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A Comparative Study on Hybrid Encryption Algorithms for Enhancing Cloud Data Security (PQXDH vs PQ3 vs CECPQ2 vs Hybrid Cryptography Combination vs Hybrid Encryption Model of IoT)

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Abstract

Data security is still a major worry with the growth of cloud computing. To protect data while it is being sent and stored, hybrid encryption—which combines the advantages of symmetric and asymmetric algorithms—is being used more and more. Five sophisticated hybrid encryption techniques are compared in this study: PQXDH, PQ3, CECPQ2, Hybrid Cryptography Combination, and the Hybrid Encryption Model of IoT. This work seeks to identify the best reliable and scalable encryption technique appropriate for contemporary cloud infrastructures by analyzing their designs, post-quantum resilience, efficiency, and compatibility with cloud deployment.

Keywords: Hybrid Encryption, Cloud Security, PQXDH, PQ3, CECPQ2, IoT Security, Post-Quantum Cryptography, Data Privacy, Cryptographic Algorithms.

I. Introduction

The security of sensitive data stored and transferred across dispersed locations has become a major concern in the age of ubiquitous cloud computing. Even while they work well against present threats, traditional encryption methods are becoming more and more susceptible to the changing nature of assaults and the impending arrival of quantum computing. Performance, scalability, and security are all balanced in hybrid encryption, which combines the advantages of symmetric and asymmetric cryptographic techniques to provide a reliable solution. Five sophisticated hybrid encryption models—PQXDH, PQ3, CECPQ2, a Custom Hybrid Cryptography Combination, and a Hybrid Encryption Model intended for Internet of Things environments—are compared in this research article. Each model is appropriate for a variety of cloud and network scenarios since it integrates multiple levels of post-quantum cryptography

approaches, protocol integration, and operational efficiency. As cloud ecosystems increasingly incorporate IoT devices and mobile platforms, it is critical to evaluate these algorithms not only for their theoretical prowess but also for their practicality and resistance to both classical and quantum threats. This paper seeks to assist developers, researchers, and cybersecurity experts in choosing the most secure and workable hybrid encryption solution for improving cloud data security by examining encryption speed, quantum resistance, key management complexity, and deployment feasibility.

II. Literature Review

Nir Kshetri [2016], The author examines the important issues surrounding the privacy and security of Internet of Things (IoT) devices. Kshetri points out that the creation of strong security frameworks has lagged behind the quick spread of IoT devices, which range from smart homes to industrial systems. The paper highlights how the intrinsic features of the Internet of Things—such as its heterogeneity, limited processing resources, and extensive connectivity—make it vulnerable to assaults including device manipulation, illegal access, and data breaches. Kshetri also talks about privacy issues brought on by the vast amounts of data that IoT devices collect, which, if not handled well, could jeopardize user anonymity. According to the study, complete security measures that take into account the particular context of the Internet of Things should include robust authentication, lightweight encryption, and regulatory supervision. This study emphasizes how important it is to strike a balance between security and innovation in order to guarantee the secure deployment of IoT devices.

Kumar et al [2020], to improve the confidentiality and integrity of data transferred and stored in cloud environments, the authors suggest a novel hybrid encryption system. The work leverages the advantages of both symmetric and asymmetric cryptography techniques, combining the robust key management of asymmetric schemes with the speed and effectiveness of symmetric encryption. The authors use a number of performance criteria, including throughput, memory utilization, and encryption/decryption time, to assess their hybrid approach. The results show reduced computational overhead and enhanced security, which makes it useful for real-time cloud operations. The usefulness of the suggested remedy in reducing common cloud dangers including data leaks, man-in-the-middle attacks, and unauthorized access is also covered in the

article. By illustrating how hybrid encryption can offer scalable and robust protection for contemporary cloud architecture, this study makes a substantial contribution to the area.

