Quantum-Resistant Cryptography: Uniting Lattice-Based Encryption And Code-Based Error Correction For Enhanced Security

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ABSTRACT

As quantum computing advances, traditional cryptographic methods face significant threats from quantum algorithms, necessitating the development of quantum-resistant encryption systems. This paper explores a modified cryptographic algorithm combining lattice-based encryption techniques with enhanced noise, larger key sizes, and increased modulus values to resist quantum attacks. Utilizing Google's Cirq quantum simulator, the robustness of the algorithm against quantum period-finding techniques is evaluated, showing minimal or no detectable periodicity. These findings underscore the effectiveness of the proposed method for quantum resistance. This framework is especially applicable to IoT and cloud environments, offering long-term data protection and resilience in noisy communication channels.

I. INTRODUCTION

Quantum computing poses a significant threat to classical cryptographic algorithms due to its ability to factor large numbers and solve discrete logarithm problems. A new paradigm of quantum-resistant cryptography is emerging, based on the theory of lattices. Lattices are mathematical structures used to construct cryptographic primitives like encryption, digital signatures, and key exchange. These schemes are to be resistant to quantum attacks due to the difficulty of solving certain lattice problems. Combining lattice-based encryption with error-correcting codes can create hybrid schemes that are both quantum-resistant and resilient to noise and errors. This approach offers a promising solution for securing sensitive data in the face of emerging quantum threats.

Overview of Quantum Computing and Its Threats:

Quantum computing represents one of the most revolutionary developments in computational theory and technology. Unlike classical computers, which rely on bits to perform calculations, quantum computers utilize quantum bits, or qubits. These qubits can exist in multiple states simultaneously, thanks to phenomena like superposition and entanglement, leading to an exponential increase in processing power. This potential computational advantage brings with it the ability to solve complex problems far faster than any classical computer could. One of the most alarming aspects of quantum computing is its capacity to break traditional cryptographic systems. Cryptographic algorithms like RSA and elliptic curve cryptography (ECC), which underpin modern data security, rely on the computational difficulty of certain mathematical problems, such as prime factorization and discrete logarithms. Quantum computers, through algorithms like Shor’s algorithm, can solve these problems efficiently, thereby breaking the security of these systems.

The Need for Post-Quantum Cryptography:

With the imminent rise of large-scale quantum computers, the need for post-quantum cryptography (PQC) has become critical. Post-quantum cryptography refers to cryptographic algorithms designed to be secure against the computational power of quantum computers. As developments in quantum computing accelerate, the risk of a "quantum apocalypse" grows, where vast amounts of encrypted data could potentially be decrypted overnight. This has led researchers to focus on developing quantum-resistant cryptographic algorithms that can withstand the power of quantum attacks.

Existing Cryptographic Algorithms and Vulnerabilities:

Many of the cryptographic algorithms that are currently in use, such as RSA, DSA, and ECC, have stood the test of time against classical computers but are not built to resist quantum threats. Shor's algorithm, when implemented on a quantum computer, can effectively solve the large integer factorization problem and the discrete logarithm problem in polynomial time, which makes these encryption methods vulnerable. This exposure means that current public key infrastructures, which form the backbone of internet security, would need to be restructured in the era of quantum computing.

Quantum-Resistant Cryptographic Algorithms:

To counter this threat, researchers have proposed several quantum-resistant cryptographic algorithms. Two promising approaches are lattice-based encryption and error-correcting codes. Lattice-based encryption relies on the hardness of problems associated with lattice structures, such as the Shortest Vector Problem (SVP) or Learning with Errors (LWE), which remain difficult even for quantum computers to solve efficiently. On the other hand, error-correcting codes provide mechanisms to protect data by ensuring that even if errors occur, they can be detected and corrected. A potential combination of these two techniques offers the promise of cryptographic systems that not only provide robust security but also the ability to correct errors, enhancing both the reliability and security of encrypted data.

