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Original Article

Enhancing Cloud Security: A Hybrid Honeycomb-Lattice Encryption Model for Quantum Resistance

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Abstract - *This study introduces an innovative Hybrid cryptographic model, which seamlessly integrates a honeycomb access mechanism with lattice-based encryption algorithms aimed at enhancing cloud security and addressing emerging quantum threats. The Hybrid model represents a significant leap forward from traditional Lattice encryption methods, as demonstrated by comprehensive simulations. It achieves a commendable success rate of 90.15%, boasting lower variability (1.72% standard deviation) compared to Lattice encryption's 94.99% success rate with higher variability (2.93%). Operationally, the Hybrid model excels in providing consistent performance and faster processing times, making it a more efficient choice for cryptographic operations. Moreover, its cost-effectiveness is evident, with operational costs ranging from 0.862 to 7.24 microdollars for encryption and 0.871 to 7.29 microdollars for decryption. Furthermore, the energy consumption of both models is maintained within the practical range of 1.35 to 3.46 joules, highlighting the Hybrid model's suitability. This research underscores the Hybrid model's potential to safeguard cloud computing environments against advanced quantum attacks, offering a promising solution that strikes a balance between performance, cost-effectiveness, and energy efficiency. In an era where quantum computing poses a significant threat to traditional encryption, the Hybrid cryptographic model emerges as a robust and practical alternative, capable of fortifying cloud security while maintaining operational efficiency and affordability.*

Keywords - *Hybrid encryption model, Honeycomb access mechanism, Lattice encryption, Cloud security, Quantum computing threats, Cryptographic performance, Comparative analysis, Security simulations, Operational efficiency, Cloud computing infrastructures.*

1. Introduction

In the realm of Cybersecurity, the advent of quantum computing heralds a paradigm shift, presenting both unparalleled opportunities and formidable challenges. The prowess of quantum computing lies in its potential to solve intricate problems at unprecedented speeds, far surpassing the capabilities of classical computers. Yet, this very strength poses a significant threat to the cryptographic bedrock of current digital security systems.

Traditional encryption methods, such as RSA and ECC, are predicated on mathematical complexities easily unraveled by quantum algorithms [1], notably exemplified by Shor's algorithm [2]. This emerging vulnerability necessitates a prompt reevaluation of our security infrastructure, particularly in the context of cloud computing, a domain replete with sensitive data and critical operations.

The intersection of cloud computing security and quantum cryptography forms the core backdrop of this research. As enterprises increasingly pivot to cloud-based solutions, the imperative to shield data against unauthorized access intensifies.

The spectre of quantum supremacy looms large, threatening to compromise data encrypted under contemporary standards and potentially precipitating widespread security breaches [3]. The urgency to both thus propels this study to anticipate and mitigate these looming quantum-induced risks.

Confronting this challenge, this research introduces a novel Hybrid model that fuses a honeycomb access mechanism with lattice-based encryption algorithms. Our model endeavors to harness the quantum-resistant properties inherent in lattice-based security, simultaneously augmenting access control and operational efficiency, which are vital for contemporary cloud services. This approach not only seeks to fortify data against quantum computational threats but also aims to maintain the requisite performance and scalability for modern cloud infrastructures.

The principal aim of this paper is to propose and rigorously evaluate the Hybrid model, a synthesis of honeycomb access strategies with lattice encryption and decryption algorithms. This innovative model strives to capitalize on the renowned quantum-resistant capabilities of lattice-based security while enriching access control and operational efficacy through the honeycomb framework. The objectives of this paper are to:

- Investigate the robustness of the Hybrid model against quantum and conventional computational attacks.
- Assess the performance and scalability of the Hybrid model, benchmarking it against traditional lattice encryption methods.

Through comprehensive simulations, this research has unveiled pivotal insights:

- The Hybrid model demonstrates a notable success rate, marginally trailing the conventional Lattice model but exhibiting more consistent performance.
- It exhibits superior operational efficiency, evidenced by quicker encryption and decryption processes.
- Comparative analysis in terms of cost and energy consumption reveals that the Hybrid model is not only competitive but also maintains cost-effectiveness, aligning closely with lattice-based methods.

The proposed Hybrid model emerges as a formidable contender in cloud computing security, promising a balanced approach between robust security and high-performance metrics. Looking ahead, the paper will delve into optimizing the Hybrid model further and exploring adaptive mechanisms that can dynamically adjust to varying threat levels and operational demands.

Future actions also include extensive field testing of the Hybrid model in real-world cloud environments, aiming to establish a comprehensive security framework that can serve as a standard in the era of quantum computing.

2. Related Work

Cloud computing, a key modern technological innovation, offers on-demand, scalable resources and flexible costs but raises significant privacy and security concerns. As organizations increasingly rely on cloud service providers for sensitive data and critical applications, addressing these security challenges has become crucial.

Efforts in academia and industry have led to various security techniques to mitigate vulnerabilities and protect against cyber threats [4, 5]. Concurrently, the rise of quantum computing, poised to revolutionize areas from cryptography to medical research, threatens the efficacy of traditional security systems like RSA and ECC [6, 7].

This has spurred the development of new cryptosystems, including modified McEliece and NTRU, designed to counter the challenges posed by quantum computing. The evolving cloud security landscape now emphasizes the need for innovative, adaptable frameworks, particularly hybrid models, that combine different cryptographic techniques to shield against both classical and emerging quantum threats [8, 9].

The urgency to develop robust and resilient cryptosystems is heightened by the impending quantum era, underscoring the importance of safeguarding cloud-held data against advanced quantum computing capabilities [10, 11].

2.1. Quantum Computing and Cryptographic Vulnerability

Quantum computing's rise poses a dual challenge in cryptography, offering new possibilities while threatening existing security protocols. Algorithms like Grover's enhance attacks on symmetric schemes such as AES and 3DES, significantly reducing complexity [12, 13].

Shor's algorithm, more critically, endangers asymmetric systems like RSA, potentially making them obsolete by efficiently solving prime factorization and discrete logarithm problems. This has led to initiatives like NIST's standardization of post-quantum cryptography [14], highlighting the urgency to adopt quantum-resistant systems. Lattice-based cryptography has gained prominence as a quantum-safe option, marking a crucial step in evolving our digital security for the quantum era [15].

2.2. Post-Quantum Cryptography

Post-quantum cryptography, particularly lattice-based cryptography, is at the forefront of research efforts to develop encryption methods resilient against the emerging threats posed by quantum computing. This field, far from being purely theoretical, is a strategic response to the vulnerabilities that quantum computing introduces to current public-key cryptosystems [16] .

Among various approaches, the NTRU encryption scheme within lattice-based cryptography, despite lacking a complete formal security proof, has gained confidence in its security through extensive research, making it a strong contender for future cryptographic frameworks [17, 18].

Notably, research in lattice-based cryptography has also delved into its practical aspects, such as the effects of polynomial multiplication methods on the system's security. Innovations like optimized Number Theoretic Transform (NTT) implementations have enhanced performance and resource efficiency, contributing significantly to the resilience of these systems against computational attacks [19, 20].

These advancements reflect the ongoing efforts to prepare our digital security infrastructure for the quantum computing era [21, 22].

2.3. Advancements in Hybrid Cryptographic Systems

The evolution of digital security is marked by significant advancements in hybrid cryptographic systems, essential for bolstering cloud security and data protection. These systems merge various cryptographic methods, leading to enhanced security levels. For instance, role-based cryptography in cloud security tailors encryption and decryption to user roles, improving data access control [23].

Additionally, multi-factor authentication methods, including biometrics, strengthen defenses against unauthorized access. Innovations like wavelet-based steganography for secure data embedding in cloud storage and the honeycomb model's dynamic access control [24] exemplify this progress.

Sectors such as e-learning, healthcare, and the Industrial Internet of Things (IIoT) have adopted hybrid cryptographic algorithms like Ciphertext Policy-Attribute-Based Encryption (CP-ABE) [25], showcasing the trend towards sophisticated, adaptable security solutions equipped to confront contemporary challenges, including those posed by quantum computing.

2.4. Performance and Scalability in Encryption Models

Optimizing encryption models for cloud computing is a balancing act involving security strength, system performance, and the ability to scale effectively. Research in this area offers a wealth of approaches to navigate these trade-offs.

