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Data Security in Internet of Things Using Customized Cryptography Algorithm

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ABSTRACT

The rapid expansion of the Internet of Things (IoT) has led to the generation of vast volumes of diverse, real-time, and often highly sensitive data across sectors such as healthcare, smart homes, and industrial automation [1], [2]. Although IoT devices provide significant benefits in terms of convenience and operational efficiency, their inherent resource limitations make them susceptible to a wide range of cyber threats [3], [4]. To address these vulnerabilities, this study introduces a customized lightweight cryptographic algorithm specifically designed for IoT ecosystems. The proposed approach integrates the advantages of a hybrid encryption model—combining both block cipher and stream cipher principles with an optimized key scheduling mechanism—to achieve an effective balance between security robustness, computational speed, and energy efficiency [5]–[7]. Experimental evaluations demonstrate that the algorithm delivers superior throughput, lower processing overhead, and stronger resistance to prevalent cryptographic attacks when compared to established IoT encryption standards such as AES-128 and PRESENT [8]–[10].

Keywords—IoT Security, Lightweight Cryptography, SPN, Key Scheduling, AES, PRESENT, SPECK.

1. Introduction

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The Internet of Things (IoT) has rapidly evolved into a critical part of modern life, connecting billions of devices such as smart home appliances, industrial sensors, wearable health monitors, and autonomous vehicles. These devices continuously collect, process, and exchange large volumes of sensitive data—ranging from personal health information to industrial control commands—over various communication networks.However, the **pervasive connectivity** and **resource-constrained nature** of IoT devices make them highly vulnerable to a wide range of cyber threats, including eavesdropping, data tampering, device impersonation, and denial-of-service attacks. Unlike traditional computing systems, IoT devices often have limited processing power, memory, and battery life, which makes implementing robust security solutions more challenging. **Data security** in IoT focuses on ensuring **confidentiality**, **integrity**, and **availability** of data while maintaining **authentication** and **privacy**. Achieving this requires a combination of lightweight cryptographic algorithms, secure communication protocols, access control mechanisms, and device-level security measures. As IoT applications expand into mission-critical domains like healthcare, transportation, and smart grids, the demand for efficient, scalable, and future-proof security solutions becomes increasingly urgent.

1.1 Background

The Internet of Things (IoT) is vastly reshaping how devices, systems, and services interact, enabling seamless connectivity across domains like healthcare, smart cities, transportation, and industrial automation. IoT systems rely heavily on real-time data acquisition, transmission, and analysis, catalyzing operational improvements, smarter decision-making, and enhanced user experience. Global forecasts anticipate that the number of IoT-connected devices could reach approximately **40 billion by 2030**, reflecting an unprecedented surge in heterogeneous and often sensitive data [1] [2].However, this connectivity comes at a cost. IoT ecosystems are increasingly exposed to security threats—including data interception, unauthorized access, device spoofing, and man-in-the-middle (MITM) attacks—stemming from their distributed architecture and device heterogeneity. Compounding these risks is the fact that most IoT devices are designed with limited processing power, low memory, and constrained energy budgets, making them especially susceptible to cyber threats [3] [4].

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1.2 Problem Statement

Traditional cryptographic algorithms such as AES and RSA, though robust, demand substantial computational and memory resources, resulting in increased latency, higher energy consumption, and reduced device lifespan in IoT settings. Furthermore, the coexistence of diverse communication protocols (e.g., Zigbee, LoRaWAN, MQTT, CoAP) complicates interoperability and widens the potential attack surface. This underscores an urgent need for **lightweight cryptographic solutions** that strike a pragmatic balance between security strength and resource efficiency to safeguard IoT data without hampering system performance.

1.3 Importance of Cryptography in IoT

Effective cryptographic schemes underpin the trustworthiness of IoT systems by providing:

- **Confidentiality**: Ensuring that information remains accessible only to authorized entities.
- **Integrity**: Preventing data tampering during transmission or storage.
- **Authentication**: Verifying device or user identities to counter impersonation attacks.
- **Non-repudiation**: Blocking denial of actions taken within the system.

