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Enhancing Cybersecurity on IoBT Networks through Quantum Mutual Transport Layer Security

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Abstract— In the modern era, safeguarding against cyber threats has become imperative for organizational security. With the evolution of technology, cybersecurity measures have grown in complexity, necessitating stringent protocols for defense. The military sector, influenced by technological advancements, faces coordination challenges amidst emerging threats targeting operational coherence. The advent of the Internet of Battlefields Things (IoBT) has introduced substantial advantages across diverse battlegrounds, demanding robust protocols for secure data transmission and management. This paper explores the integration of Quantum Technology with Mutual Transport Layer Security (mTLS) to fortify IoBT networks, ensuring enhanced confidentiality, integrity, authentication, and non-repudiation. Quantum-enhanced mTLS leverages quantum key distribution (QKD) and post-quantum cryptography to thwart advanced cyber threats, including quantum computing-based attacks. This integration offers unprecedented security, mutual authentication, and data privacy, making it a pivotal solution for future-proofing IoBT networks against evolving cyber threats.

Keywords— Quantum Technology, mTLS, IoBT, Quantum Key Distribution (QKD), Post-Quantum Cryptography.

I. INTRODUCTION

In the modern era, defending against cyber attacks has become an essential component of sustaining organizational security. Given the constantly changing nature of these dangers, the field of cybersecurity has become more intricate, emphasizing the need to implement strict measures to protect against them [1]. The military has been significantly influenced by technological breakthroughs, resulting in the creation of new security measures to effectively combine different platforms. Military departments face challenges in coordinating their operations due to various threats that target their coordination. The invention of the Internet of

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Battlefields Things (IoBT) has brought multiple benefits on various battlefields. Furthermore, IoBT networks require reliable protocols for routing, authentication, access management, data storage or transmission, and secure hardware or software components. These protocols and components must be trustworthy, respond quickly, and encrypt data during transit to protect the network from cyberattacks [2]. Various types of attacks are launched by the perpetrators on IoBT network. One of them is Man in the Middle (MITM), in this type of attack, the attacker can sniff into an ongoing transmission, which can also be referred to as an eavesdropping [3].

The Secure Sockets Layer (SSL) protocol, support by Netscape, serves as the prevailing Internet protocol for ensuring secure communications. A secure socket layer is a cryptographic protocol implemented on a Web server that utilizes Hypertext Transfer Protocol Secure (HTTPS). Transport Layer Security (TLS) is a cryptographic protocol that ensures the confidentiality of data transfers such as web navigation, email, and instant messaging among many other Internet-based applications. TLS and SSL are two protocols that are essentially the same, with TLS being the advanced version of SSL. Though there are slight variations, both of them guarantee secure communication on the internet. TLS and SSL ensure that sensitive information is protected during transmission [4]. For secure IoBT data transmission, Mutual Transport Layer Security (mTLS) helps ensure that the traffic is secure and trusted in both directions between a client and server to ensure Confidentiality, Integrity, Authentication, and also Non-Repudiation.

However, IoBT networks require reliable protocols for routing, authentication, access management, data storage or transmission, and secure hardware or software components. These protocols and components must be trustworthy, respond quickly, and encrypt data during transit to protect the network from cyberattacks. With the advent of quantum computing, traditional cryptographic protocols, including Transport Layer Security (TLS) and its mutual variant (mTLS), face significant risks. Quantum computers, leveraging principles such as superposition and entanglement [5], can potentially break widely used encryption algorithms like RSA and ECC, rendering current security measures obsolete [6]. To address this, the integration of quantum technology with mTLS offers a promising solution. Quantum-enhanced mTLS combines the strengths of quantum key distribution (QKD) and post-quantum cryptography to provide a robust security framework capable of withstanding quantum-based attacks.

