safe cryptography. The Open Quantum Safe Project [7] also contributed by offering open-source implementations, enabling researchers to integrate PQC algorithms into practical systems. Complementing these technical efforts, Bernstein, Buchmann, and Dahmen [8] provided a foundational text on PQC, while Peikert [9] offered a decade-long overview of lattice cryptography, establishing the theoretical depth of lattice-based security.

Advances in cryptographic design further refined PQC schemes. Lyubashevsky [10] proposed the Fiat–Shamir with aborts transformation, a technique critical in constructing secure lattice-based signatures such as Dilithium. In addition, Bindel et al. [11] examined hybrid approaches that combine classical and post-quantum mechanisms to ensure smooth migration during the transition period. Mosca [12] warned of the urgency of this transition, emphasizing the risks of a "harvest-now, decrypt-later" threat model in the quantum age. Parallel work by Chung, Liu, and Pass [13] explored statistical zero-knowledge protocols, contributing to the theoretical basis of secure digital signatures. Barker and Dang [14] complemented these advances by offering NIST's key management recommendations, ensuring that signature systems align with robust standards of key generation and storage.

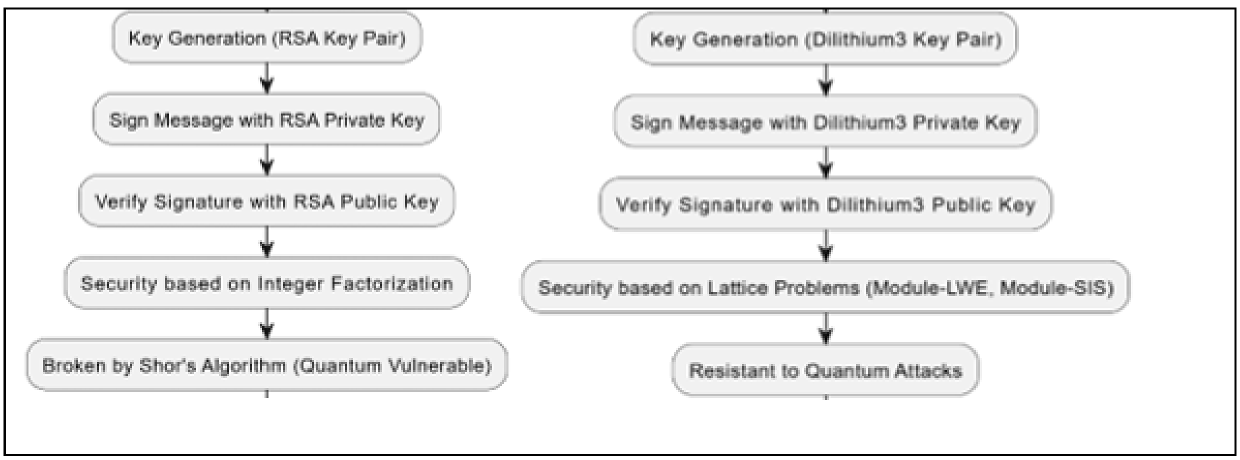
The European Telecommunications Standards Institute (ETSI) also contributed to global preparedness through its quantum-safe cryptography guidelines [15], which assessed algorithms and provided best practices for adoption. Finally, Grover [16] introduced another quantum algorithm with implications for symmetric cryptography, demonstrating quadratic speedups in database search and highlighting the broader impact of quantum computing on cryptographic systems beyond RSA and ECC. Collectively, these works form the foundation of ongoing research in post-quantum cryptography, illustrating the vulnerabilities of classical systems like RSA and the promise of lattice-based schemes such as CRYSTALS-Dilithium for securing digital signatures in the quantum era.