Given the sensitive and pervasive nature of IoT data flows, cryptographic systems must be tailored for constrained environments while remaining resistant to advanced threats such as side-channel and cryptanalytic attacks.

1.4 Research Gap

Current cryptographic options for IoT fall into two main categories:

- **Heavyweight algorithms** (e.g., AES, RSA, ECC) that deliver high security but are impractically resource-intensive for constrained devices.

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- **Lightweight algorithms** (e.g., PRESENT, SPECK, Simon) that are computationally efficient but may not provide sufficient protection against evolving attack vectors, especially in the context of quantum-enabled threats.

Most existing research focuses exclusively on either block cipher or stream cipher models. There remains a gap in hybrid approaches that could potentially blend the strengths of both paradigms while minimizing their inherent limitations.

1.5 Objective

This research sets out to craft a customized lightweight cryptographic algorithm optimized for IoT environments. The design aims to harness the speed of stream ciphers, the structure and diffusion efficiency of block ciphers, and a refined key scheduling mechanism, delivering strong security, high throughput, and minimal resource usage.

1.6 Contributions

This paper makes the following key contributions:

1. **Algorithm Design:** A novel hybrid lightweight cryptographic algorithm integrating block cipher and stream cipher features with dynamic key scheduling.
2. **Performance Evaluation:** Comparative benchmarking against AES-128, PRESENT, and SPECK, measuring parameters like encryption/decryption time, memory usage, power consumption, and throughput.
3. **Security Validation:** Rigorous testing through statistical analysis, avalanche effect measurements, and resilience assessments against differential, linear, and brute-force attacks.

2. Literature Review

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2.1 Existing IoT Security Approaches

IoT security relies heavily on cryptographic algorithms that ensure data confidentiality, integrity, authentication, and non-repudiation. The most widely adopted algorithms can be categorized as follows:

- **AES-128:**AES-128 is a symmetric block cipher standardized by NIST, offering strong security and resistance against most known cryptographic attacks. Its **128-bit key size** provides a robust security margin, but it is computationally intensive, making it less suitable for severely resource-constrained IoT devices.
- **RSA(Rivest–Shamir–Adleman)** RSA is a widely used asymmetric encryption scheme based on the difficulty of factoring large integers. While offering strong security and digital signature capabilities, RSA requires large key sizes (≥2048 bits) and high computational overhead, resulting in **high power consumption** and **slow execution** in IoT environments.
- **ECC:** ECC achieves equivalent security to RSA with smaller key sizes, reducing computational load. However, even ECC remains relatively heavy for ultra-low-power IoT devices and may still be susceptible to side-channel attacks without careful implementation.
- **PRESENT:** PRESENT is a lightweight block cipher standardized under ISO/IEC 29192, designed for constrained devices. It uses a **64-bit block size** and **80/128-bit keys**, offering low power consumption and small memory footprint. However, it provides slower throughput compared to some stream ciphers and has a smaller security margin against advanced attacks.

Algorithm	Strengths	Limitations in IoT Context
AES-128	High security; well-studied	Heavy in computation, energy, and memory
RSA	Secure key exchange, digital signatures	Very resource-intensive, slow for IoT
ECC	Smaller keys than RSA; efficient	Still heavy; susceptible to side-

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Algorithm	Strengths	Limitations in IoT Context
		channel attacks
PRESENT	Low power and compact design	Lower throughput; limited security margin

2.2 Lightweight Block Ciphers vs Stream Ciphers

- **Lightweight Block Ciphers** (e.g., PRESENT, Simon, SPECK) operate on fixed-size blocks of data and use multiple rounds of substitution and permutation . They generally offer strong diffusion properties but can introduce latency when encrypting small, real-time IoT data packets.
- **Stream Ciphers** (e.g., Trivium, Grain, Salsa20) encrypt data bit-by-bit or byte-by-byte, offering low latency and high throughput for streaming applications. However, they often rely heavily on key/IV management and can be vulnerable if reusing keystreams. A hybrid approach combining both paradigms could yield better performance and security trade-offs in IoT contexts.

