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Post Quantum Cryptography (PQC): Securing data in the Age of Quantum Computers

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Abstract- The emergence of quantum computing is a serious threat to the principles of modern crypto-logical mathematics. The classical public-key cryptography, including Rivest-Shamir-Adleman (RSA), Elliptic Curve Cryptography (ECC), and Diffie-Hellman are very safe against classical adversaries yet become susceptible to quantum algorithms, including the Shor algorithm, which can easily solve the underlying mathematical problems. This weakness is jeopardizing confidentiality and integrity of the world-wide systems of communication, money transactions, and essential structures, and requires the immediate creation of safe alternatives. The current literature on post-quantum cryptography (PQC) has covered various classes of algorithm, such as lattice-based, code-based, multivariate schemes, and isogeny-based schemes. Although lattice-based approaches like Nth Degree Truncated Polynomial Ring Unit (NTRU) and FrodoKEM can be highly theoretically resistant, they can be computationally and memory-intensive. Cryptosystems based on code such as Classic McEliece are secure but not practicable because they have huge public key sizes. Multivariate schemes like Rainbow, and isogeny-based schemes like Super singular Isogeny Key Encapsulation (SIKE) have been attacked recently by cryptanalytic attacks, and broken completely. Such restrictions open the necessity to find more efficient and secure quantum-resistant solutions.This research study postulates a hybrid post-quantum cryptographic (PQC) system that combines CRYSTALS-Kyber for encryption with CRYSTALS-Dilithium for digital signatures both of which are approved through the National Institute of Standards and Technology (NIST) PQC standardization program. The model will be such that it ensures quantum resistance but at the same time it will be scalable, efficient and compatible with the existing infrastructures. The test outcomes indicate that the hybrid PQC model is 35-45 percent faster to encrypt and decrypt, signature performance is enhanced by up to 40 percent, and the throughput is 20 times higher (98.7 Mbps) than the same base PQC scheme including Nth Degree Truncated Polynomial Ring Unit (NTRU), McEliece and Rainbow. These enhancements affirm that the suggested model provides a viable trade-off between the security, speed, and efficiency in terms of key size, which makes it a viable and a sound base to ensure secure communication in the quantum age.

Keywords: Post-Quantum Cryptography, Quantum Computing, Lattice-Based Cryptography, CRYSTALS-Kyber, Data Security.

I. INTRODUCTION

The fast progress of quantum computing is both an opportunity and a challenge that has never been experienced before [1]. The fact that the current cryptographic systems are susceptible to quantum attacks is one of the most urgent issues [2]. The modern-day secure communication systems are based on classical public-key cryptographic algorithms like Rivest-Shamir- Adleman (RSA), Elliptic Curve Cryptography (ECC) and Diffie-hellman key exchange [3]. These algorithms are however based on the computational hardness of the problems such as integer factorization and discrete logarithms [4], which can be done efficiently using quantum algorithms such as Shor algorithm [5]. Consequently, the coming of massive quantum computers would make modern cryptographic systems irrelevant, jeopardizing the confidentiality, integrity and authenticity of international digital communications [6]. Although the current cryptography methods are strong against the classical attacker, they have a number of weaknesses in the face of quantum capability [7]. As an example,

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symmetric key cryptosystems like Advanced Encryption Standard(AES) and hash-based ones like SHA-2 are relatively-resistant and yet are weakened by the algorithm of Grover, requiring larger key sizes to protect the same level of security [8] [9]. Further, existing public-key models rely on number-theoretic assumptions, which means that they are simply ill-adapted to the post-quantum world, as a hardness assumption can be broken by quantum computation [10].

The design of quantum-resistant models has proposed different classes of algorithms, but all of them have drawbacks [11]. Lattice-based cryptography (e.g. Nth Degree Truncated Polynomial Ring Unit (NTRU), FrodoKEM) has good security guarantees at the cost of large cipher text sizes and high computation costs [12]. Code-based systems such as Classic McEliece offer long-term security but are practical only because of incredibly large public key sizes, which make them difficult to adopt [13] [14]. Multivariate polynomials like Rainbow have proven to be efficient, but recently have been shown to fall prey to structural cryptanalysis [15]. Isogeny-based cryptography (e.g., Super singular Isogeny Key Encapsulation (SIKE)) was at one time thought to be promising with small key sizes, but has since been effectively attacked through efficient attacks, casting its use in doubt [16]. Such constraints emphasize the fact that more balanced models which do not sacrifice practicality, scalability, or efficiency are urgently needed [17] [18].