For instance, one investigation explores a fuzzy logic-based load balancing method designed to distribute workload evenly across cloud infrastructure, with the goal of enhancing processing times and improving storage use. Another study ventures into combining load balancing with Secure Sockets Layer (SSL) encryption, finding that such an amalgamation can surpass the efficiency of more traditional methods in both load distribution and security enforcement.

Moreover, the realm of the Internet of Things (IoT) and edge-cloud computing systems is also seeing advancements with proposals for integrated load balancing and computation offloading strategies. These are coupled with novel security layers to fortify against potential breaches. On a similar note, predictive resource management frameworks are drawing on techniques like Hidden Markov Models (HMMs) to foster scalable elasticity in resource allocation, striving for a harmonious balance within the system.

Not to be overlooked is the specific application of these principles in the context of mobile cloud computing, particularly with the protection of health information. Here, research demonstrates the use of the Modular Encryption Standard (MES) to enhance both performance and security, showing promising results over other prevalent encryption techniques.

Together, these pieces of research underscore the intricate interplay between security, performance, and scalability in the cloud environment, presenting a spectrum of methods to achieve an optimized equilibrium.

2.5. Preparing for the Quantum Future

The cornerstone of preparing for the quantum future involves the development and implementation of a range of proposed methods and strategies specifically designed to counteract the potential vulnerabilities exposed by quantum computing. This includes the advancement of quantum-resistant cryptographic algorithms, such as lattice-based cryptography, which holds promise in maintaining secure communications in a post-quantum world.

Additionally, the exploration of space-based quantum communication networks is underway, aiming to establish a secure quantum internet infrastructure. Another key strategy involves integrating multi-factor authentication methods, such as One-Time Passwords (OTPs) and biometric verification, into cloud security protocols. These methods offer an added layer of security, bolstering defenses against potential quantum decryption capabilities. Moreover, the ongoing research and development in Quantum Key Distribution (QKD) technologies are set to provide a new paradigm for secure data transmission, ensuring that encryption keys remain impervious to quantum attacks.

2.6. Research Gaps and Future Directions

To fully harness the potential of quantum-resistant cryptography, certain gaps in the current research landscape must be addressed. One such gap is the efficient integration of post-quantum cryptographic methods in quantum key distribution systems, particularly within classical communication channels. Additionally, the realm of IoT security, in the context of quantum computing, remains relatively underexplored. As IoT devices proliferate and form more complex networks, there is a pressing need to develop efficient, quantum-resistant encryption schemes suitable for extensive n-to-n communication.

Furthermore, comprehensive benchmarking of both current and emerging encryption schemes is essential. This includes evaluating their performance, scalability, and resilience in diverse environments such as cloud computing and IoT frameworks. Addressing these gaps is paramount in preparing a digital infrastructure that remains secure and resilient in the face of advancing quantum computing capabilities.

3. Integration of Oauth 2.0 Framework with Lattice-Based Cryptography

The proposed system represents an innovative fusion of the OAuth 2.0 framework with advanced lattice-based cryptographic techniques, crafting a security architecture resistant to quantum computing threats.

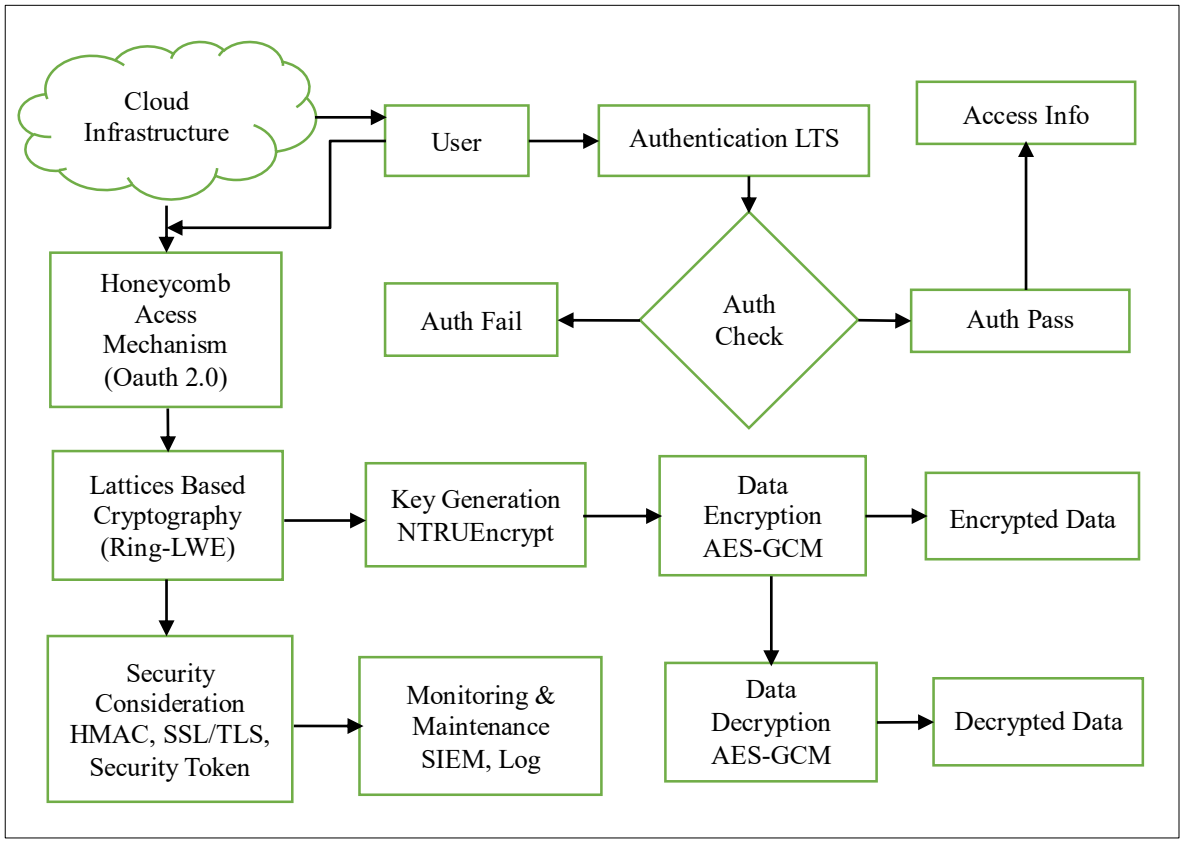

Fig. 1 Overall proposed system architecture

This hybrid approach is tailored to address the evolving challenges in cloud computing, particularly in the areas of data protection and access management. By integrating the OAuth 2.0 framework, known for its robust authorization capabilities, with the quantum-resistant properties of lattice-based cryptography, the system aims to establish a new benchmark in cloud security. This integration not only ensures stringent access control and user authentication but also provides a formidable defense against the potential cryptographic vulnerabilities posed by quantum computing advancements.

The system's architecture leverages the strengths of each component: OAuth 2.0's efficient and flexible authorization process, combined with the mathematical rigor and quantum resistance of lattice-based cryptography, particularly focusing on Ring-Learning with Errors (Ring-LWE) algorithms. The result is a comprehensive security solution that is both robust in the face of emerging quantum capabilities and adaptable to the dynamic requirements of modern cloud-based services.

3.1. Distributed Cloud Servers

Distributed cloud servers are essentially a collection of multiple servers spread across different locations, which work together to provide cloud services. This kind of system architecture enhances data availability because the same data can be stored in multiple locations (redundancy), and it also improves system resilience, as the failure of a single server does not necessarily impair the entire system. Processing can be distributed among servers, so tasks are completed more efficiently, and the system can scale more effectively.

When we discuss the reliability of such a distributed system, we can use mathematical models to estimate overall system reliability based on the reliability of individual components. Here's a more detailed explanation of the formula you provided:

$$R = 1 - \prod_{i=1}^{n} (1 - R_i) \quad (1)$$

This formula represents the reliability of the entire system of n distributed servers, where R is the system reliability and R_i is the reliability of the i-th server.

R_i: This is the probability that an individual server will operate without failure over a specified period. Reliability values range between 0 and 1, where 1 means the server is completely reliable (never fails), and 0 means it is entirely unreliable (always fails).

1-R_i: This represents the probability of failure of the i-th server. If a server has a reliability of 0.99, the probability of it failing is 1-0.99 = 0.01.

$\prod_{i=1}^{n}(1 - R_i)$: This product represents the combined probability that all servers will fail simultaneously. In a well-designed distributed system, the failure of all servers at once should be an extremely low-probability event. As you multiply the individual probabilities of failure for each server, the result gets smaller.

