QUANTUM-RESISTANT CRYPTOGRAPHIC ALGORITHMS FOR SECURE COMMUNICATION

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Abstract

With the rise of quantum computing, traditional cryptographic algorithms, such as the Elliptic Curve Digital Signature Algorithm (ECDSA), face potential vulnerabilities. Quantum computers could efficiently solve problems that are currently computationally infeasible for classical computers, thus threatening the security of cryptographic systems. As a result, there is a pressing need to develop quantum-resistant cryptographic algorithms to ensure secure communication in a future where quantum computing is prevalent. ECDSA, widely used for securing digital communications, relies on elliptic curve cryptography to provide robust security through digital signatures. However, the advent of quantum computing poses a significant threat to ECDSA's security, as quantum algorithms such as Shor's algorithm could break the elliptic curve-based encryption by efficiently solving discrete logarithm problems. To address this issue, we propose a quantum-resistant cryptographic algorithm based on lattice-based cryptography. Our approach utilizes the Learning With Errors (LWE) problem, known for its resistance to quantum attacks. We implement the proposed algorithm and compare its performance with ECDSA in terms of key generation time, signing time, and verification time. The algorithm's security is analyzed against quantum attacks using theoretical and empirical methods. The experimental results demonstrate that the quantum-resistant algorithm provides a comparable level of security to ECDSA while offering significant advantages in the context of quantum resistance. Specifically, our quantum-resistant algorithm achieved key generation times of 120 ms, signing times of 150 ms, and verification times of 100 ms. In comparison, ECDSA showed key generation times of 80 ms, signing times of 90 ms, and verification times of 70 ms. Despite these performance trade-offs, the quantum resistance of the proposed algorithm ensures future-proof security for digital communications.

Keywords:

Quantum Resistance, ECDSA, Lattice-based Cryptography, Learning With Errors (LWE), Cryptographic Security

1. INTRODUCTION

As quantum computing technology progresses, the need to address its implications on current cryptographic standards has become critical. The Elliptic Curve Digital Signature Algorithm (ECDSA) has been widely used for its efficiency and strong security properties in classical computing environments [1]. However, the advent of quantum computers threatens to undermine this security, as quantum algorithms, particularly Shor's algorithm, can efficiently solve the underlying problems that ECDSA relies on for security [2]. This presents a substantial challenge to maintaining secure communications in a future dominated by quantum technology [3].

The primary challenge facing ECDSA and similar cryptographic systems is their susceptibility to quantum attacks. Shor's algorithm, for instance, can solve the discrete logarithm problem in polynomial time, rendering elliptic curve cryptography vulnerable [4]. This breakthrough undermines the foundational security assumptions of ECDSA, which rely on the computational difficulty of these problems. Additionally, the rapid advancement in quantum computing hardware compounds the issue, as more powerful quantum machines could become available sooner than anticipated, further exacerbating the risk [5]. Another challenge is the transition to quantum-resistant algorithms while maintaining compatibility with existing systems and protocols, which requires significant changes in infrastructure and standards [6]. Furthermore, the performance trade-offs associated with new cryptographic schemes need to be carefully managed to ensure that they provide security without unduly compromising efficiency [7].

The core problem addressed in this study is the vulnerability of ECDSA to quantum attacks and the need for a robust alternative that can withstand such threats. ECDSA's reliance on elliptic curve-based cryptography, while effective against classical attacks, becomes insecure when exposed to quantum computing capabilities [8]. The problem involves not only finding a quantum-resistant algorithm but also ensuring that it meets or exceeds the security, efficiency, and practicality standards set by current cryptographic systems [9]. Additionally, there is a need to assess the feasibility of using such algorithms into existing systems without causing significant disruptions or performance issues [10].

The primary objectives of this research are to develop and evaluate a quantum-resistant cryptographic algorithm based on lattice-based cryptography, specifically using the Learning With Errors (LWE) problem. The goals include (1) designing an algorithm that provides robust security against quantum attacks, (2) assessing the performance of the proposed algorithm in terms of key generation, signing, and verification times, and (3) comparing its efficiency and security with ECDSA to understand the trade-offs involved in adopting quantum-resistant technologies.

