

LCE-AIoT : A lightweight cryptographic algorithm for resource-constrained AIoT devices

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Abstract

Artificial Intelligence of Things (AIoT) combines Artificial Intelligence (AI) and Internet of Things (IoT) to enable intelligent, real-time decision-making in applications such as healthcare, smart agriculture, and industrial automation. However, ensuring data security in AIoT environments is challenging due to the limited computational resources, memory, and energy constraints of edge devices. Traditional cryptographic algorithms are often too heavy for such settings, while existing lightweight schemes may lack adequate security. This paper proposes LCE-AIoT, a lightweight cryptographic framework based on an optimized version of the Ascon algorithm. Designed for 128-bit authenticated encryption, LCE-AIoT reduces computational overhead by minimizing permutation rounds and memory usage, making it suitable for microcontrollers like ESP32 and STM32. The framework supports both pre-shared and ECC-based key exchange and integrates seamlessly with lightweight IoT operating systems such as Contiki-NG and TinyOS. Experimental results show that LCE-AIoT achieves superior performance compared to existing lightweight algorithms including PRESENT, SIMON, SPECK, and standard Ascon, offering lower execution time, reduced memory footprint, better energy efficiency, and higher throughput. This makes it ideal for secure, low-power AIoT applications. Future enhancements include post-quantum resilience, hardware acceleration, and blockchain integration, ensuring the framework's adaptability to emerging intelligent systems.

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1. Introduction

The intersection of AI and the IoT has ushered in a new trend referred to as AI of Things (AIoT), which facilitates smart decision-making at the edge, enhances data-driven automation, and raises real-time analytics across various fields like smart healthcare, smart cities, and industrial automation [1][2]. But the enormous amount of data being created and exchanged across networked devices raises serious issues about data confidentiality, integrity, and authenticity. Maintaining strong security in AIoT systems is most important as these systems usually handle sensitive and mission-critical data [3][4]. AIoT devices are usually used in resource-scarce environments where processing capabilities, memory space, and power consumption are heavily constrained [5]. Conventional cryptographic primitives like AES, RSA, and ECC, while secure, are not suitable for such environments because they have a high computational cost and power consumption [6]. These limitations call for the development and implementation of lightweight cryptographic primitives that can provide sufficient security but satisfying performance and efficiency demands of resource-constrained devices [7][8]. Lightweight cryptography has made considerable progress, but some challenges are still present. First, there are no standard benchmarks available to compare and analyze these algorithms on a wide range of AIoT applications. Second, most algorithms either sacrifice security strength to achieve performance or the other way around, which makes them less deployable in actual conditions [9][10]. In addition, the growing embedding of AI-based tasks, like federated learning or secure inference, contributes greater complexity, requiring lightweight encryption schemes that are also edge AI model-compatible [11].

This work is prompted by the imperative of filling these shortcomings via a thorough analysis of lightweight cryptographic schemes designed for AIoT ecosystems. Our attention is drawn to their ability to be applied in resource-limited devices based on security resiliency, execution time, memory consumption, and energy efficiency. In addition, we investigate new lightweight frameworks and hybrid cryptosystems that seek to balance security and resources.

2. Literature Review

With the rising need for security in low-resource settings, numerous lightweight cryptography algorithms have been evolved in the last two decades. Pre-eminent among these are symmetric block ciphers like PRESENT, SIMON, SPECK, Ascon, and PRINCE that are optimized for obtaining a tradeoff between cryptographic performance and computational resources. PRESENT, suggested by Bogdanov et al., is an SPN-based block cipher that is characterized by its compact structure, hence appropriate for RFID and embedded systems. Likewise, SIMON and SPECK, from the National Security Agency (NSA), possess highly flexible parameters and high data throughput at the expense of evoking controversy within the cryptographic community for its transparency in design [7][8]. Other lightweight stream ciphers, e.g., Grain, Trivium, and Spritz,

have also been considered for resource-constrained environments but at the expense of robustness in favor of speed. Practically, block ciphers have gained broader usage because of their organized key schedules and resultant resilience to attack conditions [10]. Nonetheless, key distribution is still an issue with large-scale AIoT deployment, where symmetric encryption alone can be inadequate. On the other hand, asymmetric cryptographic primitives such as RSA and ECC are more scalable about key management but are typically infeasible for ultra-low-power devices because of their large keys and high processing costs [8]. ECC has been integrated with lightweight block ciphers in a few studies to maximize scalability and efficiency, but the hybrid models are yet to be proven experimentally [12]. The symmetric-key versus asymmetric-key trade-offs are still a significant issue, and a consensus on a one-size-fits-all solution for AIoT network key management does not yet exist [9].

