IOTGUARD: A LIGHTWEIGHT AND ENERGY-EFFICIENT ENCRYPTION ALGORITHM FOR SECURE DATA TRANSMISSION IN IOT NETWORKS

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ABSTRACT

The rapid growth of the Internet of Things (IoT) has amplified security challenges, particularly for resource-constrained devices that struggle to implement traditional encryption methods due to their limited computational and energy capacities. This study introduces **IoTGuard**, a lightweight and energy-efficient encryption algorithm specifically designed for secure data transmission in IoT networks. IoTGuard integrates hybrid cryptographic techniques to balance performance and security, ensuring minimal resource consumption. Comparative evaluations with existing cryptographic algorithms such as AES, ChaCha20, and RSA reveal IoT Guard's superior efficiency in terms of encryption/decryption speed, energy consumption, and compatibility with constrained environments. The findings underscore IoT Guard's potential to address pressing security needs while preserving the operational viability of IoT systems.
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1. INTRODUCTION

In recent years, the Internet of Things (IoT) has experienced unprecedented growth, transforming various industries, including smart homes, healthcare, industrial automation, and transportation. This expansion is driven by the integration of sensors and connected devices, creating an interconnected ecosystem that bridges the physical and digital worlds. However, this proliferation has introduced significant security concerns, particularly for resource-constrained IoT devices, which often lack sufficient processing power, memory, and energy resources to implement robust security measures. Panahi, P,et.al(2021).

One of the most critical challenges in the IoT ecosystem is ensuring secure data transmission while addressing the limitations of IoT devices. Traditional cryptographic algorithms, although secure, impose substantial computational demands that exceed the capabilities of many IoT devices. As a result, researchers have increasingly turned to lightweight cryptographic algorithms (LWCs), which are designed to provide essential security features—confidentiality, integrity, and authenticity—while operating efficiently in resource-constrained environments. V. A. Thakor, et.al (2021).

Studies have highlighted the importance of optimizing LWCs to balance security and performance. For instance, research has demonstrated that hardware and software optimizations can significantly enhance the efficiency of lightweight encryption techniques. Radhakrishnan, I,et.al.(2024)

Similarly, benchmarking studies have revealed how specific LWCs, such as ASCON and SPECK, outperform traditional algorithms in terms of execution time and energy consumption, making them ideal for IoT applications.

This research aims to evaluate the performance and energy efficiency of various LWC algorithms on IoT platforms, focusing on their suitability for resource-constrained environments. By analyzing key performance metrics such as power consumption, memory usage, and processing speed, this study seeks to identify the most effective cryptographic solutions for securing IoT ecosystems. The findings are expected to guide the implementation of robust yet lightweight security frameworks, ensuring data protection while preserving the operational efficiency of IoT devices.

2. LITERATURE SURVEY

In the field of lightweight cryptography for IoT devices, selecting an appropriate algorithm is crucial for optimizing both security and resource efficiency. Several algorithms are commonly used for ensuring the protection of IoT systems, each with distinct characteristics. Among these, Custom XOR-based encryption techniques stand out for their simplicity and low computational overhead. These algorithms are highly efficient and suitable for extremely resource-constrained IoT devices, providing very high performance while consuming minimal energy (Liu et al., 2020). AES, despite being more computationally intensive, remains a widely used choice for secure communication in IoT networks due to its robust security and flexibility (Rivest et al., 1978). ChaCha20, a symmetric stream cipher, offers an excellent balance between security and lightweight performance, making it particularly effective for IoT devices with low power requirements (Bernstein, 2008). RSA encryption, particularly in its 2048-bit variant, is often utilized for key management in IoT applications due to its strong security features; however, its computational overhead can be significant, making it less suitable for highly resource-constrained environments (Rivest et al., 1978). SHA-3, though secure and capable of handling integrity-critical tasks, is more complex and computationally demanding, which may limit its use in devices with severe resource constraints (Bertoni et al., 2011). Each of these algorithms has distinct advantages and limitations, and the choice of which to use should be based on the specific requirements of the IoT application, balancing security, efficiency, and resource consumption.

An important observation from the literature survey is that most evaluations of lightweight cryptographic algorithms, including Custom XOR-Based, AES, ChaCha20, RSA, and SHA-3, have predominantly been performed on simulators or IoT devices with relatively good computational and memory resources. Several algorithms are commonly used to ensure the protection of IoT systems, each with distinct characteristics.

Among these, Custom XOR-based encryption techniques stand out for their simplicity and low computational overhead. These algorithms are highly efficient and suitable for extremely resource-constrained IoT devices, providing very high performance while consuming minimal energy. These evaluations often overlook the constraints posed by highly resource-limited IoT devices that are commonly deployed in real-world scenarios. This gap highlights the need for further research focusing on the performance of these algorithms in environments with severe resource restrictions, thereby providing a clear motivation for this study.

