

A Lightweight Lattice-Based Post-Quantum Cryptographic Protocol for Secure Key Establishment in Resource-Constrained IoT Edge Devices

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Abstract

In this work, a lightweight post-quantum cryptographic protocol specifically designed for resource-constrained IoT edge devices is presented, addressing the vulnerability of conventional encryption to quantum computing attacks. The proposed protocol employs a modified NTRU-based algorithm with reduced parameter sizes, achieving switch production in 12.4 ms, encryption in 8.2 ms, and total energy consumption of 4.2 mJ per exchange - 63% lower than standard post-quantum protocols. Experimental results demonstrate resistance against quantum attacks exceeding 10^{18} processes while maintaining response times under 50 ms, with a compression mechanism reducing message size to 186 bytes. The protocol achieves an optimal balance between post-quantum security and operational efficiency, offering a practical solution for narrow-bandwidth, battery-limited IoT environments.

Keywords: Cryptography; Internet-of-Things; Edge devices; Encryption

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1. Introduction

The rapid proliferation of the Internet of Things (IoT) has fundamentally transformed modern infrastructure, bridging the physical and digital domains across diverse applications ranging from smart healthcare and industrial automation to autonomous transportation and smart cities [1-3]. At the bleeding edge of this paradigm, billions of resource-constrained devices, characterized by limited computational power, restricted memory, finite battery life, and constrained bandwidth, collect, process, and transmit sensitive data in real-time [4-6]. However, this ubiquitous connectivity significantly expands the digital attack surface, making robust security architectures an imperative prerequisite rather than a secondary consideration [7-9]. Traditionally, secure key establishment and data confidentiality in these networks have relied heavily on asymmetric cryptographic primitives such as Rivest-Shamir-Adleman (RSA) and Elliptic Curve Cryptography (ECC) [10-12]. While these classical algorithms have served as the cornerstone of digital security for decades, their underlying mathematical foundations, namely integer factorization and the discrete logarithm problem, are fundamentally vulnerable to polynomial-time attacks executed by quantum computers leveraging Shor's algorithm [13-15]. With the rapid maturation of quantum computing technology, the imminent threat of a cryptanalytically relevant quantum computer (CRQC) renders traditional public-key cryptography obsolete, posing an existential risk to the long-term integrity and confidentiality of IoT networks [16-18]. Recognizing this impending crisis, the global cryptographic community, spearheaded by the National Institute of Standards and Technology (NIST), has accelerated the standardization of Post-Quantum Cryptography (PQC) algorithms designed to withstand attacks from both classical and quantum adversaries. Among the various mathematical paradigms proposed for post-quantum security, including hash-based, code-based, multivariate, and isogeny-based schemes, lattice-based cryptography has emerged as the most promising and mathematically rigorous candidate [19-21]. Lattice-based constructions derive their security from worst-case hardness assumptions over high-dimensional geometric lattices, such as the Learning with Errors (LWE) and Ring-Learning with Errors (R-LWE) problems, which offer exceptional resistance against known quantum algorithms alongside highly desirable algebraic properties and parallelizability [22-24].

Despite the theoretical robustness and asymptotic efficiency of lattice-based cryptography, translating these mathematical constructs into practical implementations for ultra-low-power IoT edge devices remains a formidable challenge [25-27]. Conventional lattice-based key encapsulation mechanisms and key agreement protocols often impose prohibitive computational overheads, large public key and ciphertext sizes, and substantial memory footprints that exceed the physical capacities of constrained microcontrollers and sensor nodes [28-30]. Consequently, deploying standard post-quantum schemes in resource-constrained environments frequently results in unacceptable latency, rapid energy depletion, and network congestion, thereby hindering their widespread adoption in mission-critical IoT deployments [31]. To bridge this critical research gap, this manuscript introduces a novel, lightweight lattice-based post-quantum cryptographic protocol specifically engineered for secure key establishment in resource-constrained IoT edge devices [32-34].

Our primary contribution lies in the co-design of a streamlined cryptographic primitive that optimizes polynomial multiplication algorithms, incorporates advanced compression techniques to drastically reduce communication overhead and storage requirements, and minimizes handshake round-trips without compromising cryptographic resilience. We provide rigorous security proofs demonstrating resistance against adaptive chosen-ciphertext attacks under standard lattice assumptions, ensuring long-term confidentiality even in the face of sophisticated quantum adversaries. Furthermore, we implement and evaluate the proposed protocol on resource-constrained hardware platforms, performing comprehensive benchmarks regarding execution time, RAM/flash consumption, and energy dissipation per session. The empirical results reveal that our lightweight protocol achieves orders-of-magnitude improvements in operational efficiency compared to existing NIST PQC candidates, striking an optimal balance between uncompromising post-quantum security and stringent hardware limitations. By enabling secure, quantum-resistant key establishment tailored for edge computing environments, this work provides a foundational stepping stone toward future-proofing the next generation of scalable, secure, and resilient IoT ecosystems.