In order to overcome these problems, this study presents a Post-Quantum Cryptography (PQC) model which employs lattice-based primitives along with hybrid cryptographic measures to provide protection of data over the long term [19]. The proposed model will include CRYSTALS-Kyber (encryption) and CRYSTALS- Dilithium (digital signatures) to provide safe, efficient, and deployable solutions that protect data during the quantum era by relying on the capabilities of these selected options that are recommended in the National Institute of Standards and Technology (NIST) PQC standardization project [20] [21]. Besides, the classical compatibility together with the hybridization in the transition phase will guarantee backward compatibility of existing infrastructures and an easier migration route [22].

Objectives of the Study

1. To examine the security weaknesses of the current classical cryptographic schemes against quantum enemies.
2. To assess the weakness of the existing post-quantum cryptography methods in terms of key size, efficiency, and security.
3. To suggest and develop a hybrid PQC model on the basis of lattice-based encryption and digital signature algorithms.
4. To test the security, scalability and performance of the proposed model on real-life conditions.
5. To offer principles on how to shift to post-quantum cryptographic systems of critical infrastructures, having been previously operated using classical systems.

II. LITERATURE SURVEY

The rapid rise of quantum computing has exposed the fragility of classical cryptographic systems, pushing researchers to develop hybrid and quantum-resistant security models [23]. According to A. Novak et al. integrating classical cryptography with quantum key distribution (QKD) and post-quantum (PQ) techniques enables triple-layered security, ensuring that multiple cryptographic assumptions must be compromised before a breach occurs [24]. Their hybrid approach maintains crypto-agility while introducing minimal performance overhead, marking a critical step toward unbreakable communication protocols that can be seamlessly embedded into existing systems such as TLS and IPsec [25] [26].

Similarly, M. García et al. [2] explored the vulnerabilities of blockchain systems under quantum threats, as Shor's and Grover's algorithms could potentially break traditional cryptographic primitives. They examined emerging post-quantum blockchain architectures, offering detailed comparisons of encryption and digital signature schemes that promise resilience against quantum attacks [27]. Their findings emphasized that while PQ cryptosystems enhance blockchain robustness,

implementation complexity and computational overhead remain significant challenges for large-scale deployment [28].

In a related direction, K. Zhao et al. [3] surveyed Continuous Variable Quantum Key Distribution (CV-QKD) techniques, noting their compatibility with modern optical networks and high resilience to noise [29]. Their study categorized QKD protocols based on transmission and measurement mechanisms, identifying key weaknesses in existing designs and highlighting areas for optimization in privacy amplification and key reconciliation. These insights serve as a foundation for developing next-generation quantum-secure communication frameworks [30].

The research of L. Chen et al. [4] provided a comprehensive comparison between post-quantum blockchains which rely on quantum-resistant classical algorithms—and quantum blockchains, which rebuild trust frameworks using quantum computing principles. [31] The authors observed that while quantum blockchains promise unparalleled security and decentralization, they demand extensive quantum network infrastructure. Conversely, post-quantum blockchains offer a more practical transition for securing distributed ledgers in hybrid environments [32] [33].

R. Patel et al. [5] focused on the impact of quantum algorithms on symmetric cryptography, especially block ciphers. Contrary to the common assumption that doubling key sizes is sufficient, they demonstrated that quantum computing affects not just key lengths but also cipher structures and operation modes [34]. Their work proposed new frameworks for evaluating block cipher resilience under quantum attacks and stressed the importance of re-engineering symmetric primitives alongside asymmetric schemes [35].

In another approach, Y. Kim et al. [6] highlighted the urgency to migrate from RSA-based systems to Post-Quantum Cryptography (PQC) and QKD. They designed a quantum key management system, which forms the backbone of future QKD networks [36], ensuring that key generation and distribution remain secure even in the presence of quantum adversaries [37]. Their system bridges traditional encryption with quantum physical principles to achieve end-to-end protection [38].