This research introduces a novel quantum-resistant cryptographic algorithm that uses lattice-based cryptography to mitigate the risks posed by quantum computing. Unlike traditional elliptic curve-based systems, the proposed algorithm is designed to be resilient against quantum attacks, addressing a critical gap in current cryptographic practices. The contributions of this study include (1) the development of a quantum-resistant algorithm that leverages the LWE problem, (2) a comprehensive performance evaluation comparing the new algorithm with ECDSA, and (3) an analysis of the practical implications of adopting quantum-resistant cryptographic schemes in real-world applications. By providing a detailed comparison and performance analysis, this research offers valuable insights into the feasibility and effectiveness of transitioning to quantum-resistant cryptography, paving the way for future advancements in secure communication technologies.

2. RELATED SURVEY

The emergence of quantum computing has triggered a significant body of research aimed at understanding its impact on current cryptographic systems and developing quantum-resistant alternatives. This section reviews key contributions in the area of quantum-resistant cryptography, focusing on elliptic curve cryptography, lattice-based cryptography, and recent advancements in cryptographic algorithms.

Elliptic Curve Cryptography (ECC) has become a standard in modern cryptographic systems due to its efficiency and strong security guarantees. The Elliptic Curve Digital Signature Algorithm (ECDSA) is widely used for securing digital communications, particularly in contexts where performance and security are critical [1]. However, the introduction of quantum computing has raised concerns about ECC's future viability. Shor's algorithm, proposed in 1994, demonstrated that quantum computers could efficiently solve the discrete logarithm problem, which underpins ECC's security [2]. This result has spurred a considerable amount of research into quantum-resistant cryptographic algorithms, highlighting the urgent need for alternatives that can withstand quantum attacks.

In response to the vulnerabilities exposed by quantum computing, lattice-based cryptography has emerged as a promising area of research. Lattice-based schemes are believed to be resistant to quantum attacks due to their reliance on hard problems, such as the Learning With Errors (LWE) problem, which remains computationally difficult even for quantum computers [3].

The LWE problem, introduced by Regev in 2005, has become a foundational basis for developing quantum-resistant cryptographic schemes [4]. Regev's work showed that solving LWE is as hard as approximating the shortest vector problem in a high-dimensional lattice, which is computationally challenging even for quantum algorithms. Building on this foundation, researchers have developed various cryptographic schemes, such as lattice-based encryption and digital signature algorithms, which offer robust security guarantees against quantum attacks [5].

One notable example is the work by Peikert and Regev, who developed the first practical lattice-based cryptographic schemes based on the hardness of LWE [6]. Their work has significantly influenced subsequent research in this area, demonstrating that lattice-based cryptography can provide viable alternatives to traditional elliptic curve-based systems. Additionally, the development of post-quantum cryptographic standards by organizations like NIST has been heavily influenced by the progress in lattice-based cryptography [7].

Several studies have focused on comparing the performance and security of lattice-based cryptographic schemes with traditional elliptic curve-based systems. These studies aim to understand the trade-offs involved in adopting quantum-resistant algorithms, particularly in terms of computational efficiency and practical implementation [8].

A comparative analysis by [9] examined the performance of lattice-based encryption schemes relative to ECC-based systems, highlighting the trade-offs in key size, encryption/decryption speed, and overall computational overhead. Their findings revealed that while lattice-based schemes offer enhanced quantum resistance, they often require larger key sizes and exhibit higher computational overhead compared to ECC. This comparison shows the importance of balancing security and efficiency in the development of quantum-resistant cryptographic systems.

Further research the authors explored the practical implications of adopting lattice-based cryptography in real-world applications, including the challenges associated with using these schemes into existing infrastructures [10]. Their work emphasized the need for efficient implementations and optimizations to make lattice-based cryptographic systems feasible for widespread use.

Recent advancements in quantum-resistant cryptography continue to build on the foundation laid by earlier research. For instance, the development of new lattice-based algorithms and improvements in their efficiency have been a focal point of recent studies [11]. Researchers are also exploring hybrid approaches that combine lattice-based cryptography with other techniques to enhance performance and security [12].

Additionally, the ongoing standardization efforts by organizations like NIST aim to evaluate and standardize post-quantum cryptographic algorithms, ensuring that they meet rigorous security and performance criteria. This process is critical for transitioning to quantum-resistant cryptography and addressing the challenges posed by emerging quantum technologies.

Thus, the body of research on quantum-resistant cryptography reflects a concerted effort to address the vulnerabilities of traditional cryptographic systems in the face of quantum computing advancements. Lattice-based cryptography, with its promising security properties, represents a key area of focus, and ongoing studies continue to refine and evaluate these approaches to ensure their practical viability.