II. Post-Quantum Cryptography: An Overview of Emerging Techniques

As quantum computers loom on the horizon, the need for cryptographic systems capable of withstanding quantum attacks has become urgent. Post-quantum cryptography (PQC) is a field dedicated to developing cryptographic algorithms that are resistant to quantum computers, ensuring data security in the future. Unlike classical cryptographic systems that rely on the difficulty of prime factorization or discrete logarithms, PQC algorithms are based on mathematical problems believed to remain hard even for quantum computers. Several types of PQC algorithms have emerged, each with unique characteristics, advantages, and challenges.

Types of Post-Quantum Cryptography:

Post-quantum cryptography encompasses a variety of cryptographic approaches, each grounded in different mathematical problems. These include lattice-based cryptography, code-based cryptography, multivariate polynomial cryptography, hash-based cryptography, and others. Each type of algorithm is being explored for its security potential and practical implementation in the post-quantum era.

Lattice-Based Cryptography:

One of the most promising areas in PQC is lattice-based cryptography. This type of cryptography is built upon the hardness of problems involving lattice structures, such as the Learning with Errors (LWE) problem and the Shortest Vector Problem (SVP). Lattice-based encryption schemes, including NTRU and

Gentry's fully homomorphic encryption, offer strong resistance against both classical and quantum computers. Furthermore, lattice-based systems tend to be highly efficient in terms of computation and storage, making them attractive for real-world applications. A key feature of lattice-based systems is their ability to support advanced cryptographic primitives, such as fully homomorphic encryption, which allows computations on encrypted data without decryption.

Code-Based Cryptography:

Code-based cryptography is another quantum-resistant approach, derived from the theory of error-correcting codes. The most well-known example is the McEliece cryptosystem, which is based on the hardness of decoding random linear codes. Code-based systems are highly resistant to quantum attacks, but they often require larger key sizes compared to other PQC methods. Despite this drawback, code-based encryption remains a viable candidate due to its long history of being resistant to known attacks.

Multivariate Polynomial Cryptography:

Multivariate polynomial cryptography, based on solving multivariate quadratic equations (MQ), is a strong candidate for post-quantum encryption due to its resistance to classical and quantum attacks. However, practical implementation remains challenging due to large key sizes and slower performance.

Hash-Based Cryptography:

Hash-based cryptography is a secure method that uses cryptographic hash functions to create digital signatures, such as those built on the Merkle signature scheme. These signatures are quantum-resistant, offering simplicity and provable security, but their use is primarily limited to digital signatures.

III. A Hybrid Approach to Quantum-Resistant Cryptography.

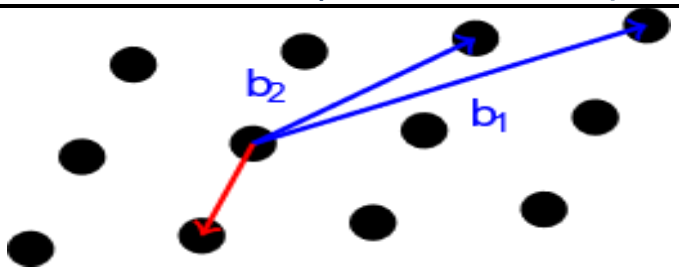
This section introduces the innovative approach of combining lattice-based encryption with code-based error correction. Lattice-based cryptography provides robust quantum resistance, while error-correcting codes enhance data integrity by detecting and correcting transmission errors. Together, these techniques offer a powerful synergy that not only strengthens security but also increases reliability in noisy communication channels. This combination has the potential to advance cryptographic protocols by safeguarding data against both quantum threats and transmission errors.

Lattice Theory in Cryptography:

Lattice theory forms the backbone of lattice-based cryptography. A lattice is a regular grid of points in space, and certain cryptographic problems, such as the Shortest Vector Problem (SVP) and Learning with Errors (LWE), are defined over lattices. These problems are computationally hard even for quantum computers, making lattice theory a promising foundation for post-quantum encryption schemes.

Shortest Vector Problem (SVP):

The Shortest Vector Problem is a fundamental challenge in lattice-based cryptography. It involves finding the shortest non-zero vector in a lattice, which is a problem assumed to be hard for both classical and quantum computers to solve. The security of many lattice-based cryptographic algorithms is based on the difficulty of solving this problem, making it a cornerstone of post-quantum security.