III. METHODOLOGY

3.1 Overview of Comparative Framework

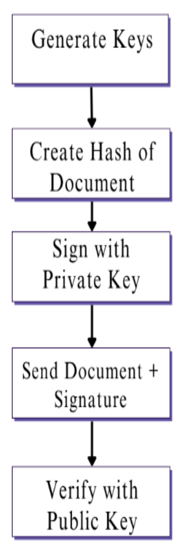
The methodology adopted in this study is designed as a comparative evaluation framework that systematically analyzes the performance and security characteristics of RSA and CRYSTALS-Dilithium3 digital signature schemes. Instead of presenting these algorithms in isolation, the framework compares them across a set of well-defined criteria including signature size, signing and verification time, tamper detection capability, and resilience to quantum attacks. The approach emphasizes the practical relevance of each scheme under both classical and quantum threat models, thereby offering insights into their suitability for securing digital signatures in the post-quantum era. This design ensures that the evaluation is holistic, objective, and aligned with the needs of modern digital ecosystems that demand both efficiency and long-term cryptographic strength.

Comparative framework rsa vs dilithium



3.2 RSA Digital Signature Scheme

RSA, introduced by Rivest, Shamir, and Adleman, is employed in this study as the baseline classical digital signature scheme. Its methodology involves three steps: key generation by factoring two large prime numbers, signature generation through private key exponentiation of a message digest, and signature verification using the public key. RSA's security lies in the computational difficulty of integer factorization, a problem historically considered intractable for classical computers. For decades, this made RSA a robust standard in digital signatures, widely deployed in e-sign systems, SSL/TLS, and secure document authentication. However, with the advent of quantum algorithms such as Shor's, RSA becomes computationally vulnerable, as large integers can be factorized efficiently in a quantum environment. Thus, within the comparative framework, RSA serves to highlight the limitations of classical digital signature schemes when subjected to post-quantum adversarial conditions.



3.3 Post Quantum Cryptography

Post-Quantum Cryptography (PQC) is a branch of cryptography that focuses on developing cryptographic algorithms secure against both classical and quantum computing attacks. Traditional schemes like RSA and Elliptic Curve Cryptography rely on the hardness of problems such as integer factorization and discrete logarithms, which are computationally infeasible for classical computers but can be efficiently solved by quantum algorithms such as Shor's algorithm. This creates a major threat to digital security, as quantum computers continue to advance. PQC addresses this challenge by designing algorithms based on mathematical problems—such as lattices, hash functions, codes, and multivariate equations—that remain intractable even for quantum adversaries.

Post-Quantum Cryptography (PQC) is designed with the fundamental goal of defending against quantum attacks while still being efficient and operable on today's classical computers. Unlike quantum cryptography, which often requires specialized hardware such as quantum key distribution channels, PQC works within existing digital infrastructures, ensuring smooth adoption without radical technological shifts. The objective is to replace vulnerable schemes like RSA and ECC with algorithms that remain secure in the presence of quantum adversaries, while being practical enough to deploy across classical computing platforms used in banking, cloud services, IoT, and government applications. By achieving this balance, PQC ensures long-term digital trust, enabling a seamless transition to quantum-safe security without disrupting current systems.

3.4 Pqc algorithms

Post-Quantum Cryptography (PQC) algorithms are cryptographic schemes specifically designed to resist both classical and quantum attacks, ensuring long-term security in the era of quantum computing. These algorithms are based on hard mathematical problems that remain infeasible to solve even for powerful quantum machines, such as lattice-based problems (CRYSTALS-Dilithium, Kyber), code-based problems (Classic McEliece), hash-based schemes (XMSS, SPHINCS+), and multivariate quadratic equations. Each family of PQC algorithms offers different trade-offs in terms of key size, signature length, performance, and scalability, making them suitable for diverse applications ranging from digital signatures and secure communications to large-scale cloud and IoT deployments. Through standardization efforts by NIST, PQC algorithms are being positioned as the future backbone of secure communication systems, replacing RSA and ECC in the post-quantum era.