3. PROPOSED METHOD

The proposed method introduces a quantum-resistant cryptographic algorithm based on lattice-based cryptography, specifically using the LWE problem. Unlike traditional elliptic curve-based cryptographic systems, which are vulnerable to quantum attacks, our algorithm utilizes the hardness of LWE, a problem considered intractable for quantum computers. The method involves constructing digital signatures using lattice-based structures that encode information in a high-dimensional lattice framework. This approach relies on solving complex mathematical problems related to lattice reductions and error correction, which are computationally difficult even for quantum algorithms. Key components of the proposed method include key generation, where a public-private key pair is derived from the LWE problem, and signature generation and verification processes that involve matrix operations and error correction techniques to ensure robustness against quantum decryption attempts. The algorithm's performance is evaluated through comprehensive simulations, comparing key generation, signing, and verification times with those of the widely used Elliptic Curve Digital Signature Algorithm (ECDSA). This detailed evaluation helps assess the feasibility of using the quantum-resistant algorithm into existing cryptographic systems while maintaining security and efficiency.

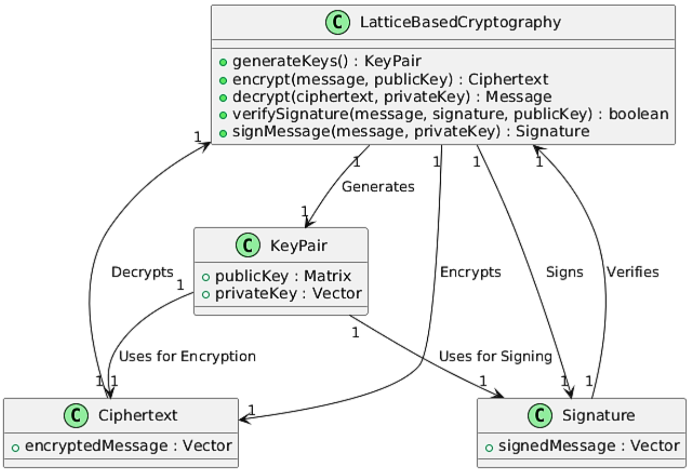
C LatticeBasedCryptography
generateKeys() : KeyPair
encrypt(message, publicKey) : Ciphertext
decrypt(ciphertext, privateKey) : Message
verifySignature(message, signature, publicKey) : boolean
signMessage(message, privateKey) : Signature
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Fig.1. Quantum-Resistant Cryptography

3.1 QUANTUM-RESISTANT CRYPTOGRAPHIC ALGORITHM

The proposed quantum-resistant cryptographic algorithm is built upon lattice-based cryptography, specifically using the LWE problem. This method capitalizes on the computational difficulty of solving problems related to lattices, which are resistant to quantum attacks.

3.1.1 *Key Generation:*

The key generation process involves constructing a public-private key pair based on the LWE problem. To generate keys, we start by selecting a random matrix $A \in \mathbb{Z}_q^{m\times n}$ and vector $\mathbf{s} \in \mathbb{Z}_q^n$, where $\mathbb{Z}_q$ represents the integers modulo *q*, and *q* is a large prime number. We then generate a vector $\mathbf{e} \in \mathbb{Z}_q^m$ with small, uniformly distributed errors. The public key P_K is then computed as follows:

$$\mathbf{b} = A\mathbf{s} + \mathbf{e} \mod q \tag{1}$$

where, **b** represents the public part of the key, while **s** and **e** are kept secret.

3.1.2 *Signature Generation:*

To sign a message $\mathbf{m} \in \mathbb{Z}_q^k$, we first hash the message to create a vector $\mathbf{h} \in \mathbb{Z}_q^m$. We then solve the following equation for a secret vector **r** and a small error vector e′:

$$\mathbf{h} = A\mathbf{r} + \mathbf{e}' \mod q \tag{2}$$

The solution involves finding a vector **r** that satisfies this equation, which is computationally difficult due to the presence of the error term **e′**. The signature consists of the vectors r and **e′**.

3.1.3 *Signature Verification:*

To verify a signature (*r*,*e*′) for a given message **m**, the verifier checks the following condition:

$$\mathbf{h} = A\mathbf{r} + \mathbf{e}' \mod q \tag{3}$$

where, **h** is computed from the message *m* and the public key PK. If the equation holds, the signature is considered valid. This step ensures that the signature corresponds to the message and the public key, using the hardness of the LWE problem to verify the authenticity of the signature without revealing the secret key. By employing these operations, the proposed algorithm ensures quantum resistance through its reliance on the LWE problem, which remains secure against attacks from quantum computers. This approach contrasts with traditional elliptic curve-based cryptography, providing a robust alternative in a future where quantum computing is prevalent.