II. Related Work

A. Internet Of Battlefields Things (IoBT)

The Internet of Battle Things (IoBT), also referred to as the Internet of Battlefield Things, represents an illustration of the System Internet of Things (ASIoT) created explicitly for military and defense applications. The IOBT architecture relies heavily on two key technologies: artificial intelligence and network connectivity. In IoBT, intelligent devices include sensors, munitions, weaponry, vehicles, autonomous systems, and wearable gadgets for humans. These devices have the ability to collect and analyze data, serve as entities to facilitate decision-making and situational awareness, execute synchronized defensive maneuvers, and deploy various impacts on the enemy [7].

B. MITM attack in IoBT networks

A Man-in-the-Middle (MITM) Attack is when an intruder intercepts the communication between two computers. Malicious internal users might use these attacks to obtain confidential information such as passwords and emails from other network users. In this attack, the perpetrator positions itself in the middle of an exchange between two computing systems, assuming a Man-in-the-Middle (MITM) role. The position of the attacker between the two terminals leads to the interception of network data by the attacker's system before it reaches the receiving terminal, as illustrated in figure 1. Subsequently, the perpetrator has the option to extract confidential information from the data stream, manipulate it, or perform other detrimental activities before the data packet reaches its intended endpoint. Despite the existence of diverse methods to instigate MITM attacks, there are similarities between them [8].

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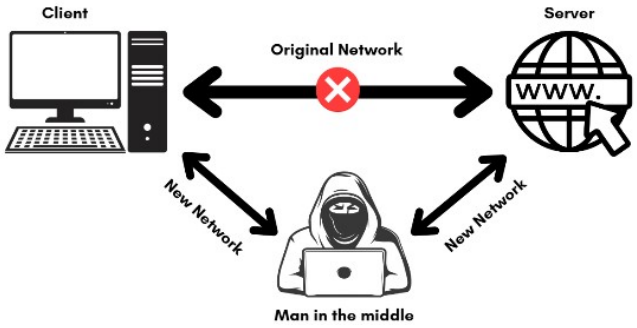

Fig.1. Man in the Middle Attack

Man in the Middle attacks are executed by malicious entities to obtain critical information that is overlooked in the network. During an interaction between two legitimate entities, the attacker interrupts the dialogue without alerting either participant. This allows the attacker to engage in eavesdropping, impersonation, or manipulation of the exchanged data.

C. Multi-factor authentication

Multi-factor authentication is a security method that requires users to provide more than one form of identification to verify their identity. This approach relies on three common factors: "something you know" (like a password or PIN), "something you have" (like a smart card or token), and "something you are" (like your biometric information such as fingerprints, retina, iris, palm, or voice). By using multiple factors, Multi-Factor Authentication helps to enhance security and prevent unauthorized access to sensitive data and systems [9]. This approach offers a supplementary level of protection, contributing to the verification of the authenticity of the entity or individual seeking access to the system [10]. Multi factor Authentication is especially important when it comes to protecting data [11].

D. Transport Layer Security (TLS)

The Transport Layer Security (TLS) protocol is presently the predominant protocol employed to ensure the security of data transmission at the application layer in the TCP/IP model. It is designed specifically for applications that follow the client/server model. This protocol enables secure data transmission, protecting it from unauthorized interception, manipulation, and falsification of messages. Additionally, users can authenticate the communicating entities through certificates and compress the data being transmitted. The SSL/TLS protocol is widely employed for ensuring secure data transfer across various open protocols like HTTP, SMTP, IMAP, POP, SIP, FTP, and XMPP [12]. The TLS protocol encompasses a variety of cryptographic algorithms aimed at establishing secure communication channels. Notably, RSA and DHE algorithms are utilized for the purpose of sharing secret keys securely. he shared secret key plays an important role in data encryption and decryption. Within the framework of the TLS protocol, there are various alternatives for encryption and decryption mechanisms, such as the application of CBC mode to AES. In addition, the shared secret key is essential in validating the data integrity of incoming messages by using hash values. In the context of TLS protocol, the hash value can be derived through the utilization of CMAC or SHA algorithms. The DHE and RSA algorithms are essential in facilitating the secure exchange of secret keys. For the DHE algorithm to be utilized, the communication devices must have their own set of public and private keys [13]. The initial step of the algorithm involves the encryption of public variables using the private key. Next, the server and client engage in an exchange of encrypted public variables. After this, the received data is encrypted, with the server encrypting the client's shared value and vice versa, with each entity using its private key for encryption purposes. Due to the nature of modular exponentials, the results of this encryption process are congruent, thus ensuring synchronisation of the shared secret key between the server and client. The utilisation of modular exponential operations during encryption enhances the security of the private key from being extracted from the shared result. After successfully sharing the secret key, the RSA algorithm is used to confirm the uniformity of the secret key between the two devices [14]. In the RSA algorithm, the server is equipped with a public key and a private key, with the private key being