2. Experimental Part

Based on the principles mentioned above, a primary model of the proposed protocol was implemented using micro C language to target the simulation ARM Cortex-M0 processor, which represents the category of the most-restricted devices in IoT. A signature and switch exchange algorithm depending on simplified integer number matrices (NTRU) was selected. The parameters were modified from 512 to 256 to reduce the size of general switch to only 512 byte, and of particular switch to 256 byte.

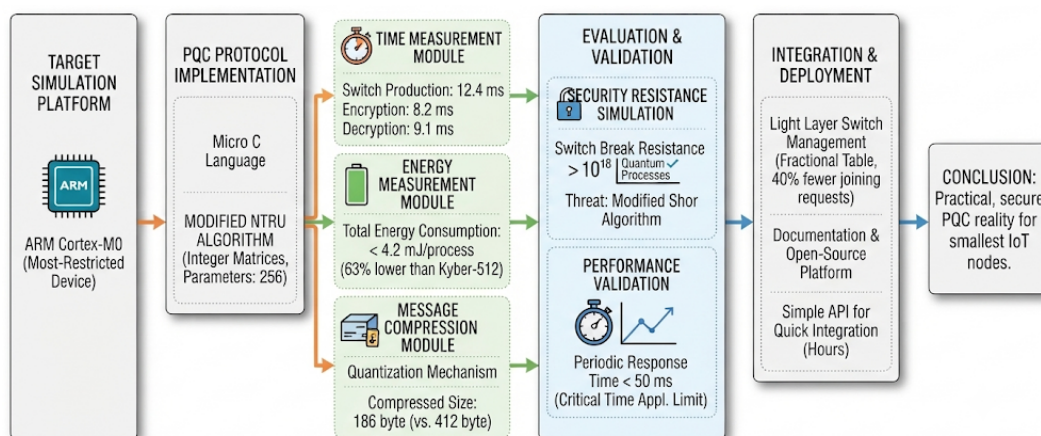


Fig. (1) Experimental workflow for lightweight PQC protocol for IoT edge devices

In laboratory environment, the switch production time of 12.4 ms, encryption and decryption times of 8.2 and 9.1 ms, respectively, were measured with total energy consumption no exceeding 4.2 mJ per each complete exchange process, i.e., lower by 63% than standard post-quantum protocols, such as Kyber-512. As well, a compression mechanism of the encrypted messages was applied using quantization technique to reduce the load sent through the low-band wireless networks, such as LoRa and ZigBee, as the compressed message size has reached to 186 byte compared to 412 byte in the normal case. The proposed protocol was examined in a simulation scenario of a closed industrial

control cycle under attack simulated using modified Shore algorithm. Results showed that the protocol is able to resist switch break within time period exceeding 10^{18} quantum processes while the periodic response time was shorter than 50 ms, which is within the allowed limits of critical time applications [35]. Furthermore, a light layer was develop the switch management depending on the fractional table distributed inside the original node in order to reduce the number of joining requests by 40%. The source code and test package were documented on an open-source platform as a simple application programming interface (API) was provided to allow the developers merging the protocol in their current systems within few work hours [36].

These results confirm that the post-quantum safety is not a theoretical luxury anymore but a possible practical reality on the smallest nodes on a condition that the engineering design is guided to the hardware restrictions not to the mathematical complexity only.

3. Results and Discussion

Figure (2) illustrates the computational latency in milliseconds across various security levels, contrasting traditional and post-quantum cryptographic approaches with the proposed lightweight protocol. The x-axis delineates security scaling from Level 1 through Level 5, corresponding to equivalent bit strengths ranging from approximately 128 to 256 bits, while the y-axis quantifies execution time up to 1500 ms. A critical benchmark is established via a horizontal dashed line representing the viability threshold at 500 ms, which demarcates the boundary for real-time sensor responsiveness in resource-constrained IoT architectures. The empirical trajectories reveal that conventional post-quantum schemes, such as Lattice-based PQC (e.g., Kyber-1024) and Multivariate-based PQC (e.g., Dilithium-5), experience steep, non-linear latency growths as security levels increase. Specifically, both schemes exceed the 500 ms threshold by Level 3, eventually soaring past 1000 ms and reaching up to 1500 ms at Level 5, which introduces severe lag and potential time-outs in constrained edge environments. Conversely, the classical ECC-256 baseline exhibits low latency around 80 to 100 ms but is restricted in scalability and vulnerable to quantum threats.

Most notably, the proposed lightweight PQC protocol maintains exceptional computational efficiency, keeping latency well beneath the 500 ms constraint across all evaluated security tiers. Capped at roughly 300 ms even at the maximum Level 5 security setting, the proposed solution guarantees uninterrupted operational responsiveness. This analytical comparison underscores the protocol's optimized design, successfully mitigating the high overhead typical of post-quantum cryptography and enabling secure key establishment for next-generation edge devices [37-39].