2.3 Symmetric vs Asymmetric Trade-offs

- **Symmetric cryptography** (e.g., AES, PRESENT) uses the same key for encryption and decryption, offering fast execution and low computational requirements but facing challenges in secure key distribution across large-scale IoT networks [3] [4].
- **Asymmetric cryptography** (e.g., RSA, ECC) uses public-private key pairs, simplifying secure key exchange but introducing significantly higher computational complexity. For IoT, symmetric cryptography (possibly with asymmetric-assisted key exchange) remains the most practical choice [5] [6].

2.4 Challenges with Existing Algorithms

Despite significant advancements in IoT cryptography, several limitations persist:

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1. **High Power Consumption** – Many existing algorithms, particularly RSA and AES-128, require multiple computationally expensive rounds, draining battery-operated IoT nodes quickly [7].
2. **Large Memory Footprint** – Heavy algorithms consume substantial RAM and flash storage, limiting firmware upgrades and multi-function capabilities in small IoT devices.
3. **Vulnerability to Side-Channel Attacks** – Physical attacks exploiting power consumption, electromagnetic emissions, or timing analysis remain a serious threat for embedded IoT devices [8].

2.5 Recent Research Trends

Emerging research is focused on addressing these challenges through innovative approaches:

- **Lightweight Cryptography Standardization** – ISO/IEC 29192 defines standardized lightweight cryptographic algorithms, including PRESENT, CLEFIA, and LEA, optimized for constrained devices. NIST's Lightweight Cryptography Project (finalized in 2023) has also identified ASCON as a recommended algorithm for authenticated encryption in IoT [3] [4].
- **AI-Assisted Cryptanalysis** – Machine learning techniques are increasingly used to detect cipher weaknesses, evaluate algorithm randomness, and identify potential attack patterns at early stages of cipher design [7].
- **Post-Quantum Cryptography (PQC) Adaptation for IoT** – With the rise of quantum computing, algorithms based on lattice, hash, and multivariate polynomial problems are being explored for IoT security. However, their computational demands still exceed the capabilities of many IoT nodes, driving research into lightweight PQC adaptations [5].

3. Proposed Methodology

3.1 System Architecture

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The proposed security framework is designed to ensure **confidentiality, integrity, and efficiency** for data generated and transmitted by IoT devices. The architecture integrates a **customized lightweight cryptography algorithm** into the IoT communication workflow, optimized for low-power and resource-constrained environments [4] [5].

3.1.1 Input Layer

The system accepts continuous **IoT data streams** from sensors, actuators, and embedded controllers.

- **Data Types:** Numerical sensor readings (temperature, pressure, humidity), event triggers, control commands, and status logs.
- **Transmission Protocols:** Compatible with IoT communication standards such as MQTT, CoAP, Zigbee, and LoRaWAN.
- **Packet Handling:** Input data is segmented into fixed-size **encryption blocks** (e.g., 64 or 128 bits), with padding applied where necessary to maintain structural integrity.

3.1.2 Encryption Module

The encryption engine is based on a **hybrid Substitution–Permutation Network (SPN)** architecture, incorporating **dynamic key scheduling** to enhance security without imposing excessive computational burden.

Core Components:

1. **Substitution Layer:**
    - Utilizes a **reduced set of lightweight S-boxes** with high non-linearity to resist linear and differential cryptanalysis.
    - S-box operations are precomputed and stored in minimal memory space for fast lookup.
2. **Permutation Layer:**

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- Performs bit-level and byte-level shuffling to maximize diffusion across the block.
- Uses a fixed permutation pattern optimized for hardware efficiency while maintaining high avalanche effect.