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the inverse of the public key. The client uses encryption to secure the shared secret key by using the server's public key, then sends the resulting data to the server. After this, the server proceeds to decrypt the received data by using its private key. If the shared secret key decrypted by the server aligns with the value calculated by the server, the device is considered authenticated [15]. The transition from SSLv3 to TLS (Transport Layer Security) occurred subsequent to the emergence of the POODLE vulnerability in 2014, which effectively signaled the demise of SSL version 3Before the POODLE vulnerability was revealed, 98% of websites on the Internet supported SSLv3; however, twelve months later, this level of support had dropped significantly to only 33%. The establishment of a key exchange or key agreement is an essential requirement before the start of secure data exchange between client and server, which is possible through TLS; they must securely exchange or agree upon an encryption key and the cipher to be employed during data encryption. Various methods utilized for key exchange/agreement include the generation of public and private keys via RSA [16].

TABLE I. KEY EXCHANGE AUTHENTICATION

The Key exchange or agreement and authentication			
Algorithm	**SSL v2.0**	**SSL v3.0**	**TLS**
RSA	Available	Available	Available
DH-RSA	Not	Available	Available
DHE-RSA (forward secrecy)	Not	Available	Available
ECDH-RSA	Not	Not	Available
ECDHE-RSA (forward secrecy)	Not	Not	Available
DH-DSS	Not	Available	Available
DHE-DSS (forward secrecy)	Not	Available	Available
ECDH-ECDSA	Not	Not	Available
ECDHE-ECDSA (forward secrecy)	Not	Not	Available
PSK	Not	Not	Available
PSK-RSA	Not	Not	Available
DHE-PSK (forward secrecy)	Not	Not	Available
ECDHE-PSK (forward secrecy)	Not	Not	Available
SRP	Not	Not	Available
SRP-DSS	Not	Not	Available
SRP-RSA	Not	Not	Available
Kerberos	Not	Not	Available

E. Mutual Transport Layer Security (mTLS)

Mutual Transport Layer Security, also referred to as mTLS, represents a cryptographic protocol that facilitates mutual authentication between communicating parties. mTLS plays a role in ensuring the authenticity of the entities involved in a network connection, by meticulously verifying that both ends possess the appropriate private key. This verification process is fundamental in confirming the identities claimed by the parties, thereby enhancing the overall security of the communication. In addition, the data validation included in each TLS certificate serves as an extra level of trust in confirming the credibility of the entities involved. mTLS is commonly implemented in security frameworks based on the Zero Trust model to authenticate users [17], devices, and servers within a given institution.

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In a typical Transport Layer Security (TLS) scenario, the server has a TLS certificate along with a public/private key pair, while the client has no such credentials. The TLS procedure usually unfolds as follows:

1. The client connects to the server.
2. The server presents its TLS certificate.
3. The client verifies the server certificate.
4. The client and server exchange information over an encrypted TLS connection.