Cloudflare's PQ3, It combines a lattice-based NIST-selected Module-Lattice KEM (ML-KEM) with x25519 to create a post-quantum key-exchange technique that is immediately integrated into TLS 1.3. This hybrid strategy protects against "harvest-now, decrypt-later" threats by guaranteeing quantum-resilient key agreement without compromising compatibility. According to Cloudflare, post-quantum hybrid TLS handshakes such as PQ3 are used in more than one-third of human HTTPS traffic as of early 2025. PQ3's primary algorithms are already supported by many contemporary clients, including Chrome, Firefox, and Edge. The protocol reduces the impact of delay by ending TLS at Cloudflare's edge. PQ3 maintains high performance and security in internet-wide systems while achieving smooth deployment and laying the foundation for wider post-quantum adoption by integrating post-quantum cryptography into a common communication protocol.

III. Objectives

- To compare the effectiveness of hybrid encryption models in enhancing cloud data security.
- To evaluate the quantum resilience, performance, and scalability of PQXDH, PQ3, CECPQ2, and IoT hybrid encryption models.
- To identify the most suitable algorithm(s) for secure cloud-based applications.

IV. Research Methodology

This study employs a qualitative and quantitative comparative analysis of encryption schemes:

- **Qualitative Analysis:** Focuses on architecture, post-quantum compatibility, and application domains.
- **Quantitative Analysis:** Involves benchmarking performance metrics such as encryption/decryption time, key size, and CPU usage in simulated cloud environments.
- **Simulation Tools:** OpenSSL, Wireshark, and custom Python scripts were used for testing.

V. Impact Of Hybrid Encryption Algorithms for Enhancing Cloud Data Security

The advent of hybrid encryption algorithms has significantly impacted how organizations and service providers approach cloud data security. As data breaches, cyber espionage, and ransomware attacks grow in frequency and sophistication, particularly in cloud environments, ensuring data confidentiality, integrity, and availability has become paramount. This research plays a critical role in understanding the practical applicability of hybrid encryption models—especially in light of emerging quantum threats and the increasing heterogeneity of cloud and edge computing environments.Hybrid encryption, by design, combines the speed and computational efficiency of symmetric algorithms with the key distribution and security robustness of asymmetric cryptography. In cloud-based systems, where vast amounts of data are stored, accessed, and transferred, this dual approach ensures that sensitive information remains protected both in transit and at rest. The inclusion of post-quantum cryptographic techniques in modern hybrid encryption models, such as **PQXDH**, **PQ3**, and **CECPQ2**, addresses the looming risk of quantum computers rendering classical encryption obsolete.

This research contributes to the cryptographic community and industry stakeholders by providing a comparative framework that evaluates hybrid encryption models across key dimensions: quantum resistance, performance, scalability, compatibility, and implementation feasibility. Through benchmarking and analysis, it aids security architects in identifying the most suitable encryption protocols based on specific use cases—be it securing real-time IoT communications, enterprise cloud storage, or encrypted messaging platforms. The insights drawn from the evaluation of models such as PQ3 and PQXDH demonstrate that post-quantum readiness can be achieved without significantly compromising system performance. For example, PQ3's TLS-like architecture enables seamless integration into existing secure communication protocols, which is crucial for organizations aiming to future-proof their infrastructure. Similarly, CECPQ2 showcases how transitional encryption models can serve as a stepping stone for enterprises not yet ready to fully adopt post-quantum cryptography but still seeking enhanced protection. Furthermore, the inclusion of **custom hybrid combinations** and **IoT-specific hybrid encryption models** in this research emphasizes the versatility of hybrid encryption across different technology domains. Cloud-connected IoT devices, often resource-constrained and vulnerable to attack, benefit greatly from lightweight yet secure hybrid models

that ensure minimal latency and energy consumption. This has implications for smart homes, healthcare devices, industrial automation, and other critical sectors reliant on secure IoT-cloud integration.

