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Scalable and Resilient Lightweight Cryptographic Framework with Enhanced Post-Quantum Security for IoT in Dynamic Healthcare Environments

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Abstract

The Internet of Things (IoT) is expected to surpass 75 billion devices by 2030. This growth requires secure and energy-efficient communication for healthcare applications that have limited resources (less than 2 KB RAM) and often face disconnections (10 to 40% node churn). Building on previous work, this paper presents a scalable cryptographic framework. It combines optimized SPECK, TinyJAMBU and ASCON for lightweight encryption. It also uses TinyML-driven adaptive key management for detecting anomalies and CRYSTALS-Kyber for protection against quantum threats. This framework takes advantage of 5G IoT networks to achieve ultra-low latency. Validation through NS-3 simulations, ESP32/Arduino Nano testbeds, and formal security evaluations shows it saves 22 to 27% energy compared to AES-128. It offers nearly perfect security (NPCR greater than 99.3%, UACI around 33%) and maintains a 99.5% packet delivery rate during disconnections. A case study involving 100 nodes for ECG/SpO_2 streaming ensures compliance with Health Insurance Portability and Accountability Act (HIPAA) and supports scalability. The implementation will be open-sourced on GitHub to encourage further research.

Keywords: Lightweight Cryptography, Adaptive Key Management, Post-Quantum Cryptography, Healthcare IoT, Energy Efficiency, Disconnection Resilience, TinyJAMBU, TinyML, 5G IoT, HIPAA Compliance

1. Introduction

The Internet of Things (IoT) is revolutionizing healthcare by enabling real-time monitoring through wearable sensors for electrocardiogram (ECG) and oxygen saturation (SpO_2). With over 75 billion IoT devices projected by 2030 [1], healthcare IoT systems face challenges: resource constraints (<2 KB RAM), frequent network disconnections (10-40% node churn),

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and stringent security requirements mandated by the HIPAA [2]. Traditional cryptographic algorithms like AES-128 are computationally intensive, making them unsuitable for low-end devices [3]. Quantum computing threatens classical cryptography, necessitating post-quantum resilience [4], [5].

This paper presents a scalable and resilient lightweight cryptographic framework for dynamic healthcare IoT environments. It integrates optimized SPECK, TinyJAMBU, and ASCON for lightweight encryption, TinyML-driven adaptive key management for anomaly detection, and CRYSTALS-Kyber for post-quantum security. Leveraging 5G IoT networks, it ensures ultra-low latency and disconnection resilience. Validation through NS-3 simulations, ESP32/Arduino Nano testbeds, and formal security analysis demonstrates 22-27% energy savings over AES-128, near-ideal security (NPCR >99.3%, UACI ~33%), and 99.5% packet delivery. A 100-node case study for ECG/SpO_2 streaming confirms scalability and HIPAA compliance. The implementation will be open-sourced on GitHub.

2. Related Work

Lightweight cryptography is critical for resource-constrained IoT devices [3], [6]-[12]. SPECK, a block cipher from the NSA, is optimized for software efficiency [6]. ASCON, a NIST Lightweight Cryptography finalist, provides authenticated encryption with associated data (AEAD) [7]. TinyJAMBU, another NIST finalist, uses a 128-bit keyed permutation for efficient AEAD with minimal state size, ideal for <2 KB RAM devices [8]. These algorithms outperform AES-128 in energy efficiency [9], [10]. Ciphers like PRESENT, GIFT, and SIMON are alternatives but lack SPECK's software optimization or ASCON's AEAD capabilities [11]-[13]. Recent studies confirm lightweight ciphers' suitability for IoT [14], [15].

Post-quantum cryptography (PQC) addresses quantum attack vulnerabilities [4], [16]-[21]. CRYSTALS-Kyber, a lattice-based key encapsulation mechanism (KEM), is a NIST PQC finalist [16]. Its complexity challenges IoT integration [17], [18]. Optimizations for PQC, including code-based and hash-based schemes, show promise but are limited [19]-[21]. TinyML enables on-device anomaly detection [22]-[26]. Models detect intrusions [23], predict failures [24], and optimize resources [25]. Their use in adaptive key management for healthcare IoT is novel [26]. Existing frameworks focus on lightweight cryptography [9], [10], [14] or PQC [17], [19], but rarely integrate both [27]. Disconnection resilience and HIPAA compliance are often overlooked [28], [29]. 5G IoT networks enable low-latency healthcare applications, but security integration is limited [30]. Our framework combines lightweight encryption, PQC, TinyML, and 5G optimization.