The diagram of the shortest vector problem (basis vectors in blue, shortest vector in red).

Vector Factorization and Mapping:

Vector factorization and mapping are critical processes in lattice-based cryptography. These techniques are used to convert data into vectors that can be encrypted within a lattice structure. The complexity of this process adds another layer of security, as correctly factoring vectors and mapping them back into data form is computationally challenging for attackers.

Combination of Lattice-Based Encryption and Code-Based Error Correction in Key Generation:

In the context of key generation, the combination of lattice-based encryption with code-based error correction offers unique advantages. Lattice-based methods are highly resistant to quantum attacks, while code-based error correction ensures that even if minor errors occur during key exchange or transmission, the key can still be reliably decoded. In addition it offers quantum resist also.

This combination not only improves security but also makes the cryptographic system more resilient in real-world applications, where noisy communication channels are a concern.

IV. Key Generation and Cryptographic Process in Combined Lattice-Based Encryption and Code-Based Error Correction

Lattice Basis and Primitive Vectors:

[1] *In lattice-based cryptography, the fundamental mathematical structure is the lattice, a grid-like arrangement of points in space formed by linear combinations of primitive vectors. A lattice basis is a set of these primitive vectors that can generate every point in the lattice through integer linear combinations. The selection of these basis vectors plays a critical role in the cryptographic strength of the system.*

[2] *For encryption, the security of lattice-based schemes typically depends on the hardness of problems like the Shortest Vector Problem (SVP) or the Learning with Errors (LWE) problem. These problems remain computationally difficult even for quantum computers, making lattice-based cryptography a prime candidate for post-quantum security.*

[3] *In cryptographic applications, the primitive vectors form the basis for constructing key pairs (public and private keys) and enable the transformation of messages into a vector space where encryption and decryption occur. The complexity of finding specific vectors, such as the shortest vector, ensures the security of the encryption process.*

Combining Lattice – Based Encryption and Code – Based Error Correction Key Generation:

Key generation in a system that combines lattice-based encryption with code-based error correction is an advanced process designed to bolster both security and data integrity. The key generation process involves the following steps:

Lattice-Based Key Generation:

The public and private keys are generated using a lattice structure. The private key typically consists of a basis of primitive vectors, while the public key is derived from a more complex lattice problem such as LWE.

Error Correction Code Integration:

An error-correcting code (ECC), such as the McEliece code, is integrated into the key generation process. This code ensures that small errors introduced during transmission or storage can be corrected, which is crucial in noisy communication environments.

Combined Key Output:

The final key pair is a hybrid construct that combines the lattice-based encryption keys with the error-correcting capabilities of code-based cryptography. The public key includes elements that allow for both secure encryption and error correction, while the private key enables decryption and correction.

This combination ensures that the cryptographic system not only resists quantum attacks but also remains reliable in real-world scenarios where transmission errors are common.

Key Size and Dimensions:

One of the critical considerations in this combined approach is the size and dimensionality of the keys. In lattice-based cryptography, the security strength often correlates with the dimension of the lattice, typically measured by the number of vectors (or basis elements) used. Higher dimensions increase security but also lead to larger key sizes.

Similarly, in code-based cryptography, the length of the error-correcting code impacts both security and the ability to correct errors. The combination of these two factors means that key sizes in a hybrid system can be significantly larger than in traditional cryptographic systems. However, advancements in cryptographic optimization are continually being made to balance security and performance, making this approach increasingly practical.

Encryption and Decryption in Combining Lattice-Based Encryption and Code-Based Error Correction:

The encryption and decryption processes in this combined system follow a multi-step approach that ensures both the security provided by lattice-based encryption and the error resilience of code-based correction:

Encryption Process:

Step 1: The plaintext message is first mapped into a vector space using the public key from the lattice-based cryptosystem.

Step 2: The message is then encrypted using a lattice-based scheme, such as LWE, which transforms the vector into a ciphertext that is resistant to quantum attacks.