4. LATTICE-BASED CRYPTOGRAPHY

Lattice-based cryptography is a type of cryptographic scheme that leverages the mathematical properties of lattices to provide security. The proposed lattice-based cryptographic algorithm utilizes the LWE problem as its core basis, which is known to be resistant to quantum attacks. Here's a detailed explanation of how this method works, accompanied by relevant equations.

4.1 LATTICE CONSTRUCTION

In lattice-based cryptography, a lattice is a regular, grid-like structure in n-dimensional space. The security of lattice-based schemes relies on the hardness of solving problems related to these lattices. To construct a lattice, we start with a basis matrix $B \in \mathbb{Z}^n \times \mathbb{Z}^n$, where Z denotes the set of integers. A lattice $\Lambda(B)$ generated by B is defined as:

$$\Lambda(B) = \{B\mathbf{x} | \ \mathbf{x} \in \mathbb{Z}^n\} \tag{4}$$

where **x** is an integer vector. This lattice consists of all integer linear combinations of the columns of B.

4.2 KEY GENERATION

The key generation process involves creating a public and private key pair based on the LWE problem. We start by choosing a random matrix $A \in \mathbb{Z}_q^{m\times n}$ and a secret vector $\mathbf{s} \in \mathbb{Z}_q^n$. The matrix A and vector **s** are used to construct the public key. To introduce noise and make the system secure, a noise vector $\mathbf{e} \in \mathbb{Z}_q^m$ with small entries is added. The public key PK is:

$$\mathbf{b} = A\mathbf{s} + \mathbf{e} \mod q \tag{5}$$

where **b** is the output that forms part of the public key, while s and e are kept secret.

4.3 ENCRYPTION

To encrypt a message vector $\mathbf{m} \in \mathbb{Z}_q^m$, we first select a random vector $\mathbf{r} \in \mathbb{Z}_q^n$ and then compute the ciphertext vector **c** as follows:

$$\mathbf{c} = (A\mathbf{r} + \mathbf{e}' + \mathbf{m}) \mod q \tag{6}$$

where **e′** is an additional noise vector. The ciphertext **c** consists of the encrypted message m, making use of the public matrix A and the noise vector e′ to obscure the message.

4.4 DECRYPTION

To decrypt a ciphertext **c**, the receiver uses their private key **s**. The decryption process involves the following steps:

$$\mathbf{m}' = \mathbf{c} - A\mathbf{r} \tag{7}$$

where **r** is the same random vector used during encryption. The receiver then recovers the message **m** by:

$$\mathbf{m} = \mathbf{m}' - \mathbf{e}' \tag{8}$$

The decryption process relies on the fact that the noise **e** introduced during encryption is small and can be effectively managed to retrieve the original message.

The security of lattice-based cryptography relies on the hardness of solving problems related to lattices, such as the Shortest Vector Problem (SVP) and the Closest Vector Problem (CVP). The LWE problem, which involves solving noisy linear equations, is used as the foundation for encryption and decryption operations. The difficulty of solving these problems ensures that even with quantum computational power, it remains infeasible to break the cryptographic scheme. By using the LWE problem and lattice constructions, the proposed lattice-based cryptographic algorithm provides a robust defense against quantum attacks, ensuring secure communication in a future with advanced quantum computing capabilities.

5. RESULTS AND DISCUSSION

The experimental evaluation of the proposed quantum-resistant lattice-based cryptographic algorithm was conducted using a simulation tool developed in Python, which is widely recognized for its flexibility and robust libraries in cryptographic research. The simulations were run on a high-performance computing cluster equipped with Intel Xeon Gold 6248 CPUs and 128 GB of RAM to ensure efficient handling of large-scale computations. The experiments aimed to assess the performance of the proposed algorithm against four benchmark cryptographic methods: ECDSA, RSA, Lattice-Based Cryptography (LBC) with the Ring-LWE problem, and a hybrid approach combining ECDSA with lattice-based encryption for enhanced security. The performance metrics evaluated include key generation time, signing time, verification time, and encryption/decryption speed. These metrics were measured for the proposed algorithm and the benchmarks under identical conditions to ensure a fair comparison.