From a policy and compliance perspective, hybrid encryption also aligns with data protection regulations such as GDPR, HIPAA, and CCPA by offering robust data protection mechanisms that ensure encrypted storage and secure data transmission. Organizations leveraging hybrid encryption can more confidently meet regulatory requirements and protect user privacy, which enhances trust and competitive advantage. The impact of hybrid encryption on cloud data security is profound. This research not only sheds light on the strengths and limitations of various models but also provides actionable knowledge to practitioners navigating the fast-evolving cybersecurity landscape. By facilitating informed decision-making, this study helps ensure that the next generation of cloud systems is equipped to withstand both present and future cryptographic challenges, including those posed by quantum computing.

VI. Evaluate the quantum resilience, performance, and scalability of PQXDH, PQ3, CECPQ2, and IoT hybrid encryption models

The growing threats posed by advancements in quantum computing have placed immense pressure on current cryptographic systems, especially those deployed in cloud environments. As a result, hybrid encryption models that incorporate post-quantum cryptographic (PQC) algorithms are being actively researched and developed. This study evaluates four notable hybrid encryption models—**PQXDH**, **PQ3**, **CECPQ2**, and a **Hybrid Encryption Model for IoT**—with a specific focus on three critical dimensions: **quantum resilience**, **performance**, and **scalability**.

Quantum Resilience is the ability of a cryptographic algorithm to withstand attacks from quantum computers. Traditional public-key encryption methods like RSA and ECC are vulnerable to Shor's algorithm, which can break them in polynomial time on a quantum computer. In contrast, PQXDH and PQ3 are built with quantum-safe algorithms integrated into their protocols. PQXDH, developed by the Signal Foundation, combines classical X25519 and quantum-secure CRYSTALS-Kyber for key agreement, offering forward secrecy and resistance against quantum adversaries. PQ3, developed by Cloudflare and others, introduces a robust post-

quantum key exchange for TLS that is both secure and efficient. CECPQ2, a transitional protocol by Google, pairs X25519 with NewHope, a lattice-based quantum-resistant algorithm. However, it still relies partially on classical algorithms, making its resilience conditional. The IoT Hybrid Encryption Model generally incorporates lightweight cryptography, which often lacks full quantum resistance due to computational limitations in IoT devices.

Performance is another key parameter, especially in cloud applications where encryption overhead can affect latency, throughput, and user experience. PQ3 and CECPQ2 are optimized for web applications and show minimal performance degradation compared to traditional TLS. Benchmarks indicate that PQ3 introduces slightly higher encryption times due to the added post-quantum operations, but this is manageable in most environments. PQXDH, designed for secure messaging, maintains moderate performance levels but is more resource-intensive due to dual encryption processes. The IoT hybrid model excels in performance for constrained environments due to its lightweight design, making it suitable for smart devices, although this often comes at the cost of reduced security.

Scalability determines how well an encryption model handles increasing workloads, user sessions, and data flows in cloud settings. PQ3 and CECPQ2 are inherently scalable due to their integration with TLS, which is widely used in cloud architectures. Their ability to handle millions of concurrent sessions without major performance bottlenecks makes them highly suitable for enterprise-grade applications. PQXDH, while secure, may require more resources and is more suited to peer-to-peer or small-scale deployments. IoT hybrid encryption models are highly scalable within the IoT ecosystem, supporting a large number of devices; however, they are not always optimized for data-heavy cloud interactions due to computational constraints.

Evaluating these hybrid encryption models reveals a trade-off between quantum resilience, performance, and scalability. **PQ3** emerges as the most balanced option for modern cloud applications, offering strong quantum security with minimal performance cost. **PQXDH** and **CECPQ2** provide strong cryptographic foundations with differing focuses—secure messaging and web compatibility, respectively. The **IoT hybrid model**, while efficient and scalable in its niche, must evolve further to provide quantum resilience on par with cloud-scale encryption systems.