3. **Dynamic Key Scheduling:**
   - Keys are generated per session using a pseudo-random function seeded by a **randomized Initialization Vector (IV)**.
   - Prevents key reuse attacks by ensuring that each encryption session uses a unique subkey sequence.
4. **Reduced Rounds for Efficiency:**
   - Implements fewer rounds than traditional ciphers (e.g., 8–12 instead of AES's 10–14), reducing execution time while maintaining adequate security margins for IoT-specific threat models.
5. **Hybrid Block–Stream Operation Mode:**
   - Operates in a **CTR-like mode** to allow parallel encryption of blocks, increasing throughput for streaming IoT data.

3.1.3 Decryption Module

The decryption process mirrors the encryption sequence in reverse order:

- Inverse permutation and substitution steps are applied using the same **dynamic key schedule**.
- IVs are synchronized between sender and receiver to ensure correct decryption.
- Lightweight error detection is incorporated to identify transmission errors or malicious tampering.

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3.1.4 Key Features of the Proposed System

The proposed customized cryptographic algorithm incorporates several design optimizations to address the unique challenges of IoT environments. It features a **variable key length** capability, supporting keys from 64 to 128 bits, enabling users to strike an optimal balance between security strength and resource consumption based on application needs. By employing a **reduced number of S-boxes**, the algorithm significantly minimizes memory usage while retaining strong resistance against common cryptanalysis techniques, including linear and differential attacks. A **randomized initialization vector (IV)** is generated for each communication session, enhancing freshness and preventing replay or pattern-based attacks. Designed for **low overhead**, the algorithm is optimized for embedded microcontrollers such as ARM Cortex-M, ESP32, and Raspberry Pi Pico, thereby ensuring minimal impact on both system performance and energy consumption. Furthermore, its **scalable architecture** allows seamless integration into diverse IoT deployments, ranging from single-node devices to large-scale networks with gateway-based data aggregation, making it a versatile and future-ready solution for secure IoT communication [12] [13].

4. Implementation & Testing

4.1 Tools and Development Environment

The proposed customized lightweight cryptographic algorithm was developed and evaluated through a dual-language implementation strategy, utilizing **Python** for rapid prototyping and **C/C++** for optimized embedded system deployment. This approach ensured both functional validation in a simulation environment and efficient execution on constrained IoT hardware. For hardware testing, two representative platforms were employed: the **Raspberry Pi 4 Model B** (quad-core Cortex-A72, 1.5 GHz, 4 GB RAM) for high-level functional testing and performance benchmarking, and the **ESP32 development board** (dual-core Xtensa LX6, 240 MHz, 520 KB SRAM) for low-power, resource-limited IoT evaluations. The software workflow incorporated **Python 3.11** for algorithm prototyping, statistical validation, and throughput testing, while

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C/C++ (Arduino IDE and PlatformIO) facilitated embedded firmware deployment. **Power efficiency** was measured using the INA219 power sensor module for real-time voltage and current monitoring, and **performance profiling** was conducted via the Python *time* module, Arduino's *millis()* function, and the Linux *perf* utility for CPU usage tracking [14]. This integrated testing framework enabled a comprehensive assessment of the algorithm's computational performance, energy consumption, and scalability in diverse IoT contexts (Zhang et al., 2023; Kumar & Gupta, 2024).

4.2 Test Dataset

The evaluation was performed using both real-world IoT sensor readings and simulated telemetry data to ensure generalizability:

- **Real Data:** Collected from DHT22 (temperature/humidity), BMP280 (barometric pressure), and PIR (motion) sensors [15].
- **Simulated Data:** Generated using Python scripts to emulate large-scale telemetry (e.g., smart city traffic sensors, environmental monitoring).
- **Data Characteristics:** Included both small, high-frequency packets and larger, aggregated data blocks to test performance under different communication loads [14].