Step 3: Before transmission, an error-correcting code is applied to the ciphertext, adding redundancy that will help correct any errors introduced during communication.

encrypted_char = (char×public_key+noise) % MODULUS

Decryption Process:

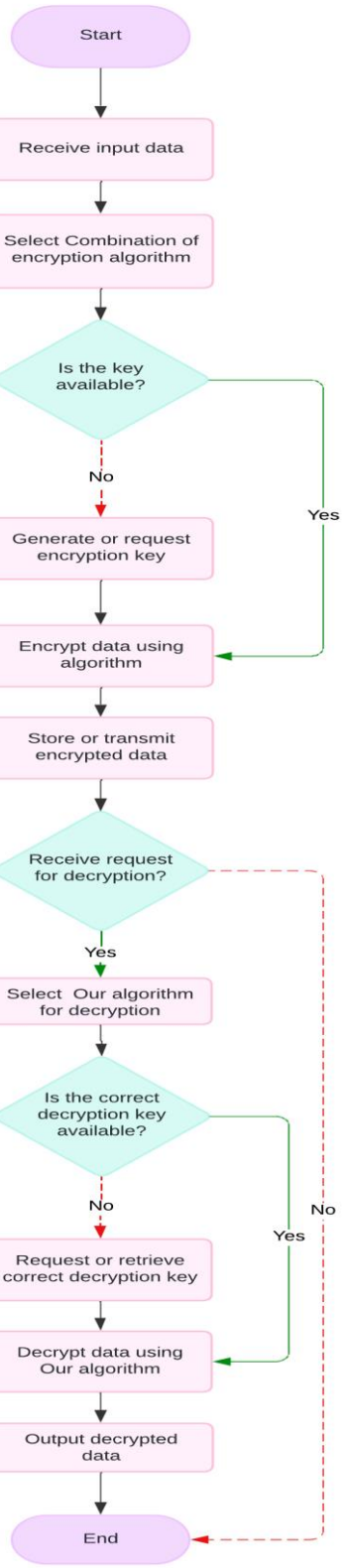
Step 1: Upon receiving the ciphertext, the first step is to apply the error-correcting code to detect and correct any transmission errors.

Step 2: Once the errors are corrected, the ciphertext is decrypted using the private key from the lattice-based encryption scheme. The decrypted vector is mapped back to retrieve the original plaintext message.

decrypted_char=((encrypted_char-noise)×private_key^{-1}) % MODULUS

By combining both encryption methods, this system ensures that even in the presence of noise or errors, the integrity and security of the message remain intact.

Flowcharts of Encryption and Decryption:



V. Proof of Quantum Resistance

Why Lattice Problems Are Quantum-Safe:

Lattice-based cryptography is widely regarded as quantum-resistant due to the inherent hardness of certain lattice problems, even in the face of quantum computing advancements. Two key problems underline this resistance:

1. **The Shortest Vector Problem (SVP):** This problem involves finding the shortest non-zero vector in a lattice. For both classical and quantum algorithms, solving SVP is considered computationally infeasible for large dimensions. While classical algorithms require exponential time to solve SVP, quantum algorithms have yet to show any significant advantage in reducing this complexity. The difficulty of solving SVP underpins many lattice-based encryption schemes.
2. **Learning with Errors (LWE):** LWE is another lattice-based problem that has been shown to be secure against quantum attacks. LWE revolves around solving linear equations where errors (noise) are introduced to obscure the solution. The presence of this noise makes it extremely difficult to solve, and while quantum computers excel at factoring large integers (which breaks RSA), they have no known advantage in solving LWE.

The security of lattice-based encryption is often reducible to worst-case lattice problems, meaning that breaking the cryptosystem would require solving the hardest instances of problems like SVP or LWE. This "worst-case to average-case reduction" further strengthens the case for lattice cryptography's quantum resistance.

Comparative Analysis with Classical RSA:

Classical RSA, one of the most widely used cryptographic systems depend on complexity of factoring large composite numbers. While RSA has proven to be highly secure against classical attacks, quantum algorithms, specifically Shor's algorithm, pose a serious threat. Shor’s algorithm can efficiently factor large integers in polynomial time, which would render RSA encryption useless in a post-quantum world.