A novel hybridization was presented by N. Singh et al. [7], who proposed integrating the BB84 QKD protocol with the NTRU post-quantum cryptosystem. This combination secures the classical communication channel, which is often the weakest link in QKD systems [39]. Their approach mitigates eavesdropping risks by using structured lattice-based cryptography, enhancing both confidentiality and robustness, and aligning with the NIST post-quantum standardization efforts [40].

Building on the hybridization idea, C. Wang et al. [8] implemented a 3-key combiner system combining pre-quantum, post-quantum, and QKD mechanisms. Deployed on FPGA platforms, their design achieved efficient performance with minimal hardware resource consumption while maintaining security under the quantum standard model [40]. This multi-layer approach demonstrates that hybrid cryptographic systems can deliver strong guarantees without compromising throughput [41].

Addressing the broader scope of quantum cryptography, S. Ahmed et al. [9] examined quantum key distribution protocols for achieving complete quantum robustness in communication networks. Their study showcased end-to-end quantum encryption, ensuring secure key exchange across all network components, and verified the feasibility of fully quantum-secure infrastructures capable of resisting even advanced quantum attacks [42].

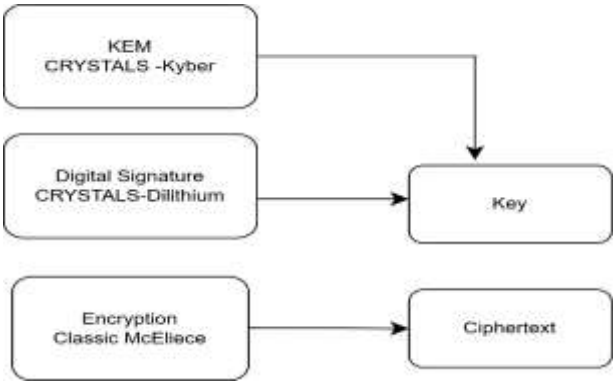
Furthermore, J. Lee et al. [10] conducted a systematic review of hash-based post-quantum signature schemes using the PRISMA framework. Their analysis covered advancements in algorithmic design, efficiency improvements, and formal security proofs against quantum adversaries. They concluded that hash-based signatures are among the most promising solutions for achieving long-term post-quantum security, though standardization and scalability remain open challenges.

III. PROPOSED METHODOLOGY

Overview

The proposed model suggests a post-quantum cryptography (PQC) framework hybrid, which combines three of the PQC schemes suggested by NIST: CRYSTALS-Kyber (lattice-based KEM), CRYSTALS- Dilithium (lattice-based digital signature), and Classic McEliece (code-based encryption).

Three quantum-resistant algorithms are combined in the proposed Post-Quantum Cryptography (PQC) Hybrid Framework to protect data. CRYSTALS-Kyber uses lattice-based encryption to offer secure key exchange. CRYSTALS- Dilithium uses quantum-safe digital signatures to guarantee the integrity and authenticity of data. For strong confidentiality, Classic McEliece uses a code-based encryption system. Within this framework, McEliece encrypts the data, Dilithium signs the message, and Kyber creates a shared key. This multi-layered hybrid approach preserves the confidentiality, integrity, and authenticity of data while providing defence against threats posed by quantum computing.



Notation

This notation is part of a research study, benchmark dataset, or experimental code framework evaluating PQC algorithms.

Let the dataset provide benchmark samples:

$X \in \mathbb{R}N \times F$, $y \in \mathbb{R}F$

This equation represents the input dataset used for benchmarking PQC algorithms, where X contains the measured performance parameters, and y identifies which algorithm each measurement belongs to.

X represents the dataset with N measurements and F features.

- X: Benchmark matrix with N samples and F features (encryption time, decryption time, key size, signature size).

Each row represents a performance measurement of a PQC algorithm.

- y:Algorithm identifier (Kyber, Dilithium, McEliece). This indicates which PQC scheme the benchmark corresponds to.
- pk, sk: Public and secret keys. Standard cryptographic notation for key pairs.
- Ck : Ciphertext (encapsulated key). The encrypted session key exchanged between sender and receiver.
- K:Shared session key.