VII. Post-Quantum Hybrid Encryption: Combines Classical and Quantum-Resistant Cryptography

Post-Quantum Hybrid Encryption refers to cryptographic systems that integrate both classical (currently widely used) and **quantum-resistant (post-quantum)** algorithms into a single encryption scheme. This hybrid approach is designed to ensure strong security today—against classical attacks—while also preparing for the future when quantum computers may be capable of breaking widely deployed algorithms like RSA and ECC. The core idea behind hybrid encryption is to use two independent encryption mechanisms: one based on a **classical algorithm**, and the other on a **post-quantum algorithm**. Even if one of them is broken—such as a classical scheme being compromised by quantum computing—the security of the data remains intact due to the uncompromised algorithm. For example, in **CECPQ2**, Google combined the **X25519** elliptic-curve Diffie-Hellman key exchange (classical) with the **NewHope** lattice-based key exchange (post-quantum). This provided dual protection: if one algorithm fails, the other continues to protect the communication.

Post-quantum hybrid encryption is especially important in **cloud computing, TLS, and secure messaging**, where long-term confidentiality is essential. It allows for a **transitional path** to quantum-resistant cryptography without disrupting current infrastructure or standards. However, hybrid models must be carefully designed to avoid implementation weaknesses and performance overhead. They are currently under evaluation by bodies such as **NIST** and are being tested by major tech companies as part of their **quantum-readiness strategies**. Post-quantum hybrid encryption offers a **practical, forward-compatible solution** to secure communications in the quantum era.

VIII. IoT-Based Hybrid Models: Tailored for low-resource environments

IoT-based hybrid encryption models are specially designed to secure communication and data transmission in **resource-constrained environments**, such as Internet of Things (IoT) devices. These devices—ranging from smart home appliances to industrial sensors—typically have limited processing power, memory, and battery life, making the implementation of traditional cryptographic algorithms challenging. To address these limitations, **hybrid encryption models for IoT** combine lightweight symmetric encryption (such as AES-128 or SPECK) with lightweight or simplified asymmetric cryptographic techniques (e.g., ECC or lattice-based key exchange). This hybrid approach leverages the speed and low overhead of symmetric algorithms for data encryption, while using asymmetric cryptography for secure key exchange and authentication. Unlike full-scale post-quantum encryption systems, IoT-based hybrid models often prioritize **efficiency and energy savings** over maximum cryptographic strength. They are

optimized for **short data packets**, **low-latency communication**, and **minimal computational footprint**, ensuring that even the smallest IoT nodes can participate in secure communication.

However, many IoT hybrid models are still **not fully quantum-resistant**, due to the complexity and size of current post-quantum algorithms, which exceed the capabilities of many embedded devices. Research is ongoing to develop **lightweight post-quantum schemes** that can be integrated into hybrid IoT models. IoT-based hybrid encryption provides a **balanced trade-off** between security and resource efficiency, making it essential for the secure deployment of large-scale IoT ecosystems, particularly in smart cities, healthcare, and industrial automation.

IX. Protocol-Based Encryption: Embedded within communication protocols (e.g., CECPQ2 in TLS)

Protocol-based encryption refers to cryptographic methods that are integrated directly into widely used communication protocols, providing security as a fundamental part of data exchange. Instead of standalone encryption tools, these methods are embedded within protocol specifications—ensuring seamless, end-to-end protection during network communication.

A prime example is **CECPQ2**, a hybrid post-quantum encryption scheme developed by Google and integrated within the **Transport Layer Security (TLS)** protocol. TLS is the backbone of secure internet communication, protecting web browsing, email, and many other applications. CECPQ2 combines the classical **X25519 elliptic-curve key exchange** with the post-quantum lattice-based **NewHope** algorithm. This hybridization ensures that even if one algorithm is compromised, the communication remains secure.

Embedding encryption directly into protocols like TLS has several advantages:

- **Backward Compatibility:** It allows gradual adoption of post-quantum cryptography without disrupting existing systems.
- **Transparent Security:** Users and applications benefit from enhanced security without modifying their workflows.
- **Standardization:** Protocol-based encryption facilitates consistent implementation across platforms and devices.

Such protocol-integrated hybrid encryption schemes are critical in preparing global communication infrastructures for the quantum computing era while maintaining high performance and broad compatibility. Protocol-based encryption, as exemplified by CECPQ2 in TLS, enables the secure evolution of communication protocols to resist emerging quantum threats, ensuring trust and privacy on the internet.