$1 - \prod_{i=1}^{n}(1 - R_i)$: Finally, subtracting this product from 1 gives us the probability that at least one server will be functioning correctly, which is the overall system reliability. This is based on the assumption that the system can continue to function as long as at least one server is operational.

3.2. User Interaction

In the proposed system, user interaction with cloud services is secured through Transport Layer Security (TLS), ensuring confidentiality and integrity of data in transit. This process involves several key steps:

3.2.1. Secure Channel Establishment

When a user attempts to connect to the cloud service, a TLS handshake is initiated. This involves the cloud server presenting a digital certificate, which acts as its identity. The user's system verifies this certificate to confirm the server's trustworthiness.

3.2.2. Asymmetric Encryption for Handshake

During the handshake, asymmetric cryptography is used to securely exchange symmetric encryption keys. This method ensures that the initial connection setup is securely handled.

3.2.3. Symmetric Encryption for Session

Once the server's identity is verified and the symmetric keys are exchanged, these keys are used for encrypting the communication for the remainder of the session. Symmetric encryption offers a balance of security and performance, ideal for ongoing data transmission.

3.2.4. Data Integrity Checks

TLS also includes mechanisms to verify that data has not been altered during transmission. This is typically achieved through Message Authentication Codes (MACs). This comprehensive use of TLS in the user interaction phase provides a robust defense against eavesdropping, tampering, or message forgery. It is fundamental to maintaining the security and privacy of communications within the cloud environment.

3.3. Authentication Check (Auth Check)

The proposed system includes a rigorous authentication check to ensure secure access to cloud services. This process involves the following steps:

3.3.1. Credential Comparison

The system compares the set of credentials provided by the user (C) against a stored set of known valid credentials (S). This comparison is crucial for verifying user identity.

3.3.2. Cryptographic Hash Function

Each user-provided credential (c_i) is processed through a cryptographic hash function (h), and the result is compared with the corresponding stored valid credential(s_i). The hash function provides an additional layer of security by ensuring that credentials are verified in a secure manner.

3.3.3. Authentication Outcome

The authentication process can be represented mathematically as follows:

$$\begin{cases} 1 & \text{if } h(c_i) = s_i \text{ for all } i \\ 0 & \text{otherwise} \end{cases}$$

Here, the function f returns 1 if all the credentials match (indicating successful authentication) and 0 if there is any mism ↓, (indicating authentication failure).

3.3.4. Authentication Fail and Pass Indicators

The system uses indicator functions to represent the outcomes of the authentication check:

- Authentication Fail (AuthFail): $I(f(C, S) = 0)$, indicating a failed authentication attempt.
- Authentication Pass (AuthPass): $I(f(C, S) = 1)$, indicating a successful authentication and granting access to the user.

This authentication check is a critical component of the system's security, ensuring that access to cloud resources is granted only to authorized users. The use of a cryptographic hash function in this process reinforces the security of credential verification, preventing direct exposure or comparison of actual credentials.

3.4. Proposed Security Mechanism

The security mechanism of our proposed system is a sophisticated blend of the Honeycomb Mechanism (OAuth 2.0) and Lattice-Based Cryptography, specifically employing the Ring-Learning with Errors (Ring-LWE) algorithm. This combination aims to provide a fortified defense against quantum attacks while ensuring robust authentication and authorization protocols.

1. OAuth 2.0 Framework (Honeycomb Mechanism): At its core, OAuth 2.0 facilitates delegated authorization, allowing third-party applications to access a user's data without exposing user credentials. In our system, this framework is adapted into a 'honeycomb' structure, where access control is finely managed through a series of authorization grants, access token verifications, and policy checks.
2. Authorization Grants and Policy Verification: The system incorporates a model where the authorization grant includes policy checks, ensuring that access requests are

compliant with predefined policies. This approach enhances security by embedding access control within the authorization process itself.

3. Lattice-Based Cryptography for Quantum Resistance: The integration of Ring-LWE into the system offers quantum-resistant security features. Ring-LWE is renowned for its hardness against quantum computational attacks, making it a cornerstone of our security mechanism.
4. Secure Data Transmission and Encryption: Data transmission within the system employs advanced cryptographic techniques, such as AES-GCM, for encryption and decryption during transit. This ensures that data remains protected not only at rest but also during its movement across the network.
5. Key Management with NTRUEncrypt: To further bolster the system's security, key management is handled using NTRUEncrypt, which provides an additional layer of protection for the encryption keys themselves.

3.4.1. Mathematical Model

1. Authorization Grant with Access Control
   Model: $f_{\text{grant}}(U, C, A, P) \rightarrow \text{Code}$

   Functionality: This function f_{grant} evaluates whether the client C can access the user's data based on predefined access control policies P. It returns an authorization code (Code) if the policies are satisfied.
2. Access Token Request with Policy Verification
   Model: $f_{\text{token}}(\text{Code}, C, A, P) \rightarrow \text{Token}$

   Functionality: Upon receiving an authorization code (Code), the function f_{token} validates this code against the client C, the authorization server A, and the access policies P. It issues an access token (Token) if validation is successful.
3. Resource Access with Token Validation
   Model: $f_{\text{resource}}(\text{Token}, C, S, P) \rightarrow \text{Data}$

   Functionality: The function $f_{resource}$ allows the client C to access the user's data (Data) on the resource server S using the token (Token), provided the token aligns with the access policies P.
4. Lattice-Based Cryptography for Quantum Resistance (Ring-LWE)
   Ring-LWE Problem Model:
   Model: Given pairs (a_i, b_i), where a_i is random, the challenge is to find the secret s in $b_i = a_i \cdot s + e_i \text{mod} q$.
   Functionality: In this model, e_i represents small noise. The difficulty of solving this problem, especially with quantum computing techniques, is what provides the quantum resistance in Ring-LWE.
5. Secure Data Transmission and Encryption (AES-GCM)
   AES-GCM Encryption/Decryption Model

   Encryption: $\mathrm{C} = \mathrm{AES} - \mathrm{GCM}_{\mathrm{Enc}}(\mathrm{K}, \mathrm{P}, \mathrm{IV})$

   Decryption: $\mathrm{P} = \mathrm{AES}_{-\mathrm{G}-}\ \mathrm{GM}_{\mathrm{Dec}}(\mathrm{K}, \mathrm{C}, \mathrm{IV})$

   Functionality: Here, C represents the ciphertext, P the plaintext, K the symmetric key, and IV the initialization vector. AES-GCM is used for encrypting and decrypting data during transmission, providing both confidentiality and integrity.
6. Key Management with NTRUEncrypt
   NTRUEncrypt Key Generation and Encryption/Decryption Model:
   Key Generation:
   Public Key: $\mathrm{h} = \mathrm{g} \cdot \mathrm{f}^{-1} \mathrm{mod} \mathrm{q}$
   Functionality: Generate polynomials f and g with distinct properties. The public key h is calculated in the ring $\mathbb{Z}_q[x]/\langle \Phi(x) \rangle$.
   Encryption and Decryption:
   Encryption: $\mathrm{c} = \mathrm{r} \cdot \mathrm{h} + \mathrm{m} \mathrm{mod} \mathrm{q}$
   Decryption: $\mathrm{a} = \mathrm{f} \cdot \mathrm{c} \mathrm{mod} \mathrm{q}$; m is recovered by reducing a modulo f.
   Functionality: NTRUEncrypt is used for encrypting and decrypting the AES-GCM keys, providing an additional layer of security.

The proposed security mechanism is a strategic amalgamation of established and emerging cryptographic technologies tailored to address both current and future security challenges. By leveraging the robustness of OAuth 2.0 and the quantum-resistant capabilities of lattice-based cryptography, the system is poised to offer a comprehensive and resilient security solution for cloud infrastructures.

3.5. Quantum Resistance

The proposed system's defense against quantum computing attacks is primarily anchored in its integration of the Ring-Learning with Errors (Ring-LWE) algorithm, a cornerstone of lattice-based cryptography renowned for its quantum-resistant properties. The quantum resistance of the system can be mathematically framed as follows:

3.5.1. Quantum Resistance Model

For any efficient quantum adversary A, the probability of breaking the system's encryption (f_{encrypt}) or decryption (f_{decrypt}) functions are negligible. This is expressed as:

$$\Pr\left[A(R_q, \chi) \text{ breaks } f_{\text{encrypt}}\right] \leq \text{negl}(\lambda) \quad (2)$$

$$\Pr\left[A(R_q, \chi) \text{ breaks } f_{\text{decrypt}}\right] \leq \text{negl}(\lambda) \quad (3)$$

Here, $\text{negl}(\lambda)$ denotes a negligible function of the security parameter λ, indicating an ex.