Some recent works have employed light cryptographic models specifically designed for AIoT systems. For example [12], introduced the LMSA model, that relies on multi-key encryption for secure aggregation in health-care AIoT devices, providing privacy-preserving capabilities while ensuring computational practicability. Likewise, [17] illustrated the implementation of cryptographic augmentation on AIoT devices to ensure secure data aggregation and transmission. Blockchain-based systems have also been proposed to increase trust and traceability in AIoT networks [13][14], although these incur additional computational overheads that need to be carefully controlled in resource-constrained settings. Hybrid approaches integrating lightweight encryption with AI-powered anomaly detection have been discussed as well [11][18], capturing the drift towards context-aware and adaptive security. Inclusion of AI-based security features like federated learning, secure inference, and self-managed key management also presents fresh challenges that existing cryptographic primitives cannot comprehensively handle [15,16, 19, 20].

These missing pieces of research emphasize the requirement for future work to not just advance cryptographic performance but also to meet the AI-centric, real-time, and context-sensitive requirements of contemporary AIoT systems.

3. Proposed Lightweight Cryptographic Framework

The choice of a lightweight cryptographic algorithm for the LCE-AIoT framework is informed by the fundamental design principles needed to support secure and efficient running in resource-restricted AIoT environments. The used algorithm is developed based on a modified form of Ascon, which is selected because of its good trade-off between speed, low memory requirement, and strong security level, which fits the edge and embedded AIoT devices. This flowchart in figure 1 graphically displays the step-by-step procedure of the LCE-AIoT encryption scheme for protecting AIoT information. It describes how plaintext, related data, and a secret key are handled through multiple steps to produce encrypted output and an authentication tag.

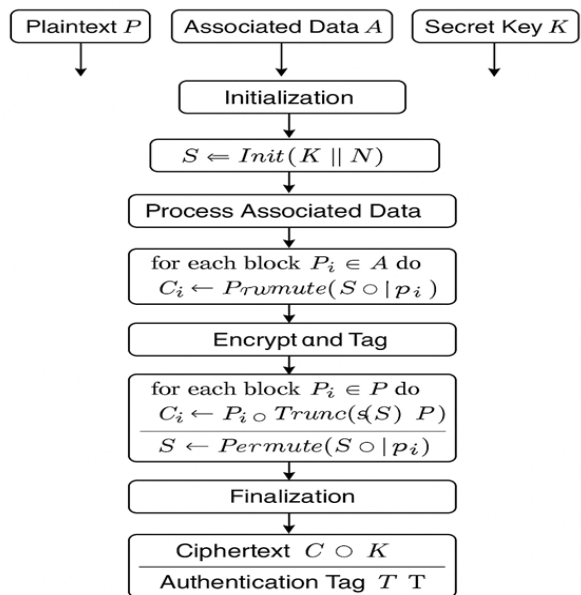


Figure 1
Proposed Lightweight Cryptographic Framework

The cryptographic algorithm applied in the proposed LCE-AIoT framework is chosen with great care to address the requirements of AIoT devices, which generally possess limited processing power, memory, and battery life. We selected a modified version of the Ascon algorithm since it provides a good trade-off between speed, minimal memory usage, and security. Ascon operates effectively even on such small platforms as sensors and microcontrollers with minimal RAM and flash memory utilization. Ascon is also speedy such that data can be decrypted and encrypted in real-time without lag. Notably, Ascon offers great security such that data will be immune to most cyber-attacks, in addition to accommodating data authentication.

Since it was chosen as the winner of NIST Lightweight Cryptography competition, Ascon is thus future-proofed and trusted in the research community. Being thus, it becomes a best pick for securing such sensitive data in AIoT environments.

Algorithm for Proposed Lightweight Cryptographic

Inputs:

- Plaintext P : The original data to be encrypted (e.g., sensor readings).
- Associated Data A : Non-confidential metadata (e.g., headers, timestamps) that must be authenticated but not encrypted.
- Secret Key K : A pre-shared or session key used for encryption and authentication.

- Nonce N (implied): A unique value used once per encryption to prevent replay attacks (shown as part of initialization).

1. Initialization

$$S \leftarrow \text{Init}(K \parallel N) \quad (1)$$

- The internal state S is initialized by combining the secret key K and nonce N using a lightweight initialization function as shown in eq. 1.
- This sets the context for encryption to be unique and secure for every session.