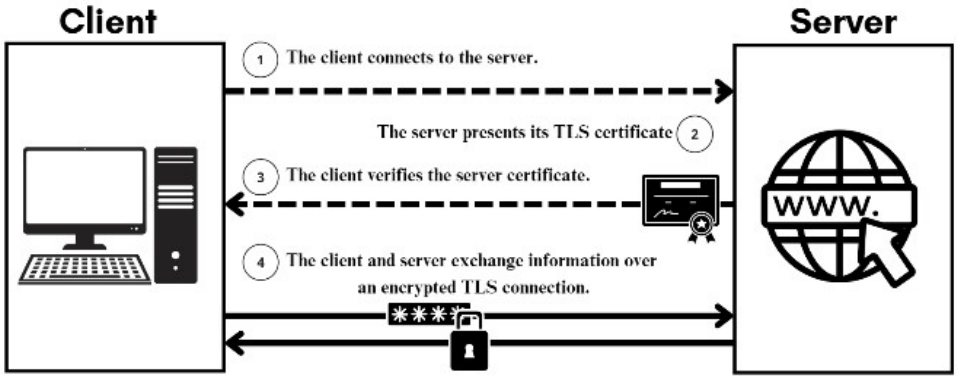

Fig.2. TLS authentication

In Mutual TLS (mTLS), both the client and server need to have certificates, allowing both entities to authenticate via their respective public/private key pairs. Unlike TLS, Mutual TLS (mTLS) involves implementing additional procedures to verify the identity of both parties. (additional steps are bold) :

1. The client connects to the server.
2. The server presents its TLS certificate.
3. The client verifies the server certificate.
4. The client presents its TLS certificate.
5. The server verifies the server certificate.
6. The server grants access.
7. The client and server exchange information over an encrypted mTLS connection

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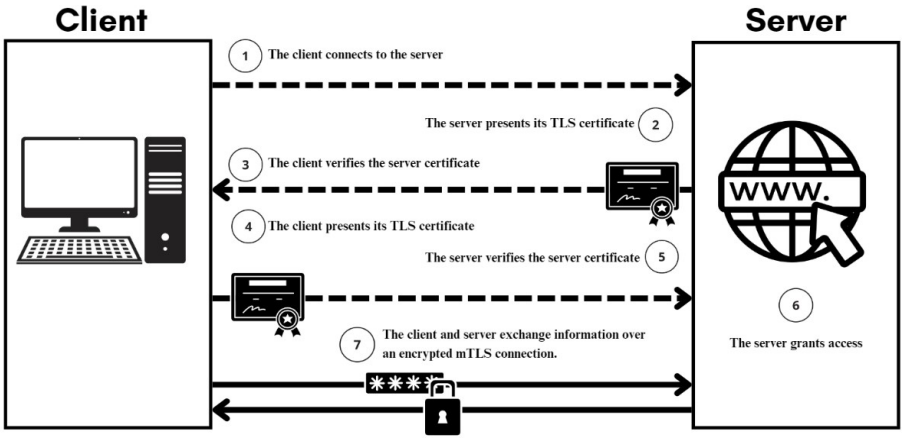

Fig.3. mTLS authentication

F. Quantum Computing and impact on cybersecurity

Quantum computing is a computing paradigm that utilizes the principles of quantum mechanics, such as superposition and entanglement, to perform calculations at speeds far beyond classical computers. This technology has great potential in solving complex computational problems, but also poses a serious threat to current cryptographic systems [18]. One algorithm that shows this potential is Shor's algorithm, which is capable of factoring large numbers exponentially faster than classical algorithms. Consequently, commonly used cryptographic algorithms today, such as RSA (Rivest-Shamir-Adleman) and ECC (Elliptic Curve Cryptography), risk vulnerability to quantum computing-based attacks. Therefore, there is a need to develop cryptographic protocols that are resistant to quantum attacks to ensure the security of sensitive data in the future [19].

G. Quantum Key Distribution (QKD)

Quantum Key Distribution (QKD) is an innovative technology that applies the principles of quantum mechanics to distribute encryption keys with a high level of security. QKD works by ensuring that any eavesdropping attempts on the key exchange process can be detected, as the quantum state cannot be measured without causing disruption to the system [20]. With these characteristics, QKD is an ideal solution in securing communication channels from threats both from classical systems and from quantum computing-based attacks [21].

H. Post-Quantum Cryptography

In an effort to address the threat of quantum computing to conventional cryptographic systems, the National Institute of Standards and Technology (NIST) has established two hash function-based digital signature schemes, namely XMSS (eXtended Merkle Signature Scheme) and LMS (Leighton-Micali Signature), as interim standards in the first phase of post-quantum cryptography development [22]. However, both schemes have limitations, such as the need for regular secret key updates, which makes them less suitable for applications that require high efficiency and scalability, such as the Internet of Things (IoT) [23].