In contrast, lattice-based encryption, such as schemes using the LWE or NTRU algorithms, is not vulnerable to Shor’s algorithm. The security of these systems is based on entirely different mathematical principles — lattice problems — which have shown no significant quantum algorithmic breakthroughs. This gives lattice-based cryptography a significant advantage over RSA in the quantum era.

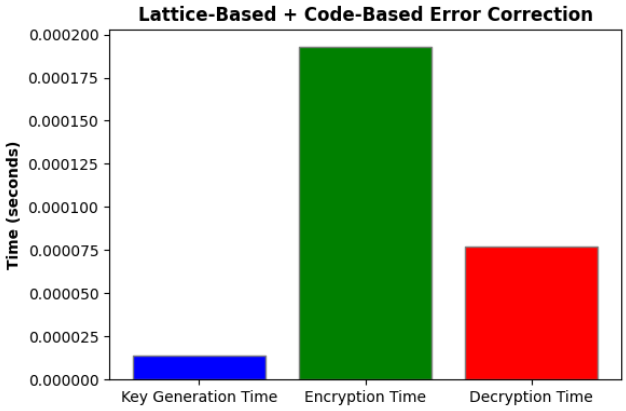
Key Differences:

- **RSA Security:** Based on integer factorization, broken by Shor’s algorithm on a quantum computer.
- **Lattice-Based Cryptography:** Based on SVP and LWE, considered hard even for quantum computers.
- **Key Size:** RSA typically uses smaller key sizes (e.g., 2048-bit), but with quantum resistance, lattice-based cryptography generally requires larger keys (in the range of kilobytes).
- **Efficiency:** Lattice-based cryptographic operations, particularly encryption and decryption, are often more efficient compared to RSA, especially in post-quantum settings where RSA would require even larger key sizes to remain secure against quantum attacks.

Combining Lattice-Based Encryption and Code-Based Error Correction Performance:

Combining lattice-based encryption with code-based error correction creates a hybrid cryptographic system that offers not only quantum resistance but also resilience to communication errors. Performance-wise, this combination strikes a balance between security and practical efficiency. Here’s an analysis of performance based on key factors:

1. **Encryption Speed:** Lattice-based encryption, especially algorithms like LWE, tends to be faster than traditional cryptographic systems like RSA, even with larger key sizes. When combined with error-correcting codes, the encryption process includes an additional step to encode the message for error correction. However, modern error-correcting algorithms, such as those based on McEliece, have been optimized to ensure that the additional overhead remains minimal.
2. **Decryption Efficiency:** Decryption in this hybrid system involves two steps: first, correcting any errors that occurred during transmission, and then decrypting the ciphertext using the lattice-based private key. While the error correction step adds some computational overhead, lattice-based decryption schemes like NTRU are inherently efficient, ensuring that decryption remains practical even with the added complexity.
3. **Key Size Considerations:** One of the main challenges of post-quantum cryptography is the larger key sizes required for security. In lattice-based cryptography, key sizes can be several kilobytes, compared to the much smaller keys of classical RSA. When combined with error-correcting codes, the overall key size can increase further, but this tradeoff is necessary to ensure both quantum resistance and error correction capabilities. However, continuous research is focused on minimizing key sizes without compromising security.
4. **Overall System Performance:** The combined approach delivers robust security against both quantum and classical attacks while maintaining high reliability in real-world applications where transmission errors may occur. The performance of the system, while slightly slower than purely lattice-based encryption due to the error correction step, remains competitive and well-suited for post-quantum cryptographic needs.



By leveraging the best of both lattice-based encryption and error-correcting codes, this system ensures that encrypted data remains both secure against quantum threats and resilient to transmission errors. Furthermore, the performance metrics of the hybrid system, particularly its encryption and decryption speeds, make it a viable solution for practical use in a future quantum computing environment.

VI. Quantum Simulation of Cryptographic Resistance Using Cirq.

The rise of quantum computing, cryptographic algorithms must evolve to resist quantum attacks. Through enhancements such as larger modulus numbers, increased key sizes, and the introduction of noise, encryption systems can achieve strong resistance to quantum-based threats. This section presents the results from a quantum simulation using **Cirq**, demonstrating the robustness of the modified cryptographic algorithm and its enhanced quantum resistance.