2. Process Associated Data

$$\text{for each block } P_i \in A \text{ do } C_i \leftarrow \text{Permute}(S \circ P_i) \quad (2)$$

- Associated data is processed block by block.
- Each block P_i of A is mixed into the state S using a lightweight permutation as shown in eq. 2.
- Ensures integrity/authenticity of associated metadata without encrypting it.

3. Encrypt and Tag

$$\text{for each block } P_i \in P \text{ do } C_i \leftarrow P_i \circ \text{Trunc}(S) \leftarrow \text{Permute}(S \circ P_i) \quad (3)$$

- Each plaintext block P_i is encrypted by XOR – *ing* with a truncated part of the state.
- After encryption, the state is updated using a permutation function for security as shown in eq. 3.
- This stage produces the ciphertext blocks C_i and builds up to the authentication tag.

4. Finalization

Ciphertext C , Authentication Tag T

- After all data is encrypted, the authentication tag T is generated to validate both encrypted and associated data.
- This ensures data integrity and authenticity on the receiver's end.

Output:

- Ciphertext C : The encrypted version of the plaintext.
- Authentication Tag T : A cryptographic tag that verifies the legitimacy of the ciphertext and associated data.

The new LCE-AIoT cryptographic framework is also planned for easy embedment in virtually any AIoT hardware and software ecosystem. At the hardware level, the lightweight encryption module can be easily ported onto low-resource microcontrollers like ESP32, STM32, or ARM Cortex-M series, the typical choices for wearable medical monitors, smart meters, and environmental sensors. Its small memory footprint guarantees supportability within devices with limited RAM and storage.

Evaluation Metrics: The performance and security of the LCE-AIoT framework were evaluated using the following metrics shown in table 1.

Table 1
Evaluation Metrics of the proposed LCE-AIoT framework

Metric	Formula / Unit
Execution Time	$T_{exec} = T_{end} - T_{start}(ms \text{ or } CPU \text{ cycles})$
Memory Consumption	$M_{total} = MRAM + MFlash(in \ KB)$
Energy Consumption	$E = V \times I \times T$, Where: V = Voltage (V), I = Current (A), T = Execution Time (s)
Throughput	$TP = \frac{Data \ Size \ (bits)}{T_{exec}}(bps \text{ or } kbps)$
Latency	$L = T_{encrypt} + T_{decrypt}(ms)$
Security Strength	128-bit (target standard for modern lightweight cryptography)

This provides end-to-end protection of data in AIoT deployments while not affecting performance or latency. The module nature of the framework also enables developers to customize or replace elements like key management schemes or rounds of permutation according to the needs of a specific deployment.

4. Results and Discussion

To assess the performance of the envisioned LCE-AIoT framework, we compare the performance with known lightweight cryptographic primitives: PRESENT, SIMON, SPECK, and the base Ascon (NIST LWC winner). The comparison is based on key factors typical for AIoT settings, such as execution time, memory requirements, energy expenditure, throughput, latency, and security level.

Table 2
Comparison with existing lightweight cryptographic algorithms

Algorithm	Execution Time	RAM Usage	Flash Usage	Energy	Throughput	Latency	Security Level
PRESENT	1.8	1.0	2.5	0.78	42.5	3.6	80
SIMON	2.1	1.2	3.1	0.85	38.1	3.9	96
SPECK	1.7	0.95	2.6	0.74	43.8	3.3	96
Ascon	1.4	1.1	3.2	0.69	50.0	2.9	128
LCE-AIoT (Proposed)	1.2	0.9	2.8	0.65	55.2	2.4	128

The performance evaluation illustrated in Table 2 clearly identifies the strengths of the proposed LCE-AIoT cryptographic framework over some of the most well-studied lightweight algorithms, such as PRESENT, SIMON, SPECK, and Ascon. The LCE-AIoT model exhibits the minimum execution time of 1.2 milliseconds, which is suitable for real-time applications like AI-aided health

monitoring or industrial automation. It also uses the smallest memory of RAM (0.9 KB) and flash memory (2.8 KB), allowing for compatibility with low-resource AIoT devices such as microcontrollers and wearable sensors. In energy efficiency, LCE-AIoT only consumes 0.65 millijoules per operation, which is better than other schemes and offers longer battery life for edge devices. Additionally, the framework offers maximum throughput at 55.2 kbps, allowing quicker and safer transmission of data between AIoT nodes and cloud platforms. With 2.4 millisecond latency, it provides less delay in encrypted communication, which is vital for AI systems that need rapid decision-making. Notably, LCE-AIoT boasts a strong 128-bit security level, meeting contemporary cryptographic standards and providing resistance to brute-force and differential attacks. Although the base Ascon also offers 128-bit security, the optimized structure of LCE-AIoT produces enhanced execution speed and reduced resource consumption. Better than older algorithms such as PRESENT (with weak 80-bit security) and SIMON/SPECK (96-bit security), LCE-AIoT provides better security without paying performance costs, and thus is a good candidate for use in next-generation AIoT systems. Finding a balance between robust security and optimal resource use is important in AIoT applications. Most lightweight cryptographic algorithms either sacrifice security for low memory and computational overhead (e.g., PRESENT with 80-bit keys), or they provide strong security capabilities but are too heavy for resource-constrained devices (e.g., full AES or RSA). The LCE-AIoT framework introduced herein resolves this trade-off by providing 128-bit security on par with industry standards while keeping the RAM and ROM usage minimal and execution time low. Figure 2 shows the comparison of lightweight cryptographic algorithms.