4.3 Evaluation Metrics

The algorithm was tested against **AES-128, PRESENT, and SPECK** for a comprehensive performance and security comparison.

1. **Encryption/Decryption Time** :To evaluate execution efficiency, the encryption and decryption times were measured in milliseconds (ms) for varying payload sizes of 64 bytes, 256 bytes, 1 KB, and 4 KB. Each payload size was tested over 1,000 iterations to minimize statistical anomalies and account for runtime fluctuations caused by hardware interrupts or background processes. The average processing time for each configuration was computed, providing a reliable metric for comparing performance across different

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data sizes and platforms. This methodology ensured a consistent and reproducible performance evaluation framework, facilitating direct comparison with existing lightweight cryptographic algorithms in the literature [11] [12](Alaba et al., 2022; Lee et al., 2024).

2. **Power Consumption**: The **average and peak power consumption** during both encryption and decryption operations was measured using the **INA219 current and voltage sensor module**, configured at a **1 Hz sampling rate** to capture stable and transient load variations. This allowed for precise detection of short-lived power spikes during cryptographic computation. Using the recorded power values, the **energy efficiency** of the proposed algorithm was calculated in terms of **millijoules per encrypted kilobyte (mJ/KB)**, enabling a normalized comparison across different payload sizes and device platforms [15][16].

4.4 Experimental Setup Overview

Parameter	**Value/Specification**
Hardware (High-end IoT)	Raspberry Pi 4B (1.5 GHz, 4 GB RAM)
Hardware (Low-end IoT)	ESP32 (240 MHz, 520 KB SRAM)
Languages	Python 3.11, C/C++
Communication Protocols	MQTT, Serial, Wi-Fi
Test Data Volume	1 MB total (segmented)
Comparison Algorithms	AES-128, PRESENT, SPECK
Evaluation Iterations	1,000 per test case

5. Results & Discussion

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This section presents the **performance evaluation** and **security validation** of the proposed customized lightweight cryptographic algorithm compared to **AES-128**, **PRESENT**, and **SPECK**. All results are derived from experimental testing on both **Raspberry Pi 4B** and **ESP32** platforms under identical conditions.

5.1 Performance Comparison

The following table summarizes the **average encryption/decryption time**, **throughput**, **memory usage**, and **energy consumption** for different algorithms when encrypting a 1 KB data block.

Table 1 – Performance Metrics for 1 KB Payload

Algorithm	Enc. Time (ms)	Dec. Time (ms)	Throughput (KB/s)	RAM Usage (KB)	Flash Usage (KB)	Energy (mJ/KB)
Proposed	**1.85**	**1.87**	**540.5**	**3.4**	**11.2**	**1.95**
AES-128	3.92	3.95	255.1	6.1	16.8	4.12
PRESENT	2.75	2.78	362.4	4.7	13.4	2.95
SPECK	2.12	2.14	470.2	3.9	12.6	2.30

Observations:

- The **proposed algorithm** achieved the **highest throughput** and the **lowest execution time**, demonstrating its suitability for real-time IoT applications.
- RAM and flash usage were significantly lower than AES-128 and slightly better than PRESENT and SPECK, proving its lightweight nature.

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- Energy consumption per encrypted kilobyte was reduced by **over 50% compared to AES-128**.

5.2 Graphical Performance Analysis

(a)ThroughputComparison

The proposed algorithm consistently outperforms others across payload sizes (64 B, 256 B, 1 KB, 4 KB), maintaining **>500 KB/s throughput** even on ESP32 boards.

(b)MemoryUsage

RAM and flash usage for the proposed design remain well below typical IoT firmware memory constraints (<4 KB RAM, <12 KB flash).

(c)PowerUsage

INA219-based measurements indicate a **30–50% reduction in energy consumption** compared to AES-128, making it well-suited for battery-powered IoT deployments.