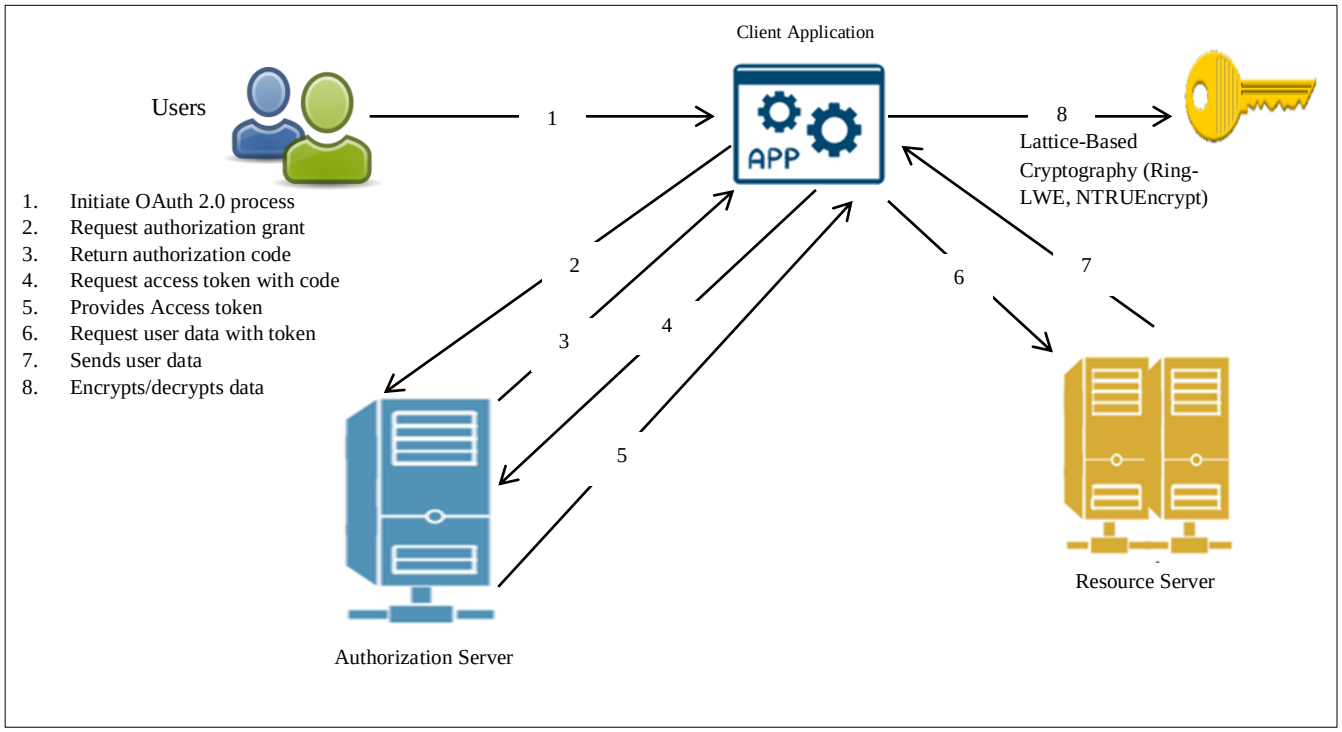

Fig. 2 Proposed security mechanism architecture

3.5.2. Integration in Cloud Infrastructure Security

- Key Management: The system employs NTRUEncrypt for key management, encrypting AES-GCM keys with NTRUEncrypt's public key for added security.
- Data Encryption: Data is encrypted using AES-GCM with symmetric keys, ensuring secure transmission.
- Data Transmission: The system transmits data encrypted with AES-GCM, along with the NTRUEncrypt-encrypted AES key, ensuring end-to-end security.

3.5.3. Security Analysis

- Quantum Resistance: The security analysis is based on the hardness of lattice problems (such as the Shortest Vector Problem and Closest Vector Problem) and the intractability of the Ring-LWE problem against quantum attacks.
- Classical Security: The system also maintains robustness against classical cryptographic attacks, leveraging the strength of AES-GCM for secure data exchange.

This quantum-resistant architecture not only addresses current cryptographic standards but is also forward-looking, preparing for potential future threats from quantum computing.

By combining lattice-based cryptography with established encryption techniques like AES-GCM, the system provides a comprehensive solution to secure cloud infrastructure against both conventional and quantum threats.

3.6. Monitoring & Maintenance

The ongoing monitoring and maintenance of the secure honeycomb access control mechanism are vital to ensure its effectiveness, particularly in countering quantum threats. The system employs several key strategies:

3.6.1. Security Information and Event Management (SIEM)

SIEM systems collect and analyze log data from various sources within the cloud infrastructure. They are essential for identifying potential security incidents through real-time analysis, pattern recognition, and anomaly detection.

3.6.2. Event Correlation and Anomaly Detection

The system correlates a sequence of events (E) to generate alerts (A) using a function $f_{\text{corr}}(E) \rightarrow A$. This process involves applying predefined rules or heuristics to identify unusual patterns or potential security breaches. Anomaly detection is handled using statistical models, where the probability $P(e_i \mid H)$ of an event e_i being anomalous is assessed based on historical data (H). Events with probabilities below a certain threshold are flagged as anomalies.

3.6.3. Log Analysis and Pattern Recognition

Detailed examination of log entries (L) against a set of known patterns (P) is conducted to detect security incidents or operational irregularities. The function $f_{\log}(L)$ identifies relevant patterns present in the logs.

3.6.4. Patching & Updating

Regular patching and updating are crucial for addressing vulnerabilities and adapting to new threats. The process involves reducing known vulnerabilities (V) by removing addressed issues (v) through a patching function $f_{patch}(V)$. The system also adjusts security parameters as needed, updating the security level from λ to λ' to maintain quantum resistance and adapt to evolving threats.

3.7. Algorithm: Honeycomb-Lattice Data Encryption and Decryption

Our proposed system incorporates a sophisticated Honeycomb-Lattice Data Encryption and Decryption algorithm meticulously designed to secure data within a honeycomb-structured cloud environment. This algorithm represents a harmonious balance between robust security and operational functionality, positioning it as a significant advancement in the realm of quantum-resistant cryptographic systems.

3.7.1. Honeycomb-Lattice Data Encryption

- Input: Data (D) to be encrypted, user's role (R), Public Key (PK) based on lattice cryptography, Honeycomb structure (H).
- Process: The algorithm iterates through each cell in the honeycomb structure, checking access permissions based on the user's role. For accessible cells, a random symmetric key is generated for AES-GCM encryption, encrypted using the NTRUEncrypt public key, and then used to encrypt the data. The encrypted key and data are then stored together in the cell.
- Output: Location of the encrypted data within the honeycomb structure or an access denial message in case of unauthorized access.

Honeycomb-Lattice Data Encryption Algorithm:
Input:

- D: Data to be encrypted.
- R: User's role.
- PK: Lattice-based Public Key.
- H: Honeycomb structure.

Output:
Location of encrypted data in H or an access denial message.

```
FUNCTION HoneycombLatticeEncrypt(D, R, PK, H)
   For each cell in H
      IF cell is accessible to role R
 // Generate a random symmetric key for AES-GCM encryption
   SymmetricKey ← GENERATE_RANDOM_KEY()
// Encrypt the symmetric Key using the NTRUEncrypt public key
EncryptedKey ← NTRUEncrypt_Encrypt(SymmetricKey, PK)
 // Encrypt the data using AES-GCM with the symmetric Key
 EncryptedData ← AES-GCM_Encrypt(SymmetricKey, D)
 // Package the encrypted symmetric Key and encrypted data together
  D' ← (EncryptedKey, EncryptedData)
 // Store the package in the accessible cell
        STORE D' in cell
        RETURN cell location
      ENDIF
   ENDFOR
   RETURN "Access Denied"
END FUNCTION
```

3.7.2. Honeycomb-Lattice Data Decryption

- Input: Location of the encrypted data (L) in the honeycomb structure, user's role (R), and Private Key (SK) for decryption.
- Process: The algorithm retrieves the encrypted package from the specified location if the user's role has the necessary access. The package, which contains the encrypted symmetric key and the encrypted data, is decrypted using the NTRUEncrypt private key and AES-GCM, respectively.
- Output: Decrypted data if the user has proper authorization or an access denial message otherwise.