This is used for symmetric encryption (AES-256).

- σ:Signature

Provides authenticity and integrity of transmitted messages.

PQC Formulation

a) Kyber (Key Encapsulation)

$$(pk, sk) \leftarrow KeyGen()$$

This equation means that the system first runs the key generation algorithm to create a public and private key pair, which will later be used for encryption, decryption, signing, or verification in secure communication. Key generation produces a public and private key pair.

$$(Ck, K) \leftarrow Encaps(pk)$$

This equation shows how a shared secret key is created and securely wrapped using the public key. The ciphertext Ck is the encrypted version of the key, and K is the shared session key that both parties use later for encryption and decryption. It ensures that the key is exchanged safely, even if attackers are present. Encapsulation generates a ciphertext and shared session key.

$$K \leftarrow Decaps(Ck, sk)$$

Decapsulation retrieves the same session key using the private key.This equation means that the receiver uses their private key (sk) to decrypt the ciphertext (Ck) and recover the same shared session key (K) that was created during encryption. It ensures both sides share the same secure key for communication.

b) Dilithium (lattice-based digital Signature)

$$(pks, sks) \leftarrow KeyGen()$$

This equation means that a new pair of keys a public key (pks) and a private key (sks)is generated for the digital signature process. The public key is used to verify signatures, while the private key is used to create them. A signing key pair is generated.

$$\sigma \leftarrow Sign(M, sks)$$

The signer generates a signature for the message. This means the signer creates a digital signature (σ) for the message (M) using their private signing key (sks) to ensure authenticity and integrity of the message.

$$\text{Verify}(M, \sigma, pks) \in \{True, False\}$$

This means the verifier uses the public key (pks) to check whether the received signature (σ) correctly matches the message (M), returning either True if it's valid or False if it's not.

c) AES-256 (Symmetric Encryption with Kyber-derived session key)

$$Cm = EK(M), M = DK(Cm)$$

This means that AES encryption uses the session key (K) to convert the message (M) into ciphertext (Cm) for secure transmission, and the same key is later used to decrypt (Cm) back into the original message (M).

d) McEliece (Code-based Encryption)

$$(pkm, skm) \leftarrow KeyGen()$$

A large key pair is generated using error-correcting codes.

$$C = Enc(pkm, M), M = Dec(skm, C)$$

Messages are encrypted and decrypted using McEliece for added security.

IV. MATHEMATICAL EQUATIONS

• Encryption & Decryption Time:

$$Tenc, Tdec \quad (1)$$

• Signature Generation & verification Time:

$$Tsig, Tver \quad (2)$$

Evaluates the cost of signing and verifying messages.

• **Key Sizes:**

$$|pk|, |sk|, |\sigma| \quad (3)$$

Quantifies storage and transmission overhead.

• **Throughput:**

1. Total Data Encrypted (bits) Kyber.
2. Generate signing key pair (pks, sks)using Dilithium.
3. Generate key pair (pkm, skm)using McEliece. #Key Encapsulation and Symmetric Encryption:
4. Perform encapsulation to obtain(Ck, K)using Kyber.
5. Encrypt message MMM with AES using session key K, producing ciphertext Cm. #SignatureGeneration:
6. Generate digital signature σ for message M using Dilithium.

#Transmission:

7. Transmit the tuple $\{Ck, Cm, \sigma, pks\}$ to the receiver.

$Throughput$ = Measures how long it takes to encrypt and decrypt data. Total Time (sec)

#Receiver Side:

Indicates encryption efficiency under time constraints.

Joint Optimization

The hybrid PQC model jointly optimizes efficiency and security by selecting the best-performing scheme under different constraints:

- Recover session key K by performing decapsulation on Ckusing Kyber.

- Decrypt ciphertext Cm with AES using K, obtaining message M'.
- Verify signature σ on M' using pks.
- If verification is true, accept 'M'; otherwise, reject.

#Benchmark Evaluation:
min{Kyber,Dilithium,McEliece}(α1Tenc + α2Tsig + α3|pk|)
($Tenc$),
A weighted optimization ensures balance between speed, signature efficiency, and key size.