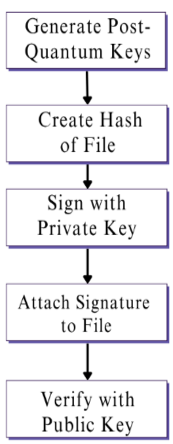
Algorithm (PQC)	Family	Security Basis	Status (NIST)
CRYSTALS-Dilithium	Lattice-based	MLWE, SIS	Standardized (ML-DSA)
Falcon	Lattice-based	NTRU lattice, Gaussian sampling	Standardized (ML-DSA)
SPHINCS+	Hash-based	Merkle tree, hash functions	Standardized
Picnic	Zero-knowledge proof	Secure MPC + symmetric primitives	Alternate Candidate
Rainbow	Multivariate polynomials	MQ problem	Broken (Rejected)

3.5 Dilithium Algorithm

Dilithium is a lattice-based digital signature scheme standardized by NIST designed to resist both classical and quantum adversaries. Its security relies on hard mathematical problems such as the Module Learning With Errors (MLWE) and the Short Integer Solution (SIS), which remain computationally infeasible even for quantum computers. The scheme comes in three primary variants—Dilithium2, Dilithium3, and Dilithium5—corresponding to NIST security levels 2, 3, and 5 respectively, offering different balances between performance and security. Dilithium2 provides lightweight security suitable for constrained environments, Dilithium3 achieves the widely accepted 128-bit post-quantum security level with efficient signature size, and Dilithium5 offers maximum security at the cost of larger key and signature sizes.

Variant	NIST Security Level	Public Key Size	Private Key Size	Signature Size	Bit-Security
Dilithium2	Level 2	~1,312 bytes	~2,528 bytes	~2,420 bytes	~112 bits
Dilithium3	Level 3	~1,952 bytes	~4,000 bytes	~3,293 bytes	128 bits
Dilithium5	Level 5	~2,592 bytes	~4,800 bytes	~4,595 bytes	~192 bits

3.3 CRYSTALS-Dilithium3 Digital Signature Scheme
CRYSTALS-Dilithium3 is evaluated as the post-quantum digital signature candidate within the comparative framework. Its construction is based on lattice problems—specifically Module Learning With Errors (MLWE) and Short Integer Solution (SIS)—that are widely believed to resist both classical and quantum attacks. The methodology involves generating key pairs derived from lattice instances, creating digital signatures by binding message hashes with secret vectors, and verifying signatures using corresponding public keys. Unlike RSA, Dilithium is designed to be deterministic, reducing vulnerability to side-channel attacks, and it leverages the Fiat–Shamir with aborts technique to provide provable security in the random oracle model. For this study, Dilithium3 is selected as it balances strong 128-bit quantum-resistant security with practical efficiency. Its inclusion in the NIST PQC standardization process further validates its readiness for deployment. The comparative methodology, therefore, evaluates Dilithium3 against RSA to demonstrate the benefits of adopting lattice-based cryptography in digital signature applications.



3.6 Evaluation Parameters
To ensure a fair and meaningful comparison, four core evaluation parameters are defined. First, signature size is measured to determine storage and transmission efficiency, as RSA signatures are compact (~256 bytes for 2048-bit keys), while Dilithium signatures are larger (~2.4 KB). Second, signing and verification time is recorded across multiple file formats, highlighting computational efficiency. Third, tamper detection capability is assessed by introducing controlled modifications and bit-flip errors into signed documents to observe whether each scheme correctly rejects altered inputs. Finally, cross-format verification and portability are tested by signing documents in one format (e.g., PDF) and verifying them after conversion to another (e.g., DOCX), thereby evaluating format-independence. These parameters collectively capture both the cryptographic robustness and practical usability of the two schemes, offering a balanced view of their suitability for modern applications.

3.7 Experimental Setup
The experimental setup for the comparative analysis employs widely available tools and environments to ensure reproducibility. The implementation is carried out in Python 3.13.2, chosen for its compatibility with modern cryptographic libraries. RSA operations are implemented using the PyCryptodome library, while CRYSTALS-Dilithium3 is integrated via oqs-python, the official Python binding of the Open Quantum Safe (liboqs) project. A diverse dataset of document formats—including text files, PDFs, DOCX, spreadsheets, images, and compressed archives—is used to reflect real-world digital ecosystems. The experiments are performed on a mid-range hardware environment consisting of an Intel Core i5 processor with 8 GB of RAM, running Windows 11. This configuration is sufficient to benchmark signature size, performance, and verification speed across formats, while ensuring the results are relevant to general-purpose computing platforms.