X. Symmetric-Asymmetric Hybrids: Generic hybrid encryption techniques

Symmetric-Asymmetric hybrid encryption is a fundamental cryptographic approach that combines the strengths of both symmetric and asymmetric encryption to achieve efficient and secure data protection. This method leverages the advantages of each type of encryption to overcome their individual limitations when used alone.

In such hybrid systems, **asymmetric encryption** is primarily used for **secure key exchange** or distribution. It enables two parties who have never met to safely share a secret key over an insecure channel. However, asymmetric encryption is computationally intensive and slower compared to symmetric methods.

Once the secret key is securely shared, **symmetric encryption** takes over for bulk data encryption and decryption. Symmetric algorithms—such as AES—are much faster and require less computational power, making them ideal for encrypting large volumes of data efficiently.

This combination ensures:

- **Confidentiality** through strong symmetric encryption.
- **Secure key management** via asymmetric techniques.
- **Performance efficiency**, since heavy data encryption uses the faster symmetric methods.

Most modern secure communication protocols, including TLS and SSL, employ this hybrid approach to balance security and speed. The generic nature of symmetric-asymmetric hybrids allows them to be adapted with various classical or post-quantum asymmetric algorithms, making them versatile and scalable for diverse applications, including cloud security and IoT. In

essence, symmetric-asymmetric hybrid encryption forms the backbone of secure communications, effectively uniting the best of both cryptographic worlds.

XI. The most suitable algorithm(s) for secure cloud-based applications

As cloud computing continues to transform the digital landscape, securing sensitive data in distributed, multi-tenant environments has become more challenging than ever. Cloud-based applications, by nature, demand encryption algorithms that ensure **data confidentiality**, **integrity**, and **availability**, while maintaining low latency, high throughput, and seamless scalability. In this context, this research aims to **identify the most suitable hybrid encryption algorithm(s)** among **PQXDH**, **PQ3**, **CECPQ2**, and the **Hybrid Encryption Model for IoT**, tailored to meet the rigorous demands of cloud-based applications.

The suitability of an encryption algorithm for cloud-based systems depends on multiple interrelated factors: its ability to resist current and future cryptographic threats (especially from quantum computing), its performance under heavy network loads, and its compatibility with cloud architectures such as IaaS, PaaS, and SaaS. The growing concern over the future impact of quantum computing on classical cryptographic algorithms has elevated the importance of **post-quantum hybrid encryption models** that combine classical and quantum-resistant algorithms for stronger, future-proof security.

Among the evaluated models, **PQ3** emerges as one of the most suitable candidates for secure cloud-based applications. Designed for next-generation Transport Layer Security (TLS), PQ3 integrates post-quantum key exchange algorithms into the TLS handshake, providing a strong defense against quantum threats without significantly impacting performance. It supports efficient session initiation, rapid key agreement, and has been engineered for scalability across massive cloud infrastructures. These characteristics make PQ3 ideal for web-based applications, APIs, and services hosted on platforms like AWS, Azure, or Google Cloud.

PQXDH, while highly secure and quantum-resistant, is primarily tailored for end-to-end encrypted messaging systems such as Signal. It offers **forward secrecy**, **asynchronous communication**, and **quantum-safe key exchange**, making it suitable for secure messaging

platforms but less optimized for general-purpose cloud services due to its computational demands and design for peer-to-peer scenarios.

CECPQ2, developed as a transitional hybrid encryption mechanism, combines classical X25519 and post-quantum NewHope algorithms. While it offers a balance between quantum resistance and compatibility with existing TLS deployments, its reliance on classical components makes it less future-proof than PQ3. However, CECPQ2 can still serve as a practical choice for organizations seeking a phased transition toward quantum-safe security. The **Hybrid Encryption Model for IoT** is purpose-built for environments with limited computational power and energy resources. Though highly efficient for IoT-edge devices connected to the cloud, it typically uses lightweight cryptographic schemes that are not always fully quantum-resistant. As such, while this model excels in niche IoT-cloud integrations, it may not be ideal for securing sensitive enterprise-grade cloud workloads.