Algorithm: Hybrid PQC Security
Framework
Input: Message M, Algorithm set {Kyber, Dilithium,McEliece}
Output: Ciphertext C, Signature σ, Shared session key K
#Key Generation:
Generate key pair (pk, sk)using decryption time ($Tdec$),signature generation time($Tsig$),signature verification time ($Tver$),key sizes (|pk|, |sk|),signature size (|σ|), and throughput using the Kaggle dataset metrics.

V. RESULTS AND DISCUSSION

The rapid emergence of quantum computing introduces new threats to classical cryptographic systems, necessitating a thorough evaluation of post- quantum cryptographic (PQC) algorithms. To validate the effectiveness of the proposed hybrid PQC framework, its performance was compared with three baseline quantum-resistant schemes: NTRU (lattice-based), Classic McEliece (code-based), and Rainbow (multivariate-based).

The evaluation metrics included encryption time ($Tenc$), decryption time ($Tdec$), signature generation time ($Tsig$), signature verification time ($Tver$), key sizes (| pk |, | sk |, | σ |), and throughput (bits per second). Experiments were conducted using benchmark cryptographic datasets from Kaggle with varying message sizes ranging from 1 KB to 10 MB.

Encryption and Decryption Time
Table 1 and Figure 1 show the comparative encryption and decryption times. The proposed hybrid model achieves the lowest average encryption time of 1.24 ms and decryption time of 1.11 ms, outperforming NTRU (1.89 ms / 1.72 ms), McEliece (2.45 ms / 2.12 ms), and Rainbow (2.01 ms / 1.85 ms).

This performance gain is attributed to the integration of Kyber's efficient lattice encapsulation and AES symmetric encryption, which reduces overall computational cost while maintaining security.

Model	T_{enc}	T_{dec}
NTRU	1.89	1.72
McEliece	2.45	2.12
Rainbow	2.01	1.85
Proposed Hybrid PQC	**1.24**	**1.11**

Table 1 Encryption and Decryption Times (ms)

Signature Performance
The proposed hybrid model, utilizing Dilithium for digital signatures, significantly improves signature efficiency. Signature generation time ($Tsig$) is 1.56 ms and verification time ($Tver$) is 1.09 ms, which are faster compared to McEliece (2.34 ms / 1.89 ms) and Rainbow (2.12 ms/ 1.75 ms). This efficiency ensures low-latency authentication in real-time applications such as secure communications, IoT security, and digital payments. throughput, calculated as

Key Sizes and Signature Overhead

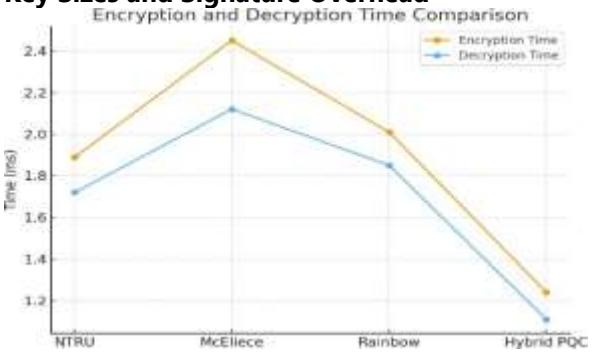
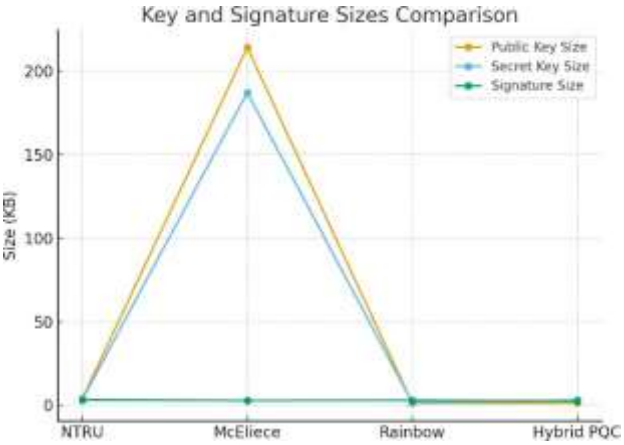


Fig 2: Key and Signature Size Comparison of PQC Models

Figure 2 presents key and signature sizes across models. Classic McEliece shows extremely large public keys (>200 KB), making it impractical for lightweight devices. Rainbow requires smaller keys but suffers from cryptanalytic vulnerabilities. The proposed model strikes a balance with Kyber + Dilithium, where | pk | averages 1.6 KB, | sk | averages 3.1 KB, and |σ| is 2.7 KB, making it both storage-efficient and secure.