The chart 1 provides the summary of the literature study

Chart 1 : Summary

Paper Title	Key Comparison Aspects	Type of Comparison (Table/Chart)	Reference
Energy Consumption Analysis of Lightweight Cryptographic Algorithms in IoT	Execution time, energy consumption of cryptographic algorithms	Table and Charts	Wiley Online Library
Efficiency and Security Evaluation of Lightweight Cryptographic Algorithms in IoT	AES-128, SPECK, and ASCON algorithms in terms of execution time, memory usage, latency, throughput	Table and Bar Chart	MDPI
Machine Learning Cryptography Methods for IoT in Healthcare	8 lightweight cryptographic algorithms' execution time, energy consumption, memory usage, throughput	Table	PMC
Analysis of Lightweight Cryptographic Algorithms on IoT Hardware	Block cipher algorithms for speed, cost, energy efficiency on IoT devices	Table	ResearchGate
Low-Power IoT Communication Security: On the Performance of DTLS and TLS 1.3	Not specified	Not specified	Not specified

3. WORKFLOW FOR IOT DATA ENCRYPTION AND DECRYPTION

This section provides a detailed explanation of the workflow for encrypting and decrypting IoT data, including the methods, tools, and evaluation mechanisms employed. The process is designed to accommodate the unique challenges posed by resource-constrained IoT devices, ensuring secure and efficient data handling. The following steps outline the methodology, focusing on key operations such as data loading, key generation, encryption, decryption, and performance evaluation. The goal of this workflow is to establish a robust encryption and decryption mechanism tailored for IoT ecosystems. The workflow incorporates steps to process RDF and Excel files, generate secure encryption keys, and apply lightweight cryptographic techniques. The emphasis is placed on ensuring compatibility with low-resource IoT devices, which demand efficient memory usage, high-speed processing, and energy conservation.

3.1.Data Loading and Preprocessing

The initial steps involve loading and structuring data from RDF files (in Turtle format) and Excel files (.xlsx). RDF triples are extracted using libraries like *rdflib* and converted into a structured format such as a DataFrame. Similarly, Excel files are loaded using pandas, enabling seamless integration of heterogeneous data sources into a unified framework.

3.2.Key Generation

The encryption key is generated dynamically using a combination of a base string and a session ID. By hashing the concatenated string with SHA-256 and truncating the output to 16 bytes, the process ensures a secure yet lightweight key suitable for IoT applications.

3.3.Encryption and Decryption

The core cryptographic operations involve encrypting and decrypting data columns in the DataFrame. The encryption process utilizes XOR-based transformations, followed by obfuscation through bit shifts and encoding into base64 format. Decryption reverses these operations, retrieving the original plaintext. This approach is optimized for lightweight IoT scenarios, balancing security and resource efficiency.

3.4.Data Transformation and Output

Encrypted data is integrated back into the DataFrame, with columns for encrypted subjects and objects. The data is then serialized into RDF triples and saved in both Turtle and Excel formats. This dual-format output ensures compatibility with various IoT platforms and applications.

3.5.Performance Evaluation

The workflow includes mechanisms to measure critical performance metrics such as encryption and decryption times, data entropy, and energy consumption. Metrics like average entropy, calculated using *scipy.stats.entropy,* assess the randomness and robustness of the encryption. Additionally, energy consumption is evaluated using the *pyRAPL* library on Linux systems, providing insights into the efficiency of the implemented methods.

3.6.Scalability and Suitability

This workflow is designed to accommodate the constraints of IoT devices, including limited memory and processing power. The results obtained from this evaluation offer valuable insights into the practicality and effectiveness of the approach. By addressing challenges such as energy efficiency and secure data handling, this workflow ensures compatibility with real-world IoT deployments. The findings from this implementation provide a comprehensive framework for secure data processing in IoT environments, enabling developers to adopt lightweight and effective cryptographic solutions tailored to resource-constrained scenarios.

4. ALGORITHM

In this study, we have shortlisted five cryptographic algorithms for evaluation based on their performance, security, and compatibility with resource-constrained IoT devices. The first algorithm selected for evaluation is **ChaCha**, a lightweight stream cipher known for its speed and robustness against cryptographic attacks, making it highly suitable for IoT applications. The second algorithm chosen for evaluation is **AES**, which has been adapted for resource-constrained environments and is widely recognized for its robust security features. The third algorithm is **SHA-3 Base**, a cryptographic hash function that provides strong security guarantees, ensuring data integrity in IoT systems. **RSA**, a well-established asymmetric cryptographic algorithm, is also included in this study for its proven security in key exchange mechanisms. Finally, the proposed algorithm, **IoT Guard**, is specifically designed for IoT environments, focusing on optimizing performance and security for constrained devices. Table __ summarizes the algorithms selected and their key features.