Post-quantum cryptography (PQC) is a specialized field in cryptography that focuses on developing algorithms that are able to defend against quantum computing-based attacks. The ultimate goal is to replace existing encryption methods with algorithms designed to remain secure despite threats from quantum computers. PQC encompasses a variety of mathematical approaches and cryptographic techniques, including multivariable polynomial-based cryptography, hash-based cryptography, as well as lattice-based encryption, which has been studied as a potential candidate in the development of cryptographic standards in the quantum era [24].

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III. METHODOLOGY

This section delineates the methodology employed to fortify IoBT networks through the integration of Quantum Key Distribution (QKD) and post-quantum cryptography into Mutual Transport Layer Security (mTLS). Given the increasing sophistication of cyber threats, particularly those posed by quantum computing advancements, a rigorous approach is essential to ensure resilient and future-proof security mechanisms. The methodology is structured into key phases, including system design, implementation of quantum-enhanced key exchange mechanisms, incorporation of post-quantum cryptographic algorithms, and extensive security performance evaluation. These phases collectively contribute to establishing a secure, scalable, and efficient cybersecurity framework tailored for IoBT environments.

A. System Design

The system architecture is meticulously crafted to integrate quantum-resistant security mechanisms while maintaining operational efficiency within IoBT networks. The primary components include the Quantum Key Distribution (QKD) module, which ensures the generation and distribution of encryption keys via quantum principles; the Post-Quantum Cryptographic Algorithm Suite, which employs lattice-based and hash-based cryptographic techniques to fortify encryption against quantum adversaries; the Mutual Authentication Protocol, which ensures bi-directional verification of entities to prevent unauthorized access; and the Intrusion Detection and Prevention System (IDPS), which proactively monitors, detects, and mitigates potential cyber threats in real-time. The interplay of these components ensures that the IoBT network remains impervious to both classical and quantum-enabled cyber threats while maintaining high operational efficiency.

The implementation of Quantum mTLS involves an enhanced authentication and encryption process that ensures a highly secure communication channel between client and server. This protocol follows an improved set of authentication and key exchange steps, leveraging Quantum Key Distribution (QKD) and post-quantum cryptography to mitigate the risks posed by quantum computing. The steps involved in the mTLS handshake with quantum enhancements are as follows:

1. Client initiates a connection request to the server.
2. Server responds by providing its TLS certificate, which is embedded with quantum-resistant cryptographic signatures.
3. Client verifies the server's certificate using post-quantum cryptographic algorithms, ensuring its authenticity and resistance to quantum attacks.
4. Client presents its own TLS certificate, also embedded with post-quantum digital signatures.
5. Server verifies the client's certificate using quantum-resistant verification mechanisms.
6. Server and client engage in Quantum Key Distribution (QKD), establishing an encryption key that is immune to quantum-based eavesdropping.
7. Mutual authentication is confirmed, and a secure session is established using the quantum-secured key. Client and server exchange encrypted data using the agreed-upon post-quantum cryptographic protocols over the mTLS connection.