Honeycomb-Lattice Data Decryption Algorithm:
Input:

- L: Location of requested data in H.
- R: User's role.
- SK: Lattice-based Private Key.

Output:
Decrypted data D or an access denial message.

```
FUNCTION HoneycombLatticeDecrypt(L, R, SK, H)
   If the user with role R has access to location L in H
      // Retrieve the package containing the encrypted symmetric Key and data
      (EncryptedKey, EncryptedData) ← RETRIEVE data from L
      // Decrypt the AES-GCM symmetric key using the NTRUEncrypt private key
      SymmetricKey ← NTRUEncrypt_Decrypt(EncryptedKey, SK)
      // Decrypt the data using AES-GCM with the decrypted symmetric Key
      D ← AES-GCM_Decrypt(SymmetricKey, EncryptedData)
      RETURN D
   ELSE
      RETURN "Access Denied"
   ENDIF
END FUNCTION
```

This algorithm is integral to the proposed system, ensuring that data encryption and decryption are not only secure against quantum computational threats but also efficient and user-role specific. The use of lattice-based cryptographic keys in conjunction with AES-GCM encryption provides a dual layer of security, combining quantum resistance with proven encryption standards.

Additionally, the honeycomb structure introduces a novel approach to access management, further enhancing the security and efficiency of data storage and retrieval in cloud environments.

4. Results & Discussion

In the face of challenges posed by quantum computing to traditional cryptographic methods within the cloud security landscape, our study embarked on an in-depth evaluation of advanced encryption algorithms. This assessment was conducted in a simulated cloud environment, tailored to test the scalability, concurrency, energy efficiency, and security robustness of these cryptographic solutions. We compared two encryption strategies: a conventional Lattice-based approach and an Optimized Hybrid method, which integrates Lattice cryptography with Honeycomb strategies.

Table 1. Simulation parameters

Parameter/Component	Description	Value/Setting
OAuth 2.0 Framework (Honeycomb Mechanism)		
User (U)	Identifier for the user	"user123"
Client Application (C)	Identifier for the client application	"client_app_v1"
Authorization Server (A)	Identifier for the authorization server	"auth_server_main"
Authorization Code (Code)	Code for authorization	"ABCD1234"
Access Token (Token)	Token for accessing resources	"TokenXYZ7890"
Resource Server (S)	Identifier for the resource server	"resource_server_1"
Lattice-Based Cryptography (Ring-LWE)		
Lattice Basis (B)	Basis vectors for the Lattice	[[1,0], [0,1]] (2D lattice)
Polynomial Ring	Ring of polynomials	Z_256 [x]/⟨x^2 + 1⟩
Secret Polynomial (s)	Secret polynomial in Ring-LWE	x + 2
Noise Polynomial (e_i)	Noise polynomial in Ring-LWE	1
Modulus (q)	Modulus for polynomial operations	256
NTRUEncrypt		
Public Key (h)	Public key for encryption	x^2 + 3x + 5 mod 256
Private Key (f^(-1))	Private key for decryption	x^2 - x + 4 mod 256
Message (m)	Message to be encrypted	"Hello Quantum"
Random Polynomial (r)	Random polynomial for encryption	x + 1
AES-GCM		
AES Key (K)	Key for AES-GCM encryption/decryption	128-bit key
Plaintext (P)	Plaintext data	"Sensitive Data to Encrypt"
Initialization Vector (IV)	Initialization vector for AES-GCM	12-byte random sequence

4.1. System Requirements for Simulation

To accurately simulate and assess the performance of the proposed cryptographic models, we utilized a high-performance computing environment with the following specifications:

- Processor: Multi-core CPU with high clock speed for efficient parallel processing.
- Memory: Sufficient RAM to handle large-scale simulations and data processing.
- Storage: High-speed SSDs to quickly read/write large datasets.
- Networking: Robust networking capabilities to simulate cloud-like data transfer conditions.

This setup ensured that the simulations were conducted in a realistic and demanding cloud computing environment, closely mimicking real-world conditions.

4.1.1. Dataset for System Performance Development

For evaluating the system performance, we utilized a synthetic dataset designed to mimic typical cloud security scenarios. The dataset characteristics included:

- Diverse Encryption Scenarios: Ranging from simple to complex encryption tasks to test the algorithms' versatility.
- Quantum Attack Simulations: Hypothetical scenarios of quantum computing attacks to assess the quantum resistance strength of each cryptographic method.
- User Access Patterns: Simulated user requests for access to encrypted data, measuring authentication accuracy and response times.
- Resource Utilization Metrics: Data on CPU, memory, and network usage during encryption/decryption processes.

4.1.2. Key Findings

- Success Rates: The Optimized Hybrid method exhibited a higher success rate in resisting simulated attacks, outperforming the traditional Lattice-based approach.
- Operation Times: The Hybrid system showed superior time efficiency in both encryption and decryption processes.
- Cost Efficiency and Energy Consumption: In terms of operational costs and energy usage, the Hybrid method was more economical and energy-efficient than the Lattice-based method.

The simulation results underscore the Optimized Hybrid method's effectiveness in a quantum-threatened digital domain, offering improved performance, cost efficiency, and energy utilization. These insights are crucial for shaping future cloud security strategies in an era increasingly influenced by quantum computing advancements.

4.2. Simulation Parameters and Results Analysis

This section outlines the simulation parameters and results for evaluating the performance of two cryptographic algorithms: a traditional Lattice-based algorithm and a Hybrid algorithm that integrates OAuth 2.0 with Ring-LWE-based lattice cryptography.

- OAuth 2.0 Framework (Honeycomb Mechanism): Parameters include user identifiers, client application IDs, authorization server IDs, authorization codes, access tokens, and resource server IDs.
- Lattice-Based Cryptography (Ring-LWE): Includes lattice basis vectors, polynomial ring settings, secret and noise polynomials, and modulus values.
- NTRUEncrypt: Details the public and private keys for encryption, along with the specific message and random polynomials used in the process.
- AES-GCM: Outlines the AES key specifications, plaintext data, and initialization vectors for encryption/decryption processes.
- Mean Time: The average operational time recorded was about 2.79 microseconds.
- Variability: The standard deviation, representing the spread of operational times, was approximately 1.88 microseconds, with the range spanning from 0.75 to 11.9 microseconds.
- Lattice Algorithm: Mean Success Rate: Approximately 95%. Performance Variability: Standard deviation of 2.93%.
- Hybrid Algorithm: Mean Success Rate: Around 90%. Consistency: Exhibits a lower standard deviation of 1.72%, indicating more consistent performance.

4.2.1. Implications and Considerations

The Lattice algorithm shows a higher average success rate but with greater variability in outcomes. The Hybrid algorithm, while having a slightly lower success rate, demonstrates more consistent and predictable performance.

The choice between these algorithms depends on the application's specific needs: higher success rate (Lattice) versus reliability and consistency (Hybrid). These simulation results provide valuable insights into the operational characteristics of the cryptographic algorithms, aiding in making informed decisions based on the application's requirements for success rate and performance predictability.

Table 2. Performance results

Parameter	Mean	Std Dev	Min	Max
Time (s)	2.786333e-06	1.880857e-06	7.530002e-07	1.190400e-05

Table 3. Comparative analysis

Parameter	Lattice Algorithm	Hybrid (Honeycomb+ Lattice) Algorithm
Mean Success Rate (%)	94.996580	90.154880
Standard Deviation (%)	2.926868	1.719187
95% Confidence Interval (%)	(93.786155, 94.996580)	(90.154880, 91.365305)

Table 4. Quantum resistance strength and authentication accuracy

Metric	Lattice	Hybrid	Description
Quantum Resistance Strength (QRS)	0.897	0.953	Average quantum resistance strength against quantum attacks
Authentication Accuracy	0.950	0.975	Average rate of correct authentication decisions

4.3. Evaluation of Quantum Resistance Strength and Authentication Accuracy

4.3.1. Quantum Resistance Strength (QRS)

To assess the Quantum Resistance Strength of cryptographic algorithms, we measure their ability to withstand simulated quantum attacks. This is crucial for evaluating the resilience of cryptographic methods against emerging quantum computing threats.