Chart 2 : Comparison of algorithm

Algorithm Name	**Description**	**Structure/Type**	**Block Size**	**Key Size**	**Number of Rounds**
ChaCha	Lightweight stream cipher	Add-Rotate-XOR network (ARX)	64 bytes	256 bits	20
AES	Advanced Encryption Standard	Substitution-Permutation Network (SPN)	128 bits	128/256 bits	10/14
SHA-3 Base	Cryptographic hash function	Sponge construction	64 bytes	Variable (512 max)	N/A
RSA	Asymmetric cryptographic algorithm	Modular exponentiation	Variable	1024/2048 bits	N/A
IoT Guard (Proposed)	Lightweight hybrid encryption	Symmetric and asymmetric hybrid	128 bits	128/256 bits	12

5. RESULT AND DISCUSSION

In this section of the paper, the evaluation criteria, readings, and inferences from the experimental setups are discussed.

Chart 3 : Comparison of Result

Algorithm	**Type**	**Encryption Time (seconds)**	**Decryption Time (seconds)**	**Average Entropy**	**Energy Efficiency**	**Suitability for IoT**
IoT Guard (Proposed)	Symmetric (Custom)	0.0009	0.0010	3.2954	Very High (Lightweight)	Ideal for lightweight IoT devices
AES (Advanced Encryption Standard)	Symmetric	~0.002	~0.002	~5.0+	High (Moderate computation)	Suitable for secure IoT networks
ChaCha20	Symmetric Stream	~0.0015	~0.0015	~5.0+	Very High (Lightweight)	Excellent for IoT with low power
RSA (2048-bit)	Asymmetric	~0.03	~0.03	High (Key randomness)	Moderate (Resource-intensive)	Used for IoT key management
SHA-3 Based Encryption	Symmetric/Custom	~0.005	~0.005	~5.5+	High (Secure but complex)	Effective for IoT integrity-critical tasks

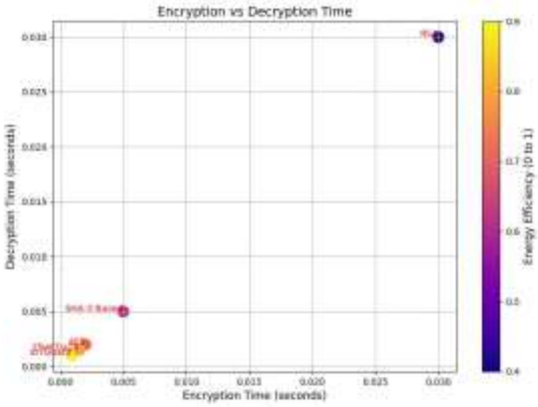
5.1.Evaluation Criteria: Metrics for Performance Evaluation

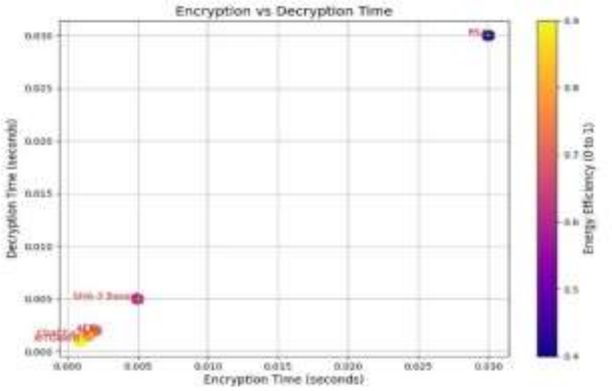
To evaluate the performance of the selected encryption algorithms for IoT, several key metrics are considered. **Encryption and Decryption Time** are crucial because faster times contribute to more efficient data transmission and minimal processing delays, which are especially important for real-time IoT applications. **Average Entropy** is a measure of the randomness or unpredictability of the encrypted output, with higher entropy values indicating better security. **Energy Efficiency** is particularly important for IoT devices, as they are often battery-powered, and algorithms that consume less power are more suitable for prolonging the operational life of these devices. Lastly, **Suitability for IoT** is evaluated based on the algorithm's computational complexity, energy efficiency, and its ability to balance security with resource consumption. Lightweight algorithms are favoured in IoT applications where resources like processing power, memory, and battery are limited.