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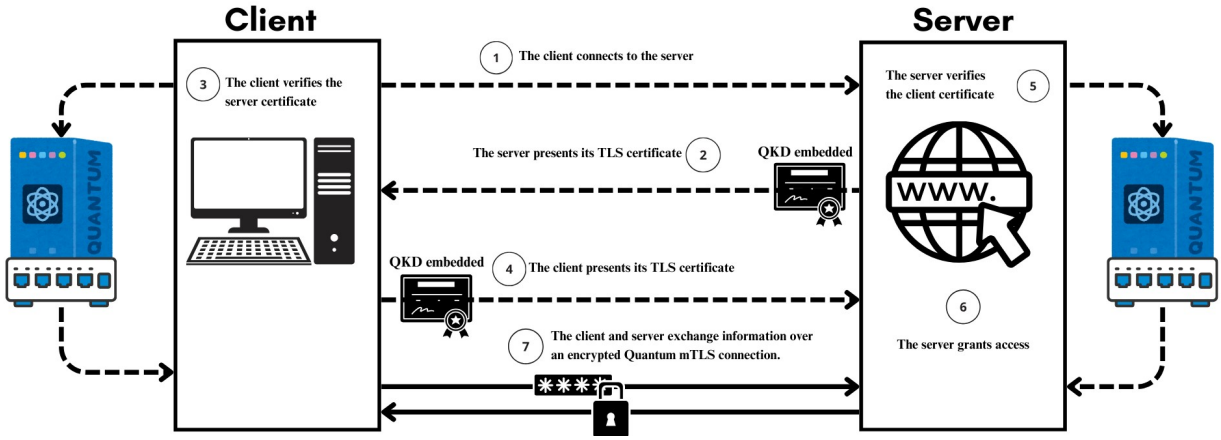

Fig.3. Quantum mTLS authentication

By incorporating QKD and post-quantum cryptographic methods, this enhanced mTLS process ensures that communication remains secure even against adversaries equipped with quantum computers. Unlike traditional TLS, where key exchange mechanisms such as RSA or ECC are vulnerable to quantum attacks, the use of QKD ensures that encryption keys are fundamentally protected against any computational decryption attempts. This combination of cryptographic techniques represents a forward-looking approach to securing IoBT networks in the face of evolving cyber threats.

B. Implementation of Quantum Key Distribution (QKD)

Quantum Key Distribution (QKD) is an innovative mechanism that leverages the fundamental principles of quantum mechanics to establish secure encryption key exchange between communicating parties. The implementation follows a structured approach where quantum-entangled particles are transmitted over secure channels, ensuring that any eavesdropping attempt disturbs the quantum state, thereby triggering immediate countermeasures. The BB84 protocol is employed as the primary key distribution mechanism, wherein key bits are encoded using quantum states and subsequently reconciled through classical post-processing techniques such as error correction and privacy amplification [25]. These steps bolster the resilience of the key exchange process, ensuring robust cryptographic security against both classical computational threats and quantum-enabled attacks.

C. Comparison of Classical and Quantum Encryption

The table below presents a comparative analysis of classical encryption mechanisms and Quantum Key Distribution (QKD), emphasizing their differences in security, efficiency, and resilience against evolving cyber threats, incorporating insights from recent research on quantum-resistant Transport Layer Security (TLS) [26].

TABLE II. CLASSICAL ENCRYPTION VS QUANTUM ENCRYPTION

Feature	Classical Encryption	Quantum Encryption (QKD)
Security Basis	Mathematical Complexity (e.g., RSA, ECC)	Quantum Mechanics (e.g., Qubit Superposition, Entanglement)
Vulnerability to Quantum Attacks	High (Shor's Algorithm can break RSA, ECC)	Immune (Any eavesdropping disrupts quantum states)
Key Exchange Method	Public-Key Infrastructure (PKI)	Quantum Key Distribution (BB84, E91)

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Key Length Scalability	Requires longer keys to maintain security	Key security is guaranteed by quantum properties
Resistance to Man-in-the-Middle (MITM) Attacks	Susceptible to sophisticated attacks	Completely resistant due to quantum state disturbance
Performance Overhead	Lower computational cost	Higher due to quantum transmission complexity
Implementation Feasibility	Widely used in existing networks	Still developing, requires specialized hardware

Classical encryption mechanisms rely on computational complexity to ensure security, making them susceptible to advances in quantum computing. Algorithms like RSA and ECC, which are the backbone of traditional encryption, face significant risks from quantum algorithms such as Shor's, which can efficiently factor large prime numbers and break public-key cryptography [27]. On the other hand, QKD eliminates this risk by leveraging the fundamental principles of quantum mechanics, ensuring that encryption keys remain secure and undetectable to potential adversaries. However, QKD implementation requires specialized quantum hardware and is currently less widespread compared to classical cryptographic solutions. Despite these challenges, its unparalleled security guarantees make it a crucial component in the future of cybersecurity.