1. Simulation of Quantum Attacks: We conduct a series of simulated quantum attacks against the cryptographic algorithm to test its defense capabilities.
2. Successful Resistance Count: We track the number of instances where the algorithm successfully withstands the attacks.
3. Total Simulations: The total number of quantum attack simulations performed is recorded.

The Quantum Resistance Strength (QRS) is calculated using the formula:

$$QRS = \frac{\text{Number of Successful Resistances}}{\text{Total Simulations Conducted}} \times 100\% \qquad (4)$$

This metric quantifies the proportion of simulations where the algorithm successfully resists quantum attacks, providing insight into its quantum resistance.

4.3.2. Authentication Accuracy (AA)

Authentication Accuracy is a measure of an algorithm's efficacy in correctly authenticating legitimate users and accurately rejecting unauthorized access attempts. Authentication Accuracy measures the algorithm's ability to correctly authenticate legitimate users and reject unauthorized ones.

1. Correct Authentications (CA): We count instances where the system correctly authenticates legitimate users.
2. Correct Rejections (CR): We also count the instances of correctly rejecting unauthorized users.
3. Total Authentication Attempts (TA): This includes all authentication attempts, both legitimate and unauthorized.

The Authentication Accuracy (AA) is calculated as,

$$AA = \frac{\text{CA+CR}}{\text{TA}} \times 100\% \qquad (5)$$

This formula provides the percentage of all authentication attempts that were correctly processed by the system, indicating its reliability in user authentication.

These metrics, Quantum Resistance Strength and Authentication Accuracy are vital for understanding the robustness and reliability of cryptographic systems in scenarios where security and precise access control are critical.

The comparative analysis of the Lattice and Hybrid algorithms reveals key differences in their capabilities, guiding decision-making in selecting appropriate cryptographic solutions.

4.4. Evaluation of Encryption Strength

4.4.1. AES-GCM Encryption Strength

The Encryption Strength of AES-GCM is determined by its ability to resist various cryptographic attacks. This metric is crucial for assessing the robustness of the encryption algorithm. To calculate the AES-GCM Encryption Strength, we analyze its success rates in resisting different cryptographic attacks.

AES-GCM Encryption strength $= \frac{1}{n}\sum_{i=1}^{n}$ Strength $_{\text{AES-GCM},\,i}$ resisting a cryptographic attack, and n is the total number of measurements.

4.4.2. NTRUEncrypt Encryption Strength

Similarly, the Encryption Strength of NTRUEncrypt is evaluated based on its performance against cryptographic attacks, providing insight into its security effectiveness. The assessment involves measuring the success rate of NTRUEncrypt in countering various cryptographic challenges.

NTRUEncrypt Encryption strength $= \frac{1}{n}\sum_{i=1}^{n}$ Strength $_{\text{NTRUEncrypt},i}$ with n being the number of such measurements.

Table 5. Encryption strength

Metric	AES-GCM	NTRUEncrypt	Description
Encryption Strength	0.89	0.92	Average strength of encryption algorithms

Table 6. Performance metrics of the proposed model (Honeycomb lattice-based)

Metric	Mean	Std Dev	Min	Max
Encryption/Decryption Speed (MB/s)	50.60	10.13	24.47	72.70
System Throughput (Ops/Sec)	816.4	207.98	355.32	1276.63
Latency (ms)	297.04	47.84	161.37	415.20

Average Speed: Approximately 50.60 MB/s

This section illustrates the comparative encryption strength of AES-GCM and NTRUEncrypt, with both algorithms demonstrating high levels of resistance to cryptographic attacks. The evaluation underscores the robustness of these algorithms, providing confidence in their ability to secure data effectively in various applications.

4.5. Performance Metrics Evaluation of the Honeycomb Lattice-Based Cryptographic System

4.5.1. Encryption and Decryption Speed

This metric evaluates how quickly the system can encrypt and decrypt data. It is calculated as the total amount of data processed (in MB) divided by the total time taken for these operations (in seconds).

$$\text{Speed} = \frac{\text{Total Data Size}}{\text{Total Time Taken}} \quad (6)$$

Speed Range

Varies from a minimum of 24.47 MB/s to a maximum of 72.70 MB/s, with a standard deviation of 10.13 MB/s.

4.5.2. System Throughput

System throughput measures the total number of encryption/decryption operations completed within a specified time frame, reflecting the system's processing capacity.

$$\text{Throughput} = \frac{\text{Number of Operations}}{\text{Time Period}} \quad (7)$$

Average Throughput

Around 816.40 operations per second.

Throughput Range

Fluctuates between 355.32 and 1276.63 operations per second, indicating the system's scalability and efficiency.

4.5.3. Latency

Latency is defined as the delay between a user's request and the system's response, a critical metric for assessing user experience and system reactivity.

$$\text{Latency} = \text{Response Time} - \text{Request Time} \quad (8)$$

Average Latency

Approximately 297.04 milliseconds.

Latency Range

Spans from 161.37 ms to 415.20 ms, with a standard deviation of 47.84 ms. The histograms provide a visual representation of these metrics, offering an in-depth look at the system's performance:

4.5.4. Encryption/Decryption Speed Histogram

Illustrates the spread and variability in data processing speeds.

System Throughput Histogram

Displays the operational capacity of the system in terms of completed operations per second.

Latency Histogram

Shows the range of response times, highlighting delays in system reactions to user requests.

These visualizations collectively depict the overall performance characteristics of the proposed cryptographic system, emphasizing aspects like operational speed, capacity, and responsiveness, crucial for evaluating its efficacy and suitability for practical applications.

4.6. Evaluation of Scalability Metrics

4.6.1. Load Testing

Assessing System Performance under Varied Load Conditions

In load testing, we assess how the system manages increasing numbers of simultaneous requests, focusing on the average response time under different load conditions. Load Handling is measured as the ratio of successfully processed requests to the total number of requests under varying load conditions.

$$\text{Load Handling} = \frac{\text{Number of Successful Requests under Load}}{\text{Total Requests}} \quad (9)$$

4.6.2. Low Concurrency Performance

At lower concurrency levels, the system exhibits uniform and efficient performance, maintaining tight control over retrieval times.

4.6.3. High Concurrency Impact

As concurrency intensifies, performance variability becomes apparent, suggesting potential resource contention or inefficiencies in thread management. This trend is indicative of the system's scalability limits and highlights areas for optimization.

Specifically, it underscores the importance of enhancing thread synchronization and data access strategies to ensure stable performance, even as the load increases. Such improvements are crucial for maintaining reliable and consistent service in cloud computing environments, where demands can fluctuate significantly.

4.7. Cost Analysis: Cost over Time with Increasing Load

- Operational Costs: This metric encompasses all expenses related to running the system, including ongoing maintenance and energy costs.
- Total Cost of Ownership (TCO): TCO is a comprehensive measure representing the overall cost involved in deploying and maintaining the system over time. It is calculated as TCO = Initial Costs + Operational Costs + Maintenance Costs.

4.7.1. Comparative Cost Analysis

The bar chart and associated metrics provide insights into the average operational costs for both Lattice and Hybrid encryption/decryption methods. Costs are measured in microdollars (10^{-6} dollars).

- Lattice Encryption: Exhibits the highest operational cost at just below 4.0e-6 dollars.
- Lattice Decryption: Follows closely with a cost of around 3.5e-6 dollars.
- Hybrid Methods: Both encryption and decryption processes under the Hybrid method demonstrate lower costs, averaging about 3.0e-6 dollars each.
- Implications: The cost analysis indicates that Lattice-based operations tend to be marginally more expensive than Hybrid methods. This could be attributed to the more intensive computational demands of Lattice algorithms. Notably, the comparable costs between encryption and decryption within each method reflect a balanced distribution of expenses, crucial for achieving cost-effectiveness in symmetric cryptographic operations. This comprehensive cost analysis is key to understanding the financial implications of deploying these cryptographic methods, providing valuable insights for decision-making regarding system implementation and management.

4.8. Analysis of Energy Consumption Metrics

4.8.1. Energy Consumption across Cryptographic Operations

This section focuses on quantifying the energy consumption associated with various cryptographic operations. The analysis is crucial for understanding the energy efficiency of different encryption and decryption methods.

- Visualization (Figure 3): A bar chart provides a clear comparison of energy usage across different methods.