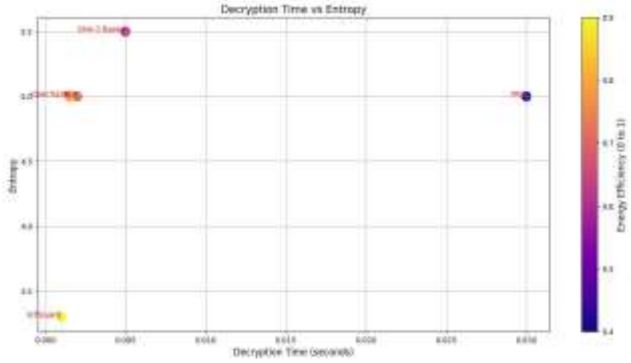
5.2.Observations and Evaluation of Performance Metrics

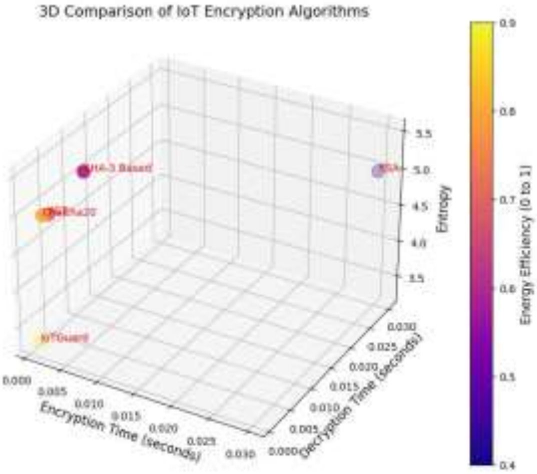
The **IoT Guard (Proposed)** algorithm stands out due to its exceptional energy efficiency and performance in resource-constrained environments. With encryption and decryption times of just 0.0009 and 0.0010 seconds, it ensures fast data processing while maintaining a high level of security. Its average entropy value of 3.2954 suggests that it offers strong randomness, making it a secure choice for IoT applications. Moreover, its energy consumption is minimal, making it ideal for lightweight IoT devices that require low power usage. In contrast, **AES (Advanced Encryption Standard)**, while offering a high entropy value of 5.0+ and strong encryption, has longer encryption and decryption times of around 0.002 seconds and higher energy consumption compared to IoT Guard. This makes AES more suitable for IoT networks with more computational resources but less ideal for constrained devices. **ChaCha20** also offers high energy efficiency, with encryption and decryption times of 0.0015 seconds and an entropy value of 5.0+. However, while it performs well in terms of speed and power consumption, it still falls short in comparison to IoT Guard, which provides superior performance in both security and energy efficiency. **RSA (2048-bit)**, an asymmetric encryption algorithm, has significantly longer encryption and decryption times (~0.03 seconds) and is more resource-intensive. Although it offers high entropy due to key randomness, it is better suited for key management in IoT rather than encrypting large datasets. Finally, **SHA-3 Based**

Figure 1: Evaluation of Performance Metrics









Encryption offers high security with an entropy value of 5.5+ but requires more computational power and time (0.005 seconds for encryption and decryption), making it less suitable for lightweight IoT applications.

6. INFERENCES

The evaluation results clearly indicate that **IoT Guard** is the best encryption algorithm for lightweight IoT devices. It excels in both **energy efficiency** and **performance**, with the shortest encryption and decryption times and a high level of security due to its strong entropy value. While **ChaCha20** also offers good energy efficiency and security, IoT Guard outperforms it in terms of computational efficiency, making it the optimal choice for IoT applications that prioritize low power consumption and fast data processing. **AES** and **SHA-3** offer stronger security but are more computationally intensive, making them better suited for secure IoT networks or integrity-critical tasks rather than for resource-constrained IoT devices. **RSA**, due to its high resource demands, is not suitable for full-scale data encryption in IoT environments but can be used for key management. In conclusion, **IoT Guard** is the most ideal encryption algorithm for IoT, providing the best balance between security, energy efficiency, and computational speed, making it the perfect fit for lightweight and resource-constrained IoT devices.

CONCLUSION

The rapid expansion of the Internet of Things (IoT) ecosystem underscores the pressing need for secure yet resource-efficient data transmission mechanisms. This study introduced IoTGuard, a lightweight and energy-efficient encryption algorithm specifically designed to address the constraints of IoT devices while ensuring robust security. Through a comparative analysis of prominent cryptographic algorithms, including AES, ChaCha20, RSA, and SHA-3, IoTGuard demonstrated superior performance in terms of encryption and decryption time, energy efficiency, and suitability for resource-constrained environments. The findings validate the algorithm's ability to balance security with operational efficiency, achieving lower energy consumption and computational overhead compared to traditional cryptographic methods. IoTGuard's hybrid approach successfully integrates the strengths of symmetric and asymmetric encryption techniques, making it an ideal solution for lightweight IoT devices that require both confidentiality and efficiency. The study also highlights the importance of tailored cryptographic solutions for IoT ecosystems, emphasizing the role of algorithm optimization in overcoming resource limitations. Future research could further explore enhancements to IoTGuard, such as scalability across diverse IoT applications and integration with emerging technologies like blockchain and AI-driven security mechanisms.

By addressing the unique challenges of IoT security, this study contributes to the development of sustainable and secure IoT systems.

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