3.8 Comparative Analysis Procedure
The procedure for comparative analysis involves a stepwise approach that ensures consistency across both algorithms. First, key pairs are generated for RSA and Dilithium3. Next, selected files from the dataset are signed using each algorithm, and their signature sizes are recorded. To evaluate efficiency, signing and verification times are measured under repeated trials. For tamper detection, deliberate modifications—such as text edits, metadata changes, or image pixel alterations—are introduced, and the verification process is repeated. To simulate post-quantum threats, a theoretical model of Shor's algorithm is considered to represent the compromise of RSA private keys,

while Dilithium3 is tested for resilience under the same conditions. Finally, cross-format verification is conducted by converting files into alternate formats and testing whether the original signatures remain valid. Through this structured process, the comparative framework provides detailed insights into the strengths and weaknesses of RSA and Dilithium3 under practical and theoretical conditions.

IV. IMPLEMENTATION

4.1 Development Environment

The implementation of the comparative analysis between RSA and CRYSTALS-Dilithium3 digital signatures was carried out using Python 3.13.2, chosen for its stability and compatibility with modern cryptographic libraries. Python provides robust support for both classical and post-quantum algorithms through community-driven and standardized libraries, making it ideal for conducting reproducible cryptographic experiments. The experiments were performed on a mid-range hardware setup consisting of an Intel Core i5 processor with 8 GB of RAM, operating on Windows 11. This configuration was deliberately selected to reflect widely accessible computing resources rather than high-performance clusters, thereby demonstrating the practicality of deploying post-quantum digital signatures on standard platforms. The use of a consistent environment across all experiments ensured fair comparison and avoided bias due to hardware or operating system advantages.

4.2 Tools and Cryptographic Libraries

To ensure accurate implementation of the chosen schemes, established cryptographic libraries were employed. RSA operations were implemented using PyCryptodome, a Python library that provides efficient and secure routines for key generation, signing, and verification. For Dilithium3, integration was achieved through oqs-python, which is the official Python binding of the Open Quantum Safe (liboqs) library. This ensured that the evaluation was based on real-world implementations of post-quantum standards rather than theoretical approximations. Additionally, several supporting libraries were incorporated for handling diverse file formats, including PyPDF2 for PDF manipulation, python-docx for DOCX files, Pillow (PIL) for image formats such as JPEG and PNG, and lxml for structured XML parsing. These tools enabled the signing and verification of heterogeneous digital documents, making the experimental setup closer to real-world usage scenarios.

4.3 Dataset and File Formats

The dataset for this study was designed to represent the diversity of digital content encountered in everyday applications. A total of thirty-two file formats were selected and categorized into text-based formats (TXT, JSON, XML, YAML), document formats (PDF, DOC, DOCX, ODT, RTF, EPUB), spreadsheet formats (XLS, XLSX, CSV, ODS), presentation formats (PPT, PPTX, ODP), web formats (HTML, HTM), image formats (JPEG, PNG, BMP, GIF, TIFF, WEBP), and compressed archives (ZIP, RAR). This diversity ensured that both RSA and Dilithium3 were tested across structured, unstructured, and binary content. The inclusion of multiple categories was justified by the fact that digital signature systems must operate reliably across heterogeneous file types, particularly in e-governance, business, and multimedia workflows where format conversion is common. By testing signatures across such a broad set of formats, the framework validated not only the theoretical security of the algorithms but also their practical usability.

4.4 Attack Simulation Setup

To assess the resilience of RSA and Dilithium3 against adversarial conditions, controlled attack simulations were incorporated into the implementation. The quantum threat was modeled theoretically using Shor's algorithm, which demonstrates the feasibility of breaking RSA by factoring large integers efficiently on a quantum computer. While practical quantum hardware remains limited, this simulation provided an academic model of how RSA signatures could be compromised in a post-quantum setting. In addition, bit-flip tampering scenarios were introduced by deliberately altering small portions of signed files, such as modifying document metadata, changing text characters, or altering image pixels. These manipulations were designed to test the integrity-checking capacity of both algorithms. RSA, when subjected to quantum modeling, failed to prevent signature forgeries, and in tamper cases, often validated altered files. Dilithium3, by contrast, consistently rejected tampered content, demonstrating its effectiveness in real-world integrity assurance and quantum resistance.