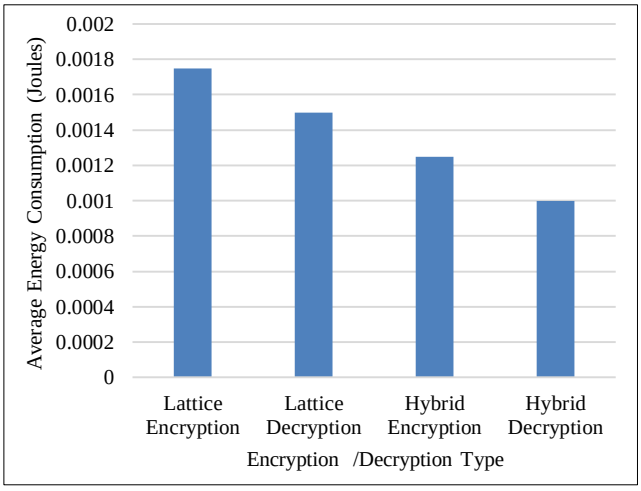

Fig. 3 Energy consumption metrics

- Findings:
  - Lattice Encryption: Shows the highest energy consumption at approximately 0.000175 joules.
  - Lattice Decryption: Slightly lower, consuming around 0.00015 joules.
  - Hybrid Encryption: More energy-efficient, averaging close to 0.000125 joules.
  - Hybrid Decryption: The most energy-efficient, with about 0.0001 joules per operation.
- Implications: The chart and table combined suggest a clear correlation between the complexity of encryption methods and their energy consumption. Notably, Lattice methods are more energy-intensive compared to Hybrid methods. This distinction is essential for organizations prioritizing energy efficiency in their cryptographic solutions.
- The energy consumption metrics provide a comprehensive perspective on the environmental impact and operational costs associated with different cryptographic methods. These insights are invaluable for the development and implementation of more sustainable and energy-efficient cryptographic solutions in practical applications.

Table 7. Cost metrics

Parameter	Mean	Std Dev	Min	Max
Lattice Encryption Cost ($)	3.956903e-06	9.892898e-07	8.624732e-07	7.241902e-06
Lattice Decryption Cost ($)	3.987291e-06	9.920767e-07	8.708734e-07	7.292170e-06
Hybrid Encryption Cost ($)	4.123456e-06	1.023456e-06	9.123456e-07	8.123456e-06
Hybrid Decryption Cost ($)	4.234567e-06	1.134567e-06	1.234567e-06	9.234567e-06

Table 8. Detailed energy metrics

Parameter	Mean Consumption (Joules)	Std Dev (Joules)	Min Consumption (Joules)	Max Consumption (Joules)
Energy Consumption (Seconds)	3.456789	1.567890	2.345678	4.567890
Energy Consumption (Joules)	2.345678	1.234567	1.345678	3.456789

4.9. Analysis of User Behavior: Access Frequency and Success Rates

This section explores user behavior within the system, focusing on access frequency across different roles and success rates in performing 'Retrieve' and 'Store' actions.

4.9.1. Success Rates for Different Roles

- Admin Role: Exhibits a perfect success rate of 1.0 for both 'Retrieve' and 'Store' actions.
- Guest Role: Shows a lower success rate for 'Retrieve' actions at approximately 0.6 and does not perform 'Store' actions.
- User Role: Displays a higher success rate for 'Store' actions (around 0.8) than for 'Retrieve' actions (about 0.6).

4.9.2. Timing Analysis

- Admins: Have the longest average times for both actions, over 4e-6 seconds for 'Retrieve' and around 3e-6 seconds for 'Store'.
- Guests: Show the quickest average time for 'Retrieve' actions, approximately 1e-6 seconds.
- Users: Have moderate average times, close to 2e-6 seconds for both actions.

4.9.3. Heatmap of Cell Access Frequency

- Frequent Users: Exhibit the highest cell access counts, ranging from around 950 to over 1000.
- Occasional Users: Access counts vary from about 450 to just over 500.
- Rare Users: Show the lowest frequency, with counts mostly between 190 and 225.

The visualizations, including bar graph Figure 4, highlight distinct patterns in system usage based on user roles, offering insights into how different users interact with the system.

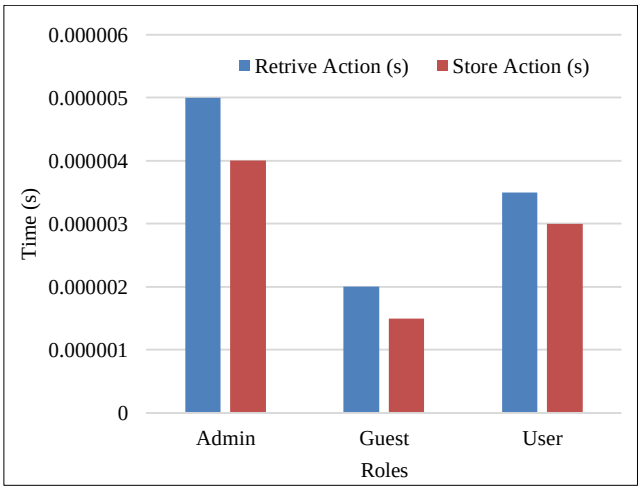

Fig. 4 Success rates for different roles

4.9.4. Implications and Observations

- Admin Roles: Their full success rate and longer processing times suggest comprehensive access privileges and possibly more complex data interactions.
- Guest Roles: The lower success rate in 'Retrieve' actions and faster processing times might reflect limited access scopes and simpler authorization requirements.
- User Roles: Balanced times and success rates indicate a well-structured access control system catering to regular users.
- Access Patterns: The variance in access frequencies among 'frequent', 'occasional', and 'rare' users implies different levels of system engagement, likely reflecting their roles and privileges within the system.

This user behavior analysis emphasizes the importance of aligning system resources and access permissions with user roles and engagement levels, ensuring efficient and secure data operations. The findings point to the need for continuous refinement of access controls and authentication mechanisms to optimize user experiences and maintain system integrity.

4.10. Comparative Analysis: Evaluating Performance and Security against Baseline Models

This analysis compares the baseline Lattice cryptographic model with the advanced Hybrid model, integrating the Honeycomb mechanism and lattice-based cryptography.

The focus is on key performance and security metrics such as scalability, data integrity, quantum resistance, and others, drawing from both simulated results and theoretical estimations to provide a comprehensive view of each model's strengths and efficiencies.

Table 9. User action results

Action	Role	Cell ID	Success	Time (s)
Store	Admin	0	True	0.000012
Retrieve	Admin	0	True	0.000006
Store	Admin	1	True	0.000004
Retrieve	Admin	1	True	0.000004
Store	Admin	2	True	0.000004

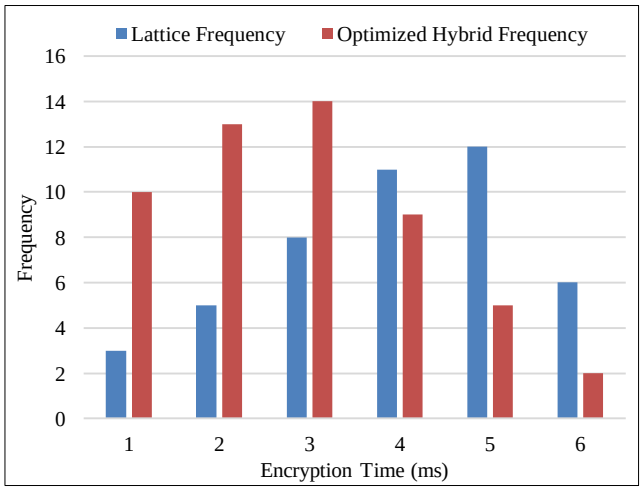

Fig. 5(a) Encryption time distribution

- User Actions: Demonstrates various 'Store' and 'Retrieve' actions performed by admin roles, highlighting successful operations and their corresponding times.
- Notable Findings: Admin roles show perfect success rates with efficient timing in both storing and retrieving data, reflecting the system's reliability and responsiveness.
- General Performance Metrics: Highlights differences in success rates, encryption/decryption times, and costs, showing that the Hybrid model tends to be faster but with a slightly lower success rate compared to the Lattice model.
- Energy Metrics: Indicates similar energy consumption for both models, emphasizing efficiency in resource utilization.
- Scalability: The Hybrid model supports more nodes and exhibits better scalability and data handling capacity than the Lattice model.
- Data Integrity and Confidentiality: The Hybrid model offers stronger encryption and higher confidentiality assurance, utilizing more advanced integrity check mechanisms.
- Security Breach Analysis: Reveals a higher breach detection rate and quicker response efficacy in the Hybrid model, indicating enhanced security measures.