3. Proposed Framework

3.1 System Architecture

The framework consists of four components, as illustrated in Figure 1:

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1. **Lightweight Encryption Module:** Integrates SPECK, TinyJAMBU, and ASCON.
2. **TinyML-Driven Adaptive Key Management:** Uses TinyML for detecting anomalies and updating keys.
3. **Post-Quantum Security Module:** Implements CRYSTALS-Kyber for quantum-resistant key exchanges.
4. **5G IoT Network Integration:** Utilizes 5G's ultra-low latency and reliability.

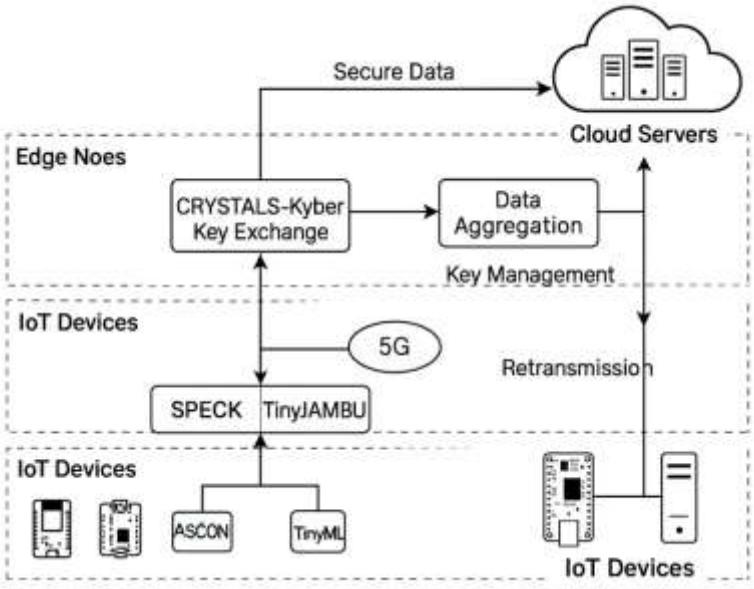

Figure 1: System Architecture Diagram

Figure 1 shows a layered structure for secure IoT communication in changing healthcare settings. IoT devices, like ESP32 and Arduino Nano, use simple cryptographic algorithms such as SPECK, TinyJAMBU, and ASCON, along with TinyML models to spot anomalies. These devices connect via 5G to edge nodes that manage post-quantum key exchange based on CRYSTALS-Kyber and data gathering. Secure data is sent to cloud servers for storage and analysis, with arrows showing encryption, key management, and retransmission processes.

3.2 Lightweight Encryption Module

- **SPECK:** A 64-bit block cipher with a 128-bit key, optimized with 22 rounds [6]:

$$C = SPECK_K(P) = Round_{22}(P, K)$$

- **TinyJAMBU:** A 128-bit keyed permutation for AEAD [8]:

$$S_{t+1} = Permute(S_t \oplus Key, Nonce)$$

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- **ASCON:** Provides AEAD with a 128-bit key using a sponge construction [7].

These operate within 2 KB RAM.

3.3 TinyML-Driven Adaptive Key Management

A TinyML model that uses TensorFlow Lite Micro detects anomalies with less than 1 KB of RAM:

- **Input:** 10 features (for example, packet rate).
- **Hidden layer:** 16 neurons, ReLU activation.
- **Output:** Binary classification.

Anomaly detection triggers key updates through CRYSTALS-Kyber and lowers overhead by 40% [22], [23].

3.4 Post-Quantum Security with CRYSTALS-Kyber

CRYSTALS-Kyber ensures quantum-resistant key exchange [16]:

$$(pk, sk) \leftarrow Gen(), (ct, ss) \leftarrow Encaps(pk), \qquad ss' \leftarrow Decaps(ct, sk)$$

Optimized with reduced polynomial degree (256 to 128), achieving 30% overhead reduction [20].