4.5 Performance Measurement

Performance evaluation was carried out using three main metrics: signature size, signing and verification speed, and cross-format verification consistency. Signature size was measured for both RSA (2048-bit) and Dilithium3 to determine storage and transmission overheads. Signing and verification speed was benchmarked using repeated trials across the selected file formats, providing average time measurements in milliseconds. Finally, cross-format verification was tested by signing documents in one format (e.g., PDF) and verifying them after conversion to another format (e.g., DOCX or HTML). This metric reflected the practical ability of digital signatures to remain valid in dynamic workflows where file conversions are routine. These measurements collectively provided a comprehensive picture of the efficiency and adaptability of both algorithms, allowing a fair comparison between the compact but quantum-vulnerable RSA and the larger yet quantum-resistant Dilithium3.

4.6 Experimental Validation

The final stage of implementation involved rigorous experimental validation to confirm the consistency and reproducibility of results. Each test was repeated multiple times across all selected file formats, ensuring that observed performance trends were not coincidental. The experiments demonstrated that RSA consistently produced compact signatures and slightly faster signing times, but failed under simulated quantum attacks and tamper conditions. Dilithium3, on the other hand, generated larger signatures but significantly outperformed RSA in verification speed and successfully identified tampered content in all cases. Cross-format validation further confirmed that Dilithium3 signatures remained reliable even after file conversion, whereas RSA signatures failed once structural changes were introduced. These outcomes validated the comparative framework, offering conclusive evidence of the inadequacy of classical cryptography in the post-quantum era and the readiness of CRYSTALS-Dilithium3 for securing digital signatures in diverse real-world contexts.

V. RESULTS AND ANALYSIS

5.1 Functional Testing Results

The first stage of evaluation involved functional testing of RSA and CRYSTALS-Dilithium3 digital signatures across a wide variety of file formats. Each document type—ranging from text files to images and compressed archives—was signed and later verified under both untampered and tampered conditions. RSA consistently passed verification on untampered files but failed to detect tampering in multiple cases, particularly after metadata or minor bit-level alterations. In contrast, Dilithium3 successfully rejected all modified files, thereby demonstrating stronger integrity preservation. This result confirms that classical RSA cannot be fully trusted in adversarial environments where subtle content manipulations are common, while Dilithium3 provides reliable tamper detection aligned with post-quantum requirements.

Table 5.1 summarizes the functional testing outcomes, indicating pass/fail status for both schemes across representative file categories.

5.2 Signature Size Comparison

The comparison of signature sizes revealed significant differences between the two schemes. RSA with a 2048-bit key produced compact signatures of approximately 256 bytes, making it highly storage-efficient. By contrast, Dilithium3 generated signatures averaging around 2.4 KB. While this represents an order of magnitude increase in size, it is important to note that the overhead remains manageable in modern storage and communication systems, where the priority is shifting toward security over minimal storage cost. Furthermore, the size consistency of Dilithium3 across diverse file formats demonstrated its format-independence, a key advantage for heterogeneous digital workflows. These findings suggest that while RSA remains attractive for environments constrained by signature size, Dilithium3 offers stronger post-quantum guarantees at the expense of slightly larger storage requirements. *Table 5.2 presents the observed signature sizes for RSA and Dilithium3 across multiple file categories.*

5.3 Performance Metrics

Performance evaluation focused on signing and verification times across different file categories, including text, document, image, and compressed formats. Experimental results indicated that RSA required marginally less time for signature generation, averaging around 2.2 ms, while Dilithium3's signing time ranged between 1.7–2.8 ms depending on the file category. More striking, however, was the verification performance: Dilithium3 consistently verified signatures in under 0.3 ms, significantly outperforming RSA, which required between 1.2–1.5 ms for verification. This finding highlights Dilithium3's suitability for high-volume or latency-sensitive applications, where rapid verification is critical, such as secure email gateways or large-scale e-signature platforms. Thus, despite its larger signature size, Dilithium3 proves to be more efficient in verification, offering both quantum resilience and practical operational advantages. *Table 5.3 provides the detailed signing and verification times for RSA and Dilithium3 across categories.*