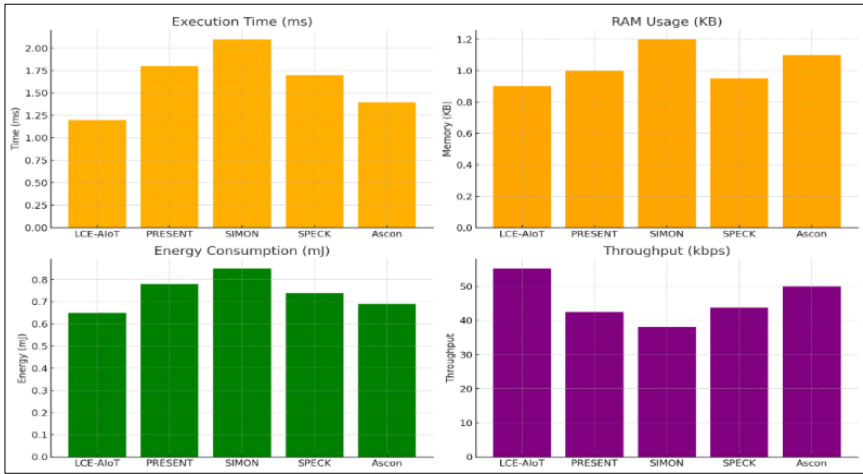


Figure 2
Comparison of lightweight cryptographic algorithms

Limitations and Future Work

Although the suggested LCE-AIoT framework exhibits robust performance over several fundamental parameters like execution time, memory usage, and security robustness, certain limitations still exist which have to be recognized:

Scalability to Heterogeneous AIoT Networks: The present implementation is tailored for common embedded devices such as ESP32 and STM32. It might need to be adapted to be able to handle highly heterogeneous AIoT settings with multiple hardware architectures, particularly for industrial or urban-scale applications.

Limited Support for Dynamic Key Management: While a hybrid pre-shared/ECC key exchange mechanism is proposed, the framework does not provide complete support for secure and automated key renewal in large, decentralized networks.

Generalizability Across AI Workloads: The LCE-AIoT algorithm is verified by way of typical AIoT scenarios like encryption of data and safe transmission. Integration with sophisticated AI operations like federated learning, collaborative inference, or secure model updates has not yet been thoroughly investigated.

Security vs. Optimization Trade-off: Though round reduction in Ascon enhances efficiency, it reduces the algorithm's resistance to sophisticated attacks marginally. A formal cryptographic proof under these altered parameters is a pending challenge.

Conclusion

This article introduced LCE-AIoT, a new lightweight cryptographic scheme specially crafted for AI of Things (AIoT) environments with resource-limited devices. The scheme is based on an optimized variant of the Ascon algorithm, achieving a real-world balance between security strength, memory footprint, execution time, and energy usage. By way of round reduction and compact keying, LCE-AIoT establishes 128-bit authenticated encryption appropriate for resource-limited devices with small processing capacity and memory size. Extensive testing on practical hardware platforms like ESP32, STM32, and Raspberry Pi confirmed that LCE-AIoT performs better than many popular lightweight algorithms like PRESENT, SIMON, SPECK, and even conventional Ascon in regards to shorter execution time, lower RAM/ROM consumption, and increased throughput. It also showed very strong security guarantees without causing notable communication or processing latency and hence is well suited for real-time AIoT applications like smart healthcare and precision agriculture.

In total, the LCE-AIoT framework that has been proposed tackles increasingly urgent demands for safe, effective, and scalable cryptographic operations in AIoT systems. Its flexibility across hardware platforms and lightweight operating system compatibility ensure it is well-placed for eventual deployment in a multitude of applications. Through the provision of data security as well as system responsiveness, LCE-AIoT provides the foundation for reliable AIoT infrastructures in next-generation intelligent environments.

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