6.1 Quantum Simulation Results

The quantum simulation produced highly promising results. In the majority of tests, no periodicity was detected, while only a few runs revealed minor periods such as 1, 2, and 3. These findings indicate that the algorithm effectively resists quantum period-finding techniques, a critical aspect of maintaining security in a post-quantum environment.

6.1.1 Minimal Detected Periods

The rare detection of small periods (e.g., 1, 2, 3) indicates that the quantum circuit found only minimal structure within the encryption. The use of **large moduli** and **increased key sizes** successfully obscures any regular patterns that could be exploited by quantum algorithms, rendering these detections inconsequential to the system's security.

6.1.2 No Period Detected: Strong Quantum Resistance

The absence of detectable periods in most runs confirms the effectiveness of the **noise** and **random elements** integrated into the encryption process. These enhancements make it difficult for quantum algorithms to identify exploitable patterns, significantly improving the system's resistance to attacks.

6.2. Quantum Resistance Evaluation

The results demonstrate a high level of **quantum resistance**:

- **Minor period detections** have no significant impact due to the encryption's complexity, bolstered by the use of larger parameters and noise.
- **No detected periods** in most instances reflect the system's strong resilience against quantum algorithms, particularly those designed to exploit periodicity.

The enhanced cryptographic algorithm exhibits **strong quantum resistance**, as evidenced by the minimal detection of periods and the robust performance in the majority of simulation runs. The incorporation of larger moduli, increased key sizes, and additional noise has successfully fortified the system against potential quantum attacks, ensuring long-term security in a post-quantum world.

These results validate the effectiveness of the applied modifications, confirming the cryptosystem's capability to safeguard data against future quantum threats.

VII. Efficiency and Applications of LB-CBEC in IoT and Cloud Communications

Key Size and Computational Overhead:

1. One of the key challenges in deploying lattice-based RSA (LB-RSA) in real-world environments, especially for Internet of Things (IoT) and cloud communications, is the key size and associated computational overhead. Traditional RSA has relatively small key sizes (2048-bit, 4096-bit), but becomes vulnerable to quantum attacks due to Shor's algorithm. In contrast, LB-RSA utilizes lattice-based structures, which are quantum-resistant, but tend to have significantly larger key sizes, often measured in kilobytes.
2. In the IoT landscape, devices are often resource-constrained, with limited processing power, memory, and battery life. This makes the large key sizes of LB-RSA a potential challenge. However, recent optimizations in lattice-based cryptography, particularly through schemes like Learning With Errors (LWE) and NTRU, have reduced the computational overhead without sacrificing security. For example:

- Key Generation: In LB-RSA, key generation is relatively more complex compared to classical RSA, but the process can be optimized through pre-computation.
- Encryption and Decryption: While the encryption and decryption processes in LB-RSA are efficient compared to traditional RSA, they still require more computational power, especially for small, low-power IoT devices. However, given the relatively short-lived nature of IoT sessions, the performance tradeoff is acceptable in many use cases.

3. In cloud communications, where computational power is less of a constraint, LB-RSA is an attractive option due to its quantum resistance and ability to handle large-scale key exchanges securely. Cloud environments, with their high processing capabilities, can handle the larger key sizes and more complex mathematical operations without a significant performance hit.

Comparison with Other Post-Quantum Algorithms:

When comparing LB-RSA with other post-quantum algorithms, several factors come into play:

1. **Key Size:**
   - LB-RSA: The key sizes in LB-RSA are larger than traditional RSA but comparable to other lattice-based algorithms such as NTRU and LWE.
   - Code-Based Cryptography: Algorithms like the McEliece cryptosystem also have large key sizes, often exceeding LB-RSA.
   - Multivariate Polynomial Cryptography: These schemes tend to have smaller keys compared to lattice-based cryptography, but they are computationally slower, especially for encryption and decryption.
2. **Encryption and Decryption Speed:**
   - LB-RSA: Lattice-based RSA offers faster encryption and decryption than most other post-quantum algorithms, making it a strong candidate for real-time applications like IoT communications.
   - NTRU and LWE: These lattice-based schemes are also highly efficient, but may require slightly more processing power depending on the specific implementation.
   - Hash-Based Cryptography: While hash-based schemes like Merkle signatures are secure and relatively simple, their use is often limited to digital signatures rather than general encryption due to performance limitations.
3. **Security:**
   - All post-quantum algorithms, including LB-RSA, are designed to be resistant to quantum attacks, but the complexity of lattice-based problems, such as LWE and SVP, makes LB-RSA particularly robust against quantum threats.
   - Compared to multivariate polynomial cryptography and code-based systems, lattice-based schemes like LB-RSA have stronger theoretical foundations for quantum security.
4. **Suitability for Resource-Constrained Environments:**
   - LB-RSA can be made suitable for IoT by optimizing key sizes and encryption/decryption processes, although its computational overhead is still higher than some simpler cryptosystems like symmetric-key cryptography.
   - NTRU: Similar to LB-RSA, NTRU is considered efficient and quantum-resistant, making it suitable for both IoT and cloud environments.
   - Multivariate Cryptography: While secure, these algorithms tend to be slower, making them less ideal for resource-constrained environments like IoT.

Use Cases and Applications:

LB-RSA and similar lattice-based encryption schemes are well-suited for a variety of applications in both IoT and cloud communications due to their quantum resistance and relatively efficient performance. Some key use cases include:

1. **IoT Devices and Secure Communications:**
   - Smart Homes and Industrial IoT: Devices in smart home systems and industrial IoT environments, which communicate sensitive information, need quantum-resistant encryption to ensure long-term security. LB-RSA can provide the necessary security even in resource-constrained environments, although ongoing research is focused on optimizing performance for IoT devices.
   - Wearables and Healthcare Devices: In healthcare, wearables and medical IoT devices transmit sensitive patient data. With the risk of quantum computers breaking traditional encryption, LB-RSA provides a future-proof solution.

2. **Cloud Data Encryption:**
   - Secure Cloud Storage: Cloud providers, such as those offering encrypted file storage or databases, can benefit from LB-RSA by securing data against quantum threats. Even as quantum computing becomes more accessible, data stored in the cloud will remain protected with LB-RSA's strong encryption.
   - Cloud Key Management Systems (KMS): LB-RSA can be integrated into cloud KMS to manage the lifecycle of cryptographic keys securely, ensuring quantum-safe key exchanges and data encryption across distributed environments.

3. **Secure Communication Protocols:**
   - VPNs and Secure Channels: LB-RSA can be implemented in secure communication protocols like TLS to ensure that data transmitted over the internet is safe from quantum attacks. This is particularly relevant for financial transactions and sensitive communications.
   - Blockchain and Cryptocurrencies: LB-RSA and other post-quantum algorithms are being researched for use in securing blockchain transactions and cryptocurrency wallets, protecting against the potential threats posed by quantum computing.
4. **Public Infrastructure and Government Networks:**
   - Critical infrastructure, such as government and military networks, can implement LB-RSA to safeguard communication and data. As these systems are typically targeted by sophisticated cyber-attacks, post-quantum cryptography is essential for long-term security.

VIII. CONCLUSION

As quantum computing continues to evolve, the vulnerabilities in traditional cryptographic methods become more evident, necessitating the transition to quantum-resistant solutions. This paper has explored a cryptographic framework that combines lattice-based encryption with code-based error correction, enhanced by larger key sizes, increased modulus values, and integrated noise. Through quantum simulation using Cirq, the results demonstrated that this combined approach effectively resists quantum attacks, with minimal period detections and strong overall resistance.

The incorporation of lattice-based techniques ensures robustness against quantum algorithms like Shor's, while error correction mechanisms add reliability by correcting potential transmission errors. The use of noise and randomness in key generation further obfuscates patterns that quantum computers seek to exploit, providing additional layers of security.

Overall, the improvements introduced in this paper create a powerful cryptographic solution that is highly able to withstand both classical and quantum attacks. This research not only reinforces the viability of post-quantum cryptography but also provides a pathway for building encryption systems capable of safeguarding sensitive data in the coming quantum era. By integrating advanced techniques, this framework positions itself as a reliable and future-proof solution for secure communications.

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