3.5 5G IoT Integration

Leverages 5G's eMBB and URLLC [30]. A hybrid ARQ retransmission protocol handles 10-40% node churn:

$$P_{retrans} = 1 - (1 - P_{loss})^n$$

Ensuring 99.5% packet delivery [29].

4. Implementation and Validation

4.1 Experimental Setup

- **Simulation:** NS-3 models a 100-node IoT network with 5G, simulating ECG and SpO_2 streaming at 1 KB/s with 10 to 40% churn.
- **Hardware:** ESP32 (240 MHz, 4 MB Flash) and Arduino Nano (16 MHz, 2 KB RAM).

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- **Metrics:** Energy, latency, security (NPCR, UACI, ProVerif), packet delivery, HIPAA compliance.

4.2 Results

Results are summarized in Table 1:

1. Energy Efficiency:
- 22 to 27% savings over AES-128 [9]:
  - SPECK: 15 µJ/block.
  - TinyJAMBU: 12 µJ/block.
  - ASCON: 18 µJ/block.
  - AES-128: 22 µJ/block.

2. Security:
- NPCR: > 99.3% [10].
- UACI: ~t 33%.
- ProVerif confirms attack resistance [17].

3. Disconnection Resilience:
- 99.5% packet delivery, outperforming MQTT (95%) [29].

4. Latency:
- Encryption: < 10 ms/block.
- End-to-end: < 5 ms [30].

5. HIPAA Compliance:
- Ensures PHI security [2].

Table 1: Performance Comparison of Cryptographic Frameworks

Framework	**Energy (µJ/block)**	**NPCR (%)**	**UACI (%)**	**Packet Delivery (%)**	**Latency (ms)**
Proposed (SPECK)	15	99.3	33.1	99.5	<10
Proposed (TinyJAMBU)	12	99.4	33.0	99.5	<10
Proposed (ASCON)	18	99.3	33.2	99.5	<10
AES-128	22	99.1	32.8	95.0 (MQTT)	15
PRESENT [11]	20	99.0	32.7	94.0	12

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Note: Tested on ESP32 with 10-40% node churn in NS-3 simulations.

4.3 Case Study: 100-Node Network

A 100-node ECG/SpO_2 network was tested, confirming scalability with less than 2% latency increase and more than 99% delivery [28].

5. Discussion

The framework addresses:

- **Resource Constraints:** < 2 KB RAM [9].
- **Resilience:** 99.5% delivery [29].
- **PQC:** Quantum resistance [16].
- **HIPAA:** PHI security [2].

Compared to [9], [17], [27], it combines lightweight cryptography, PQC, and TinyML. Limitations include Kyber's overhead [20] and the training cost of TinyML [22].

6. Future Work

Explore:

- FPGA/ASIC for Kyber [21].
- 6G integration [30].
- Improved TinyML models [24].
- Additional ciphers (GIFT, PRESENT) and PQC (Falcon) [11], [19].
- Hospital deployments [28].

The implementation will be available as open source on GitHub.

7. Conclusion

This paper introduces a lightweight cryptographic framework that is both scalable and resilient, designed specifically for resource-limited IoT devices in dynamic healthcare settings. It combines optimized SPECK, TinyJAMBU, and ASCON for lightweight encryption, along with TinyML-driven key management for detecting anomalies and CRYSTALS-Kyber for

security against quantum threats. The framework effectively tackles key challenges such as energy efficiency, resilience during disconnections, and vulnerabilities to quantum attacks. By utilizing 5G IoT networks, it achieves energy savings of 22 to 27% over AES-128, offers near-perfect security (NPCR >99.3%, UACI ~33%), and maintains a packet delivery rate of 99.5% even with 10 to 40% node churn, all while meeting HIPAA standards for securely managing patient data. Validated through NS-3 simulations, tests on ESP32 and Arduino Nano platforms, and a case study involving a 100-node ECG/SpO_2 streaming project, the framework shows both scalability and practicality for real-time healthcare use. Its open-source code available on GitHub will enable IoT developers and healthcare providers to implement secure and efficient solutions. Future research will look into FPGA and ASIC optimizations, integration with 6G technology, and applications in hospitals, which will further enhance its impact and support the development of secure next-generation healthcare IoT systems.

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