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OPTIMIZING ENERGY-EFFICIENT ENCRYPTION IN IOT: EXPLORATION OF STREAM AND LIGHTWEIGHT BLOCK CIPHERS

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ABSTRACT

The massive proliferation of the IoT devices has posed intricate problems in the protection of data delivery within limited computational resource. Such environments are usually very demanding to conventional encryption protocols. The paper fills an urgent knowledge gap because it critically compares lightweight block ciphers and stream ciphers to provide an energy-efficient encryption in the IoT-networks. Although the available studies tend to consider performance or security as a key aspect, our study is unique in that it combines the aspects of the throughput, latency and energy consumption of a system to give a multi-dimensional assessment. We can characterize the actual tradeoffs and applicability of the three modes, CTR, OFB, and CFB by deploying them over a real-time testbed. Findings reveal CTR mode offers high efficiency and performance trade off. The study offers practical information on cipher selection which is part of the future development of lightweight encryption approaches with an (energy-constrained environment) focus.

Keywords: *Lightweight Encryption, IoT Security, Stream and Block Ciphers, Energy Efficiency, CTR, OFB, CFB Modes*

1. INTRODUCTION

Such an extraordinary number of new devices has been seen and created by the proliferation of IoT through the collection, analysis, and transmission of enormous amounts of data from industrial sensors to wearables. Such devices normally have significant resource constraints regarding processing speed, memory, and even battery power. There are, however, many automated measures such as encrypted data that provide a means for securing devices, and these methods are now proving highly difficult to implement in a traditional society. As a result, it has become essential to have lightweight cryptography that can

provide a high quality of security to IoT devices while being lightweight on the device's resources.

Two key technologies used within lightweight cryptography are the stream ciphers and block ciphers. As stream ciphers encrypt data serially, they inherently support real-time data processing making them an ideal fit for low-powered IoT devices. In addition, since they operate on a bit level, messages need less memory in contrast, which is suitable for small IoT devices. In contrast, lightweight block ciphers like PRESENT and SIMON have a structured nature of encryption. Such block ciphers are considered user-friendly and efficient in performance, making them apt for use in IoT. Processing data in blocks allows block ciphers to strike a safety resource consumption balance with strength in encryption.

However, choosing the most appropriate encryption technique does involve striking a balance involving considerations such as device computing ability, degree of memory space, and sources of energy. Stream ciphers may be less energy-inefficient than the former but do not necessarily offer the same degree of security that the latter promises. Some IoT devices may not be able to meet the minimum system requirements for block cipher security standards such as PRESENT and SIMON. This paper focuses on the analysis and comparison of advantages and disadvantages of stream ciphers and that of lightweight block ciphers concerning their energy efficiency, their memory requirements, and their security in IoT environments. The study will promote an understanding of cryptographic mechanisms that can be used on low-powered IoT devices by assessing the strengths and weaknesses of each strategy promoting security on IoT networks while ensuring energy is not drained.

This contribution addresses the critical gap in the Internet of Things, namely to demonstrate that proper encryption selection results in better security and performance across a range of IoT applications.

2. LITERATURE SURVEY

Lightweight Symmetric Key Algorithm Ferreira, Weber, and dos Santos advance a lightweight symmetric key algorithm based on encryption through CTR mode for IoT devices, this being a compact, low-consumption secure solution for applications like these. With respect to traditional methods, the study shows improved power efficiency and the consumption of less energy in comparison. Speed tests show that it is suitable for resource-constrained devices, thereby enhancing the security of the Internet of Things without impacting the performance of the devices [1]. The AES encryption in its Counter (CTR) mode was efficiently implemented in a device developed by Singh and Ghosh within an FPGA for the Internet of Things. The proposed configuration maximizes speed and resource use while maintaining safety. Due to the experimental data, we can say that these developments vary positively in terms of efficiency, which is why they are fitting for low-power IoT devices with strong encryption requirements [2]. Khalid et al. explore lightweight counter (CTR) mode cryptography algorithms for purposes related to the Internet of Things. It was investigated that some algorithms can be optimal for IoT with deficient resources, since the ratio is appropriate between security and efficiency after the analysis of several algorithms on speed, energy, and security [3]. In the Internet of Things contexts, Alaboud and Alkhateeb assess the speed security capabilities and energy efficiency of stream and block ciphers. Their analysis demonstrates the need for the particular requirements in the selection of the chosen cipher for an IoT application by proving that even if the stream ciphers are simple and faster, block ciphers will offer better security [4]. In such a case, Nguyen and Le propose a simple Counter mode-based encryption scheme focused toward intelligent IoT applications. The work focuses significantly on energy and security concerns and proves that such a usage effectively decreases the computation overhead it demands for adequate encryption. The proposed scheme works well for resource-constrained IoT devices which need secure communication [5].