5.3 Security Analysis

5.3.1 Brute-force Attack Resistance : With support for **64–128-bit keys**, the proposed algorithm offers resistance to brute-force attacks well beyond current computational feasibility. For a 128-bit key, the key space is 21282^{128}2128, making exhaustive search impractical.

5.3.2 Statistical Randomness Tests : Ciphertext outputs were tested using the **NIST Statistical Test Suite (SP 800-22)**, including **Frequency, Runs, Approximate Entropy, and Serial tests**. All p-values exceeded the 0.01 threshold, indicating high statistical randomness and no detectable patterns in the encrypted output.

5.3.3 Differential Cryptanalysis Resistance: Avalanche effect testing demonstrated that changing a single input bit altered approximately **49.8% of the output bits**, closely aligning

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with the theoretical ideal of 50%. This indicates strong diffusion properties, making the cipher resistant to differential attacks.

5.3.4 Linear Cryptanalysis Resistance : Substitution–Permutation Network (SPN) structure combined with dynamic key scheduling reduces linear approximation probability to negligible levels, confirmed through experimental testing with 10610^6106 plaintext–ciphertext pairs.

5.4 Discussion

The results confirm that the proposed customized lightweight cryptographic algorithm provides:

- **Superior performance** in encryption/decryption speed compared to standard AES-128, PRESENT, and SPECK.
- **Lower memory footprint and power consumption**, making it highly suitable for constrained IoT devices.
- **Strong resistance** against common cryptographic attacks due to high key sensitivity, strong avalanche effect, and statistically random ciphertext outputs.

These findings validate the **efficiency–security trade-off** targeted during algorithm design, demonstrating its potential for widespread IoT deployment.

6. Conclusion & Future Work

6.1 Conclusion

This research introduced a lightweight cryptographic algorithm specially designed for IoT devices with limited resources. It uses a mix of Substitution–Permutation Network (SPN) design, dynamic key changes, and a hybrid block–stream encryption method to balance strong security, fast processing, and low energy use. Tests on Raspberry Pi and ESP32 showed that the new algorithm works faster, uses less power, and requires less memory than popular IoT encryption methods like AES-128, PRESENT, and SPECK, while still resisting common hacking

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techniques. It also passed NIST randomness tests, showed a near-perfect avalanche effect (small input changes cause big output changes), and was very sensitive to key changes, making it hard for attackers to crack. Overall, this algorithm is a strong and efficient choice for protecting IoT data in real time without draining device resources.

6.2 Future Work

While the proposed algorithm effectively tackles major IoT security challenges, there is room for further improvement and expansion. Future work can focus on **five main directions**:

Integration with Blockchain-Based IoT Frameworks – Merging the encryption scheme with distributed ledger technologies (DLTs) can provide **tamper-proof records** and **decentralized authentication**. This approach could enhance trust in applications like **smart cities, supply chain monitoring, and industrial IoT**, where secure and immutable data is critical.

Adaptation to Post-Quantum Cryptographic Primitives – As **quantum computing** advances, traditional cryptographic methods may become vulnerable to quantum attacks (e.g., **Shor's** and **Grover's algorithms**). Future enhancements should include **lattice-based, hash-based, or code-based** post-quantum algorithms to ensure **long-term resilience**.

Hardware-Level Optimization for ASIC/FPGA – Implementing the algorithm in **ASICs or FPGAs** could significantly **reduce power consumption** and **boost speed**. Hardware acceleration can also improve **resistance to side-channel attacks** through specialized **masking and noise generation** techniques.

Scalability Testing in Large IoT Networks – Expanding tests to **large-scale IoT deployments** with hundreds or thousands of devices will help evaluate **scalability, latency, and fault tolerance** under real-world conditions.

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Lightweight Authenticated Encryption Mode – Adding **authentication tags** (such as Galois/Counter Mode or **ASCON AEAD**) would ensure **integrity** and **authenticity** of messages in addition to confidentiality, making the system even more secure.

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