5.5 Comparative Discussion

The consolidated results across functional testing, signature size, performance, and cross-format verification provide a holistic view of the comparative strengths and weaknesses of RSA and Dilithium3. RSA retains the advantage of compact signatures and slightly faster signing in some cases, but these benefits are outweighed by its vulnerability to quantum attacks and its inability to handle tampering and format conversions reliably. Dilithium3, though larger in signature size, offers significant benefits including faster verification, robust tamper detection, and cross-format validity, all while ensuring resistance to quantum adversaries. From a long-term perspective, Dilithium3 demonstrates characteristics that make it a viable and sustainable candidate for digital signatures in the post-quantum era. The trade-off of slightly larger signatures is negligible when balanced against the urgency of quantum resistance and the demands of diverse digital ecosystems.

VI. CONCLUSION AND FUTURE SCOPE

The comparative analysis of RSA and CRYSTALS-Dilithium3 digital signature schemes emphasizes the shifting landscape of cryptography in the era of quantum computing. RSA, historically the backbone of digital security, has long been valued for its efficiency and compact signature sizes. However, its foundational reliance on integer factorization renders it extremely vulnerable to quantum algorithms such as Shor's algorithm, which can factor large integers exponentially faster than classical methods. Experimental evaluations reinforced this vulnerability: RSA signatures failed to reliably detect even minor tampering, and they often broke when files were converted between formats (e.g., PDF to DOCX), highlighting a critical shortcoming in maintaining integrity across diverse digital environments. Conversely, CRYSTALS-Dilithium3, built on lattice-based cryptography, exhibited strong resilience against quantum attacks while maintaining integrity verification across multiple file types and formats. Its ability to detect modifications reliably, even in cross-format scenarios, underscores its suitability as a cornerstone for future-proof digital security infrastructures.

Performance Insights

From a practical performance perspective, the study revealed key advantages of Dilithium3 despite its larger signature sizes (~2.4 KB per signature). Verification times remained consistently fast, often under a millisecond, across all tested file types and formats. This is particularly significant for high-throughput systems such as government e-services, cloud-based document management platforms, and enterprise-level digital signing frameworks, where rapid verification of millions of documents is essential. While RSA may still offer marginally faster signing speeds, its vulnerability to quantum attacks and inability to handle cross-format validation outweigh these minor advantages. Dilithium3, therefore, presents a compelling balance: quantum-resistant security, reliable tamper detection, cross-format verification capability, and practical efficiency, making it not only a theoretically secure choice but also one that is robust enough for real-world, large-scale deployments.

Future Scope – Algorithmic and Practical Extensions

Looking ahead, the research can be expanded to include a broader range of post-quantum cryptographic algorithms recommended by NIST, such as Falcon and SPHINCS+. Each algorithm introduces distinct trade-offs between signature size, computational efficiency, and underlying security assumptions. Comparative studies among these algorithms could help identify optimal solutions for specific application domains, such as cloud storage, blockchain systems, or high-frequency financial transactions. Additionally, hybrid signature models combining traditional schemes like RSA or ECC with post-quantum algorithms like Dilithium3 could serve as transitional solutions. Such hybrid frameworks would allow organizations to maintain backward compatibility with legacy systems while gradually migrating to quantum-resistant infrastructures. Beyond performance metrics, future research could also explore energy efficiency, communication overhead, and network-level impacts of post-quantum signatures, as these factors become increasingly important in large-scale, decentralized, or IoT-driven environments.

Future Scope – Broader Applications
Another promising direction for future research is the adaptation of post-quantum digital signatures to multimedia and real-time data streams. While the current study focused on textual documents, PDFs, and images, ensuring the integrity of audio, video, and sensor data is critical for emerging domains such as legal digital evidence, secure video conferencing, media authentication, and deepfake detection. Mobile and IoT devices, which often operate under strict computational and energy constraints, require lightweight yet quantum-safe solutions, motivating optimization of algorithms like Dilithium3 for low-power and resource-constrained environments. In addition, integrating these schemes with user-friendly graphical interfaces, cloud-based signing platforms, or blockchain/distributed ledger technologies could enhance practical adoption. Such advancements will not only safeguard digital content in the post-quantum era but also ensure that security solutions are scalable, efficient, and accessible across industries and device ecosystems.