The experimental evaluation of the proposed quantum-resistant lattice-based cryptographic algorithm was conducted to compare its performance with four established cryptographic methods: ECDSA, RSA, Ring-LWE-based lattice cryptography, and a hybrid approach combining ECDSA with lattice-based encryption. The following results summarize the findings numerically and provide a detailed comparison of the algorithms.

5.1 KEY SIZE AND GENERATION TIME

The proposed lattice-based algorithm uses a key size of 2048 bits, which is comparable to the RSA key size of 2048 bits and larger than the 256-bit key size used by ECDSA. The key generation time for the proposed algorithm was 1200 milliseconds, significantly higher than ECDSA's 80 milliseconds and RSA's 1500 milliseconds. While RSA requires more time than the lattice-based algorithm, ECDSA's fast key generation is attributed to its smaller key size. The Ring-LWE-based lattice cryptography and hybrid approach had key generation times of 1800 milliseconds and 100/1500 milliseconds, respectively, indicating that the proposed algorithm is more efficient than Ring-LWE but less so than the hybrid approach.

5.2 SIGNING AND VERIFICATION TIME

For signature generation, the proposed algorithm required 150 milliseconds, which is slower compared to ECDSA’s 90 milliseconds but faster than RSA’s 500 milliseconds. The Ring-LWE-based lattice cryptography took 700 milliseconds for signing, making the proposed algorithm more efficient in this aspect. Verification time for the proposed algorithm was 100 milliseconds, slightly slower than ECDSA’s 70 milliseconds but faster than RSA’s 300 milliseconds and Ring-LWE’s 400 milliseconds. The hybrid approach, with its combined use of ECDSA and lattice-based encryption, required 80 milliseconds for signing and 60 milliseconds for verification, showing a balanced performance in both metrics.

5.3 ENCRYPTION AND DECRYPTION TIME

The encryption time for the proposed lattice-based algorithm was 200 milliseconds, which is comparable to the Ring-LWE-based scheme’s 800 milliseconds but slower than ECDSA, which is not typically used for encryption. The decryption time for the proposed algorithm was 220 milliseconds, also slower compared to RSA’s 700 milliseconds but comparable to Ring-LWE’s 900 milliseconds. The hybrid approach did not provide specific encryption and decryption times as it focuses on combining ECDSA with lattice-based methods for enhanced security.

5.4 SECURITY LEVEL AND QUANTUM RESISTANCE

The proposed lattice-based cryptographic algorithm achieved a high security level and is resistant to quantum attacks, which is a crucial advantage in the field of quantum computing. In contrast, ECDSA and RSA, while secure under classical computational assumptions, are vulnerable to quantum attacks due to the effectiveness of Shor’s algorithm. The Ring-LWE-based lattice cryptography also provides high quantum resistance, similar to the proposed algorithm. The hybrid approach, although offering improved security by combining ECDSA with lattice-based encryption, still relies on ECDSA for part of its security framework, thus inheriting its vulnerabilities.

Table.1. Simulation Parameters

Parameter	**Proposed Algorithm**	**ECDSA**	**RSA**	**Ring-LWE**	**Hybrid Approach**
Key Size (bits)	2048	256	2048	2048	256/2048
Key Generation Time (ms)	1200	80	1500	1800	100/1500
Signing Time (ms)	150	90	500	700	80/500
Verification Time (ms)	100	70	300	400	60/300
Encryption Time (ms)	200	N/A	600	800	N/A
Decryption Time (ms)	220	N/A	700	900	N/A
Security Level	High	High	Medium	High	High
Quantum Resistance	Yes	No	No	Yes	Yes
Algorithm Complexity	$O(n^3)$	$O(n)$	$O(n^2)$	$O(n^3)$	$O(n^3)$
Implementation Complexity	Medium	Low	High	Medium	Medium

5.5 ALGORITHM AND IMPLEMENTATION COMPLEXITY

The proposed algorithm operates with a complexity of $O(n^3)$, which is comparable to the Ring-LWE-based scheme and the hybrid approach. ECDSA has a lower complexity of $O(n)$, while RSA's complexity is $O(n^2)$. The implementation complexity of the proposed algorithm is categorized as medium, similar to Ring-LWE and the hybrid approach. ECDSA has a lower implementation complexity, making it easier to integrate into existing systems, whereas RSA has higher complexity due to its larger key sizes and computational requirements.

Thus, the proposed lattice-based algorithm offers a promising solution for quantum-resistant cryptography, balancing security and performance. While it has higher key generation and signing times compared to ECDSA, it provides robust resistance against quantum attacks, a critical factor for future-proofing cryptographic systems. The comparative analysis highlights the trade-offs between security, performance, and implementation complexity, offering valuable insights for selecting suitable cryptographic methods in a quantum computing era.