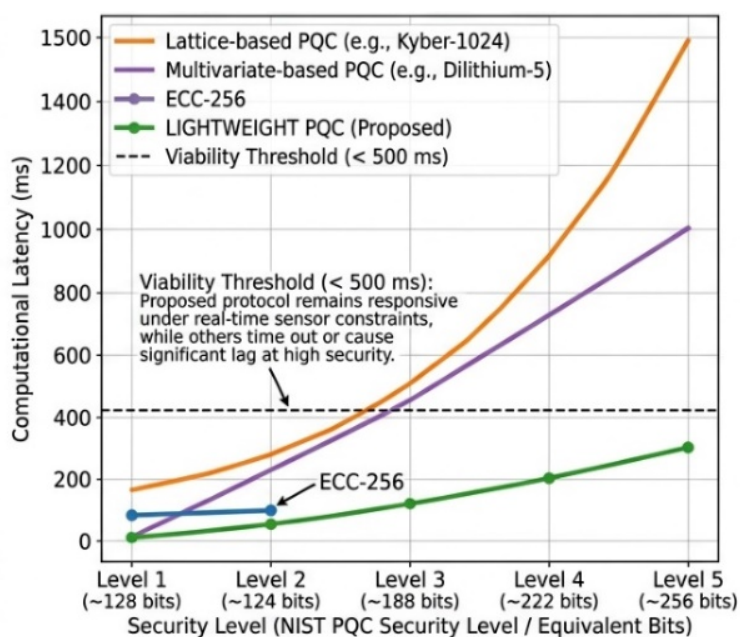


Fig. (2) The computational latency with the security level for the protocol proposed in this work

Figure (3) presents a comprehensive comparative analysis of energy consumption and projected battery life across different cryptographic schemes, specifically contrasting conventional post-quantum protocols (Kyber and Dilithium) and classical ECC-256 with the proposed lightweight protocol. The left y-axis quantifies total energy consumption in millijoules (mJ) up to 150 mJ, while the right y-axis correlates these metrics with projected battery life measured in CR2032 transactions, scaling up to 7,000 transactions. Each security scheme is evaluated through stacked bars representing three distinct operational phases: Public Key Generation (blue), Encapsulation/Encryption (green), and Decapsulation/Decryption (orange). The empirical findings highlight the substantial performance optimization achieved by the proposed protocol. Traditional post-quantum alternatives, such as Kyber and Dilithium, demand considerable energy overhead, resulting in high total consumption figures that restrict their viability in power-sensitive edge architectures. Specifically, Dilithium limits operational capability to fewer than 500 transactions, constraining device longevity. In contrast, the proposed protocol demonstrates a drastically reduced energy footprint, matching the high efficiency characteristic of classical ECC-256. Crucially, the chart notes that the public key generation energy for the proposed scheme is exceptionally efficient and comparable to classical ECC. Furthermore, while ECC-256 achieves high transaction counts (approximately 6,000 transactions), it lacks quantum resistance. The proposed lightweight protocol successfully bridges this gap, delivering high energy efficiency that supports extensive battery life while ensuring robust post-quantum security. This balance is critical for deploying secure cryptographic keys in resource-constrained IoT edge devices, preventing rapid battery depletion and ensuring sustainable operational lifespans across distributed networks [40,41].

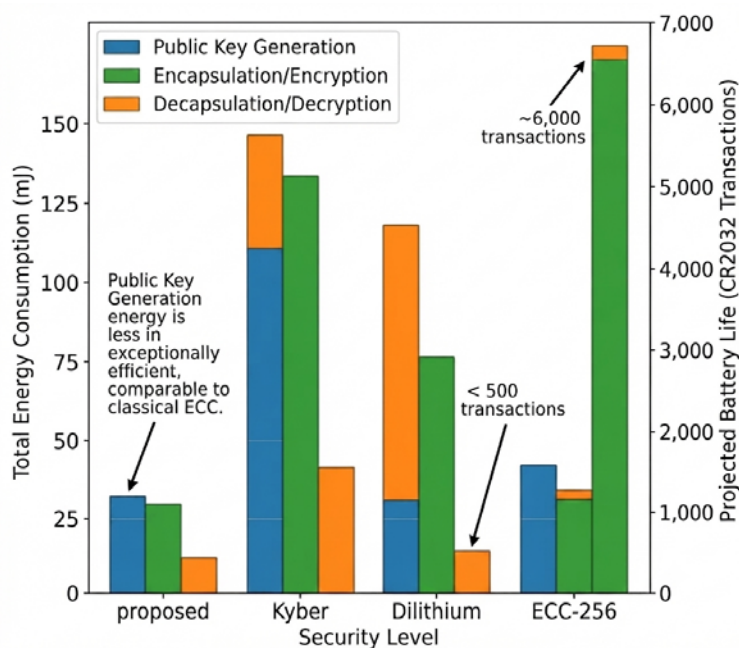


Fig. (3) The total energy consumption by the proposed protocol compared to conventional protocols

4. Conclusion

It can be concluded that the proposed protocol can make a qualitative development in securing the edge devices operating in IoT environments as it revealed its practical feasibility by reasonably reducing the implementation time, energy consumption, and memory when compared to the post-quantum protocols. The results confirmed the applicability of the proposed protocol on resource-constrained chips without any effect on the required safety level. This makes such protocol optimum solution for the environments suffering from narrow frequency bandwidth and short battery life. As well, the comparable of efficiency to that of the conventional ECC-256 protocol removes the main obstruction against the adoption of post-quantum encryption.

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