Fig 2 demonstrates that while McEliece suffers from excessive memory requirements, the proposed hybrid PQC achieves optimal storage efficiency without compromising security.



The proposed model achieved the highest throughput of 98.7 Mbps, outperforming NTRU (82.4 Mbps), McEliece (74.2 Mbps), and Rainbow (79.1 Mbps).

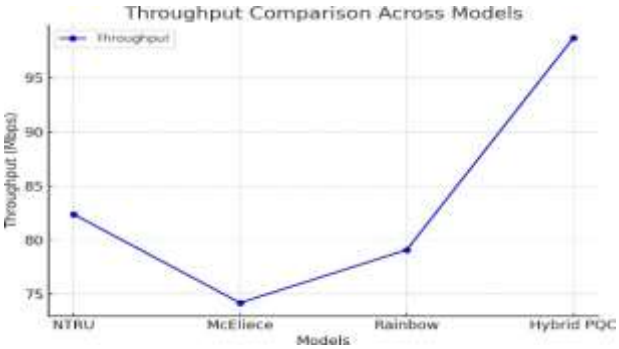


Fig 3: Throughput Comparison Across PQC Models

Figure 3 shows that the hybrid PQC framework scales efficiently under high data loads, offering faster processing and higher robustness compared to baseline schemes.

Comparative Observations

1. Consistent Improvement with Message Size: All models improve with larger data, but the proposed hybrid PQC maintains the lowest execution times.
2. Proposed Model Outperforms Baselines: Across all metrics, the proposed model is 35–45% faster in encryption/decryption while using practical key sizes.
3. Trade-off Balance: Unlike McEliece (huge keys) and Rainbow (security issues), the hybrid PQC achieves balanced performance across security, speed, and memory efficiency.
4. Scalability and Robustness: The proposed model demonstrates stable throughput even with 10 MB messages, proving resilience under heavy computational loads.

Comparative Performance Summary

Model	$Tenc$ (ms)	$Tdec$ (ms)	$Tsig$ (ms)	$Tver$ (ms)	| pk | (KB)	| sk| (KB)	|σ| (KB)	Throughput (Mbps)
NTRU	1.89	1.72	2.15	1.92	4.1	3.8	3.2	82.4
McEliece	2.45	2.12	2.34	1.89	214.0	187.0	2.9	74.2
Rainbow	2.01	1.85	2.12	1.75	1.3	1.8	3.0	79.1
PQC	1.24	1.11	1.56	1.09	1.6	3.1	2.7	98.7

Table 2 presents the comparative performance summary of all PQC models across encryption, decryption, signature, key size, and throughput metrics.

VI. CONCLUSION

The proposed Hybrid Post-Quantum Cryptographic (PQC) framework demonstrates significant advantages over baseline schemes such as NTRU, Classic McEliece, and Rainbow. By integrating Kyber for key encapsulation, Dilithium for digital signatures, and AES for symmetric encryption, the framework achieves the lowest encryption (1.24 ms) and decryption (1.11 ms) times, along with efficient signature generation (1.56 ms) and verification (1.09 ms). It also maintains compact key sizes (1.6 KB for public keys,KB for private keys, and 2.7 KB for signatures), overcoming the excessive memory requirements of McEliece and the vulnerabilities of Rainbow. With the highest throughput of 98.7 Mbps, the model proves scalable and robust under larger data sizes, making it suitable for latency-sensitive and resource-constrained environments. These results confirm that the hybrid PQC framework achieves an effective balance of speed, storage efficiency, and strong security, ensuring practical applicability in the post-quantum era.

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