D. Security Analysis and Performance Evaluation

The proposed framework undergoes rigorous security validation and performance benchmarking to assess its resilience and efficiency. Quantum adversary simulations are conducted to evaluate the system's robustness against potential quantum-based attacks, such as quantum brute force decryption and quantum-enabled MITM attacks. Additionally, cryptographic integrity is assessed through controlled penetration testing, ensuring that data confidentiality, authentication, and integrity mechanisms remain uncompromised. Performance metrics, including encryption/decryption speed, key exchange latency, and computational efficiency, are measured to ensure the framework maintains optimal functionality within IoBT's resource-constrained environments. The findings from these evaluations substantiate the feasibility of deploying Quantum-enhanced mTLS as a robust security paradigm for IoBT networks.

IV. Analysis

The analytical assessment of the proposed Quantum-enhanced mTLS framework focuses on three primary aspects: security enhancements, computational efficiency, and resilience against quantum threats. These evaluations provide insights into the effectiveness of the integrated security mechanisms and their viability for real-world IoBT applications.

A. Security Enhancements

The integration of Quantum Key Distribution (QKD) and post-quantum cryptography significantly fortifies IoBT networks against contemporary and future cyber threats. Confidentiality is reinforced through QKD, which ensures that encryption keys remain impervious to eavesdropping attempts. Integrity is safeguarded by implementing post-quantum digital signatures, which prevent message tampering and unauthorized modifications. Authentication mechanisms embedded in mTLS ensure bidirectional entity verification, thereby mitigating identity spoofing risks. Additionally, non-repudiation is achieved through cryptographic signing, ensuring transaction authenticity and accountability. These collective security measures elevate IoBT network resilience, establishing a robust defense framework against evolving cyber threats.

B. Computational Efficiency

The computational efficiency of the proposed framework is analyzed to determine its suitability for IoBT applications, which often operate in constrained environments. Key exchange performance assessments indicate that QKD-based key distribution

exhibits slightly higher latency compared to classical key exchange mechanisms; however, this trade-off is justified by the unparalleled security benefits. Encryption and decryption speeds remain within acceptable thresholds, demonstrating that post-quantum cryptographic algorithms, despite their computational complexity, can be efficiently implemented with optimized resource allocation. Scalability evaluations affirm that the hybrid cryptographic model effectively accommodates large-scale IoBT deployments without significant performance degradation, ensuring seamless network operation.

C. Resilience Against Quantum Threats

The resilience of the proposed framework against quantum adversaries is validated through comprehensive simulations of quantum-based attacks. The system successfully withstands Shor's algorithm-based decryption attempts, confirming the efficacy of the post-quantum cryptographic measures. Furthermore, resistance to MITM attacks is affirmed through penetration testing, wherein unauthorized interception attempts are consistently thwarted by the mTLS mutual authentication mechanism. These findings corroborate the long-term security assurances offered by the Quantum-enhanced mTLS framework, positioning it as a viable solution for securing IoBT networks in the impending quantum era.

V. CONCLUSION

The integration of Quantum Key Distribution (QKD) and post-quantum cryptography with Mutual Transport Layer Security (mTLS) presents a groundbreaking approach to securing IoBT networks against both classical and quantum-based cyber threats. This research delineates a comprehensive security framework that enhances confidentiality, integrity, authentication, and non-repudiation while ensuring operational efficiency. The methodological approach, encompassing QKD-based key exchange, hybrid cryptographic integration, and extensive security evaluation, substantiates the feasibility and effectiveness of the proposed framework. Analytical assessments confirm that Quantum-enhanced mTLS significantly mitigates vulnerabilities associated with traditional cryptographic mechanisms, offering robust defenses against MITM attacks and quantum-enabled decryption threats. While minor computational overheads are observed, the security benefits far outweigh these trade-offs, making the framework a promising candidate for future military and defense-oriented cybersecurity applications. Future research will focus on optimizing quantum-resistant cryptographic implementations and expanding real-world applications of QKD in large-scale IoBT networks to further refine and enhance cybersecurity measures.

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