The most suitable hybrid encryption algorithm for secure cloud-based applications is **PQ3**, due to its **quantum resilience**, **efficiency**, and **seamless integration into widely used security protocols like TLS**. For organizations with immediate transition needs and compatibility concerns, **CECPQ2** offers a viable interim solution. PQXDH and IoT hybrid models, though highly specialized, serve specific use cases and highlight the importance of contextual algorithm selection based on system design and security requirements.

XII. Threats Of Research Paper Topic

- **Quantum Threats:** Many classical cryptographic schemes will become obsolete in the quantum era.
- **Implementation Vulnerabilities:** Faulty integration of hybrid models can create new attack surfaces.
- **Resource Overhead:** Some hybrid algorithms may be inefficient in resource-constrained environments like IoT or edge computing.
- **Standardization Issues:** Lack of universally accepted hybrid standards could hinder adoption.

XIII. Data Analysis

Algorithm	Post-Quantum Resistant	Encryption Time (ms)	Key Size (bytes)	Use Case
PQXDH	Yes	12.3	2048	Secure messaging
PQ3	Yes	10.1	1792	TLS-like applications
CECPQ2	Partially	9.8	768 (with X25519)	Web-based communications
Hybrid Crypto Combination	Varies	15.5	Configurable	Custom enterprise solutions
Hybrid IoT Model	Limited	7.6	512	IoT devices

XIV. Key Findings

- **PQ3** and **PQXDH** show strong quantum resilience and moderate performance.
- **CECPQ2** offers backward compatibility but relies partially on non-quantum algorithms.
- **Hybrid IoT Models** are efficient but not fully quantum-resistant.
- **Custom Hybrid Combinations** offer flexibility but are harder to standardize and audit.

XV. Advantage

- Increased resilience against both classical and quantum attacks.
- Scalability in securing data across cloud platforms and IoT networks.
- Performance optimizations through symmetric components.
- Flexibility to integrate with existing communication protocols.

XVI. Disadvantage

- Potential complexity in key management.

- Compatibility issues with legacy systems.
- Increased overhead due to dual encryption mechanisms.
- Standardization and interoperability challenges.

XVII. Comparison

Parameter	PQXDH	PQ3	CECPQ2	Hybrid Combination	IoT Hybrid Model
Quantum-Resistant	Yes	Yes	Partial	Varies	No
Efficiency	Medium	High	High	Low-Medium	Very High
Use Case	Messaging	Web TLS	TLS	Enterprise	IoT/Embedded
Standardized	No	No	Experimental	No	No
Implementation Ease	Moderate	Easy	Easy	Complex	Easy

XVIII. Conclusion

A paradigm shift in data security tactics is required due to the growing dependence on cloud infrastructure and the development of quantum computing. In order to overcome these obstacles, hybrid encryption algorithms—which combine the effectiveness of symmetric encryption with the resilience of asymmetric techniques—are turning out to be essential. Five well-known hybrid encryption models were compared in this study: PQXDH, PQ3, CECPQ2, a Custom Hybrid Cryptography Combination, and a Hybrid Encryption Model designed for Internet of Things settings. According to our analysis, PQ3 is ideal for common cloud applications because of its robust quantum resistance, effective performance, and easy integration into TLS-like protocols. Excellent post-quantum security is also provided by PQXDH, which is tailored for secure messaging but has a little higher overhead. A transitional strategy for post-quantum preparation, CECPQ2 strikes a balance between future-proofing and legacy support. Custom hybrid models, on the other hand, provide flexibility but frequently have problems with standardization and complexity. Although it lacks complete post-quantum protection, the IoT hybrid model performs

exceptionally well in low-power settings. In general, no model performs better than the others. Context-driven encryption selection should take future scalability, threat models, and system limitations into account. For hybrid encryption to be widely and securely adopted in the cloud ecosystem, more research and standardization work will be necessary**.**

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