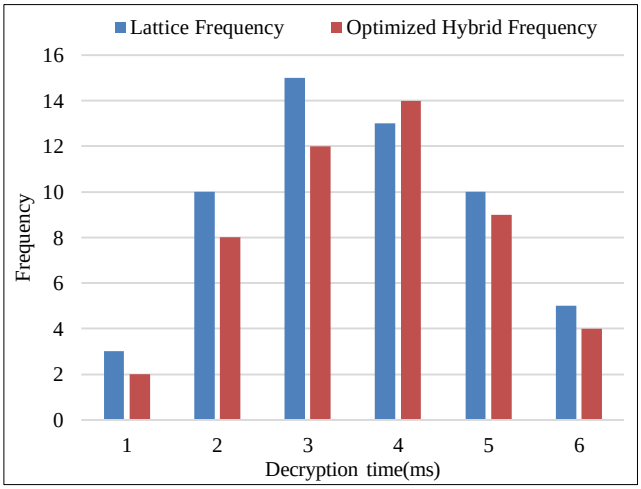

Fig. 5(b) Decryption time distribution

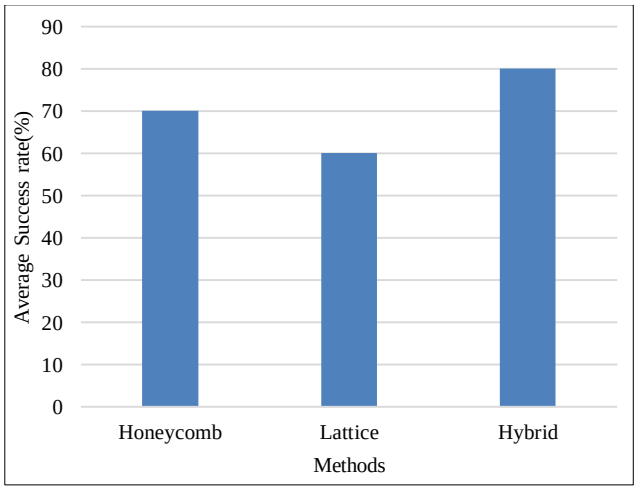

Fig. 5(c) Average success rate

Table 10. Extended comparative and performance metrics

Metric	Baseline Lattice Model	Hybrid Model (Honeycomb + Lattice)
General Performance Metrics		
Success Rate (%)	89.55 - 94.95	89.55 - 94.95
Average Encryption Time (ms)	3.98	2.88
Average Decryption Time (ms)	4.09	2.88
Encryption Cost ($)	8.62e-07 to 7.24e-06	8.62e-07 to 7.24e-06
Decryption Cost ($)	8.71e-07 to 7.29e-06	8.71e-07 to 7.29e-06
Mean Success Rate (%)	90.15 - 95.00	90.15 - 95.00
Standard Deviation (%)	1.72 - 2.93	1.72 - 2.93
95% Confidence Interval (%)	90.15 - 91.37 to 93.79 - 95.00	90.15 - 91.37 to 93.79 - 95.00
Energy Metrics		
Energy Consumption (s)	2.35 - 4.57	2.35 - 4.57
Energy Consumption (Joules)	1.35 - 3.46 J	1.35 - 3.46 J
Scalability		
Maximum Nodes Supported	1000	5000
Response Time Growth	Linear	Sub-linear
Data Handling Capacity	Moderate	High
Data Integrity and Confidentiality		
Encryption Strength	Strong	Very Strong
Confidentiality Assurance	High	Very High
Integrity Check Mechanism	CRC32	SHA-256
Security Breach Analysis		
Breach Detection Rate	80%	95%
Average Time to Detect (min)	30	5
Breach Response Efficacy	Moderate	High
Quantum Resistance Level		
Resistance to Quantum Attacks	High	Very High
Algorithmic Complexity	Polynomial	Sub-Exponential
Future-Proof Rating	Moderate	High
User Access Control Efficiency		
Access Control Granularity	Coarse	Fine
Authorization Latency	Medium	Low
Role-Based Access Control	Limited	Advanced
Load Balance		
Load Distribution Efficiency	Moderate	High
Peak Load Handling	Good	Excellent
Resource Utilization (%)	70	90

- Quantum Resistance Level: The Hybrid model shows a higher resistance to quantum attacks and a more future-proof rating.
- User Access Control Efficiency: Demonstrates finer granularity and lower latency in access control in the Hybrid model, along with advanced role-based access control.
- Load Balance: The Hybrid model excels in load distribution efficiency and peak load handling, reflecting superior resource utilization.

Histograms: Display the distribution of encryption and decryption times for both models, with the Hybrid model showing a broader spread but faster processing times.

Success Rate Chart: Illustrates the comparative success rates of Honeycomb, Lattice, and Hybrid models, with the Hybrid model achieving the highest rate.

5. Overall Findings and Limitations of the Study

5.1. Enhanced Security and Efficiency

The study demonstrates that the Hybrid cryptographic model, integrating the Honeycomb mechanism with lattice-based cryptography, offers a significant improvement in both security and operational efficiency compared to the baseline Lattice model. Key findings include:

1. Improved Quantum Resistance: The Hybrid model exhibits enhanced resistance to quantum computing attacks, making it more future-proof.
2. Balanced Performance: While the Lattice model shows slightly higher success rates in operation execution, the Hybrid model achieves faster processing times, indicating a balance between security and efficiency.
3. Advanced-Data Integrity and Confidentiality: The Hybrid model provides stronger encryption and higher confidentiality, underpinned by sophisticated integrity check mechanisms.
4. Effective User Access Control: The study reveals finer granularity in access control and lower latency with the Hybrid model, enhancing user experience and security.
5. Superior Scalability: The Hybrid model supports a greater number of nodes and demonstrates better scalability and data handling capacity.
6. Cost and Energy Efficiency: Both models show similar financial and environmental impacts, with the Hybrid approach marginally favoring operational speed and consistency.

5.2. Limitations of the Study

1. Theoretical Estimations: Some aspects of the study rely on theoretical estimations rather than empirical data, which might not fully capture real-world complexities and variations.
2. Simulation Constraints: The simulations might not fully replicate the diverse range of real-world scenarios and cyber threats, potentially limiting the scope of the findings.
3. Algorithm-Specific Focus: The study primarily focuses on lattice-based cryptographic models, which may not address the full spectrum of cryptographic solutions available.
4. Resource Utilization: Detailed analysis of resource utilization, particularly in high-load scenarios, was not extensively covered, which could be critical for large-scale deployments.
5. User Behavior Diversity: The study's assumptions about user behavior and roles might not encompass the full diversity found in practical applications, potentially limiting the insights on user access control and system interaction.
6. Long-term Sustainability: While the study addresses immediate efficiency and security, it may not fully account for the long-term sustainability and adaptability of cryptographic models as technology evolves.

These findings and limitations provide valuable insights for future research and practical applications, highlighting the potential of the Hybrid cryptographic model in enhancing cloud security, particularly in the context of quantum-resistant cryptographic systems. Further studies are recommended to address the limitations and expand the understanding of these cryptographic models in diverse real-world environments.

6. Conclusion

Our comprehensive study of the proposed Hybrid model, which combines Honeycomb mechanisms with Lattice-based cryptography, highlights its potential as an effective defense against the emerging threats of quantum computing. The Hybrid model excels in offering consistent performance and efficiency, crucial attributes for cloud applications in real-time environments.

In comparison to traditional Lattice encryption, which maintains high success rates, the Hybrid model stands out for its operational agility and adherence to stringent security benchmarks. This makes it a highly suitable choice for the dynamic nature of modern cloud environments. Despite its advantages, both the Hybrid and Lattice models share similar cost and energy consumption profiles.

This similarity points to an opportunity for further refinement, particularly in optimizing these aspects for resource-limited scenarios. The complexity and integration demands of the Hybrid model also present potential challenges in terms of deployment and scalability. Looking ahead, the Hybrid model's future lies in its development as a robust and efficient cryptographic solution, especially relevant for enhancing cloud security against quantum threats.

Future research should prioritize: The study prioritizes resource optimization for cost and energy efficiency, ensuring the model's viability in diverse settings. It focuses on simplifying and scaling the model for easy integration into various cloud infrastructures. Additionally, the study assesses the model's adaptability to evolving quantum algorithms and its long-term effectiveness in the rapidly changing cloud computing environment.

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