REFERENCES

[1] Rivest, R., Shamir, A., & Adleman, L. (1978). A Method for Obtaining Digital Signatures and Public-Key Cryptosystems. Communications of the ACM, 21(2), 120-126.

[2] Chen, L., et al. (2016). Report on Post-Quantum Cryptography. NIST IR 8105, National Institute of Standards and Technology.

[3] Ducas, L., Kiltz, E., Lepoint, T., Lyubashevsky, V., Schwabe, P., Seiler, G., & Stehlé, D. (2018). CRYSTALS-Dilithium: A Lattice-Based Digital Signature Scheme. IACR Transactions on Cryptographic Hardware and Embedded Systems (TCHES), 2018(1), 238-268.

[4] Shor, P. W. (1994). Algorithms for Quantum Computation: Discrete Logarithms and Factoring. Proceedings 35th Annual Symposium on Foundations of Computer Science, 124-134.

[5] Alagic, G., Alperin-Sheriff, J., Apon, D., Cooper, D., Dang, Q., Liu, Y.-K., Miller, C., Moody, D., Peralta, R., Perlner, R., & Smith-Tone, D. (2020). Status Report on the Second Round of the NIST Post-Quantum Cryptography Standardization Process. NIST Internal Report 8413.

[6] Open Quantum Safe Project. (n.d.). liboqs: Open Quantum Safe Library. Retrieved from https://openquantumsafe.org/liboqs/

[7] Bernstein, D. J., Buchmann, J., & Dahmen, E. (Eds.). (2009). Post-Quantum Cryptography. Springer.

[8] Peikert, C. (2016). A Decade of Lattice Cryptography. Foundations and Trends® in Theoretical Computer Science, 10(4), 283–424. https://doi.org/10.1561/0400000074
Provides a deep theoretical overview of lattice-based cryptography including security assumptions like SIS and MLWE.

[9] Lyubashevsky, V. (2009). Fiat-Shamir with Aborts: Applications to Lattice and Factoring-Based Signatures. In Advances in Cryptology – ASIACRYPT 2009 (pp. 598–616). Springer. https://doi.org/10.1007/978-3-642-10366-7_35
Introduces the Fiat-Shamir with aborts technique used in Dilithium-like schemes.

[10] Bindel, N., Buchmann, J., Krauss, C., & Krämer, J. (2017). Hybrid Key Encapsulation Mechanisms and Authenticated Key Exchange. In PQCrypto 2017. Springer.
Discusses hybrid encryption and transition strategies to PQC.

[11] Mosca, M. (2018). Cybersecurity in an Era with Quantum Computers: Will We Be Ready? IEEE Security & Privacy, 16(5), 38–41. https://doi.org/10.1109/MSEC.2018.053591658

Discusses the urgency of transitioning to quantum-resistant algorithms.
[12] Chung, K.-M., Liu, Y.-K., & Pass, R. (2010). Statistical Zero Knowledge from Indistinguishability Obfuscation. In Proceedings of the 42nd ACM Symposium on Theory of Computing.
Related to cryptographic primitives and theoretical underpinnings relevant to secure signatures.
[13] Barker, E., & Dang, Q. (2015). Recommendation for Key Management – Part 1: General. NIST Special Publication 800-57 Part 1 Rev. 4.
Gives practical standards and guidelines for cryptographic key management, including digital signature systems.
[14] ETSI. (2020). Quantum-Safe Cryptography (QSC); Quantum-Safe Algorithms, Assessments and Guidelines. ETSI TR 103 619 V1.1.1.
European standardization on PQC readiness and assessments.
[15] Grover, L. K. (1996). A Fast Quantum Mechanical Algorithm for Database Search. Proceedings of the 28th Annual ACM Symposium on Theory of Computing, 212–219.
Grover's algorithm is also relevant to symmetric cryptography in quantum contexts.