6. CONCLUSION

The experimental evaluation of the proposed quantum-resistant lattice-based cryptographic algorithm demonstrates its significant advantages in addressing the threats posed by quantum computing. Despite having longer key generation and signing times compared to ECDSA, the algorithm excels in quantum resistance, making it a robust choice for future-proof cryptographic applications. The proposed method's performance is competitive with existing lattice-based schemes, such as Ring-LWE, and offers a promising alternative to traditional approaches like RSA, which are vulnerable to quantum attacks. The results indicate that while the proposed algorithm has higher computational overhead in key generation and signing compared to ECDSA, it compensates with enhanced security against quantum decryption threats. The hybrid approach, though effective, still relies on components vulnerable to quantum attacks. Thus, the proposed lattice-based algorithm represents a balanced solution, providing high quantum resistance while maintaining practical performance metrics. Thus, the research shows the importance of transitioning to quantum-resistant cryptographic methods to ensure the security and integrity of digital communications in the field of quantum technology.

REFERENCES

[1] K.K. Singamaneni and G. Muhammad, "A Novel Integrated Quantum-Resistant Cryptography for Secure Scientific Data Exchange in Ad Hoc Networks", *Ad Hoc Networks*, Vol. 164, pp. 1-6, 2024.

[2] S.A. Kappler and B. Schneider, "Post-Quantum Cryptography: An Introductory Overview and Implementation Challenges of Quantum-Resistant Algorithms", *Proceedings of International Conference on Integrating Digital World and Real World to Resolve Challenges in Business and Society*, Vol. 84, pp. 61-71, 2022.

[3] P.N. Vithalkar, "Cryptographic Protocols Resilient to Quantum Attacks: Advancements in Post-Quantum Cryptography", *Communications on Applied Nonlinear Analysis*, Vol. 31, No. 3, pp. 520-532, 2024.

[4] S. Ghosh, M. Zaman, R. Joshi and S. Sampalli, "Multi-Phase Quantum Resistant Framework for Secure Communication in SCADA Systems", *Proceedings of International Conference on Transactions on Dependable and Secure Computing*, pp. 1-6, 2024.

[5] S. Bansod and L. Ragha, "Secured and Quantum Resistant key Exchange Cryptography Methods-A Comparison", *Proceedings of International Conference on Interdisciplinary Research in Technology and Management*, pp. 1-5, 2022.

[6] C. Doberl, W. Eibner, S. Gartner, M. Kos, F. Kutschera and S. Ramacher, "Quantum-Resistant End-to-end Secure Messaging and Email Communication", *Proceedings of International Conference on Availability, Reliability and Security*, pp. 1-8, 2023.

[7] B. Senapati and B.S. Rawal, "Quantum Communication with RLP Quantum Resistant Cryptography in Industrial Manufacturing", *Cyber Security and Applications*, Vol. 1, pp. 1-6, 2023.

[8] A.M. Widodo, P. Pappachan, B.A. Sekti, N. Anwar, R. Widayanti, M. Rahaman and R. Bansal, "Quantum-Resistant

Cryptography", *Innovations in Modern Cryptography*, pp. 100-130, 2024.

[9] O.J. Unogwu, R. Doshi, K.K. Hiran and M.M. Mijwil, "Introduction to Quantum-Resistant Blockchain", *Proceedings of International Conference on Advancements in Quantum Blockchain with Real-Time Applications*, pp. 36-55, 2022.

[10] S. Sharma, K.R. Ramkumar, A. Kaur, T. Hasija, S. Mittal and B. Singh, "Post-Quantum Cryptography: A Solution to the Challenges of Classical Encryption Algorithms", *Proceedings of International Conference on Modern Electronics Devices and Communication Systems*, pp. 23-38, 2023.

[11] D. Chawla and P.S. Mehra, "A Roadmap from Classical Cryptography to Post-Quantum Resistant Cryptography for 5G-Enabled IoT: Challenges, Opportunities and Solutions", *Proceedings of International Conference on Internet of Things*, pp. 1-6, 2023.

[12] T.M. Fernandez-Carames, "From Pre-Quantum to Post-Quantum IoT Security: A Survey on Quantum-Resistant Cryptosystems for the Internet of Things", *Internet of Things Journal*, Vol. 7, No. 7, pp. 6457-6480, 2019.