Such a scheme type is not permanent, but Nguyen and Le proposed an encryption system over a Counter mode-based which is very basic and easy for intelligent IoT modules. Crucial points here are security as well as energy efficiency, and it is shown how these applications do significantly lower the resource load needed for strong encryption. The proposed scheme works efficiently for resource-constrained IoT devices that need secure communication [6]. Weber and Weber analyze cryptographic strategies that can be used in securing the IoT and provide modifications that allow them to improve performance but at the cost of security and efficiency in energy usage. The author underlines that there is a need for developing secure cryptographic methods that can meet the needs of the IoT environment in terms of its resource-constrained devices IoT devices here [7]. Shao and Chen present the optimal application of lightweight block ciphers for the Internet of Things. This optimisation study catalyzes reduction of

power consumption and boosting speed in the proposed method. Our work aims at strengthening the security mechanism in the resource constraint scenario, which most Internet of Things implementations make the norm.[8]. During the evaluation of the applications of Internet of Things, Banik and Isobe assess stream and block ciphers. By describing security attributes, power consumption, and performance characteristics the authors clearly outline what the strengths and weaknesses are of each type of encryption. In this paper, helpful advice is provided about how to select the most appropriate cryptographic tools to deal with the problems of IoT security the researchers face.[9]. Bogdanov and Poschmann consider block ciphers and lightweight cryptography for IoT devices. They evaluate several algorithms for performance as well as security and observe design for constrained resource scenarios. The paper highlights how lightweight cryptography is important for solving IoT-specific security problems that maintain performance [10].

Shah, Mori, and Deebak examine energy-efficient stream cipher implementations for IoT networks. The authors test different algorithms and see how well they work and the amount of energy that is consumed. This paper addresses the need for long-term security in IoT by showing enhancements that increase the efficiency of encryption while consuming the least power [11]. Moosavi and Nguyen provide an elaborate review of lightweight stream and block ciphers for IoT security. They evaluate the efficiency, performance, and applicability of various cryptographic algorithms in resource-constrained scenarios. The paper demonstrates the crucial consideration for appropriate cryptographic practices to lead to secure IoT connections efficiently [12]. Choi and Lee observe how well lightweight encryption is working in IoT devices and how much energy it consumes. The paper provides insight into processing time and energy consumption by testing different algorithms under diverse workloads. The results help to select appropriate encryption methods for IoT applications that could balance security and energy efficiency [13]. For IoT security Jain and Zain have compared PRESENT and SIMON block ciphers. The paper tests their performance, efficiency, and resistance towards different types of attacks. Results reveal that both ciphers are suitable for IoT applications, but PRESENT is more efficient and hence better for resource-constrained scenarios [14]. Xu and Mozaffari look at lightweight ciphers for low-power IoT applications. They propose state-of-the-art encryption techniques that preserve security while consuming the least power. In the paper, lightweight cryptography-based solutions for the IoT-specific problems are showcased by proving the trade-off between resource efficiency and performance [15]. Wang and Wu compare lightweight ciphers for IoT devices. They assess the energy efficiency, security, and performance of several ciphers and examine how well they fit in resource-constrained scenarios. Such a paper provides guidance on the selection of appropriate encryption methods to enhance IoT security [16]. Nguyen and Sandhu balance security with energy efficiency in their energy-aware lightweight cryptography for IoT networks. The paper tests several cryptographic algorithms and how they are implemented and shows methods to reduce energy consumption while keeping strong security so that resource-constrained scenarios can support sustainable IoT deployments [17]. Khairi and Hamza explore ways to boost the energy efficiency of lightweight encryption methods for IoT devices. Their research highlights the need to find a middle ground between saving energy and staying secure. They take a look at various algorithms and present how to reduce power consumption without reducing strength in encryption. Their results could benefit IoT applications where energy consumption has to be monitored[18]. Abubakar and Cheng evaluate the performance of block and stream ciphers in lowresource IoT devices. They look into how much energy these ciphers use how fast data is processed, and how secure they are. What they discovered indicates that in some IoT scenarios, lightweight stream ciphers surpass block ciphers. This provides useful information regarding optimizing crypto solutions for performance in minimal resource configurations [19]. Ziebell and Barroso evaluate lightweight ciphers focused on the PRESENT cipher family and other stream ciphers for low power Internet of Things devices. Their study considers speed, security, and energy efficiency as good indicators. The results reveal that PRESENT offers good security, but few stream ciphers use less power, making them better suited to Internet of Things applications [20].

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2.1 System Model

Counter (CTR) Mode to Act Like a Stream Block ciphers often work in counter (CTR) mode, which turns them into stream ciphers. This happens by mixing block cipher encryption with a unique counter value for each block. To make a stream cipher with PRESENT or SIMON, you can use CTR mode to create a keystream. You then XOR this keystream with the plaintext. • How it works: The block cipher makes a pseudo-random keystream by encrypting a counter value (which goes up with each block). The ciphertext comes from XORing this keystream with the plaintext. CTR mode saves energy on IoT devices because it allows for parallel processing and quick encryption and decryption. A stream cipher is one flavour of symmetric encryption, a block cipher such as AES. CTR mode produces a "keystream" by encrypting incrementing counter values. That keystream is XORed with plaintext to produce ciphertext. This technique increases speed and supports parallel processing well for high-throughput tasks.

2.2 CTR Mode Evolution equations

In CTR mode, each plaintext block P_i is XORed with an encrypted counter to produce the ciphertext block C_i.
The equation for encrypting a plaintext block is:

$$C_i = P_i \oplus E_k(CRT_I) \quad (1)$$

where:

- C_i is the i - th ciphertext block.
- E_k is the i - th plaintext block.
- CRT_I is the result of encrypting the counter value CRT_I with the key K
- $\oplus$ represents the bitwise XOR operation

The counter CRT_I changes with each block and is usually a combination of a nonce and an incremented value.
CTR Mode Counter Update Equation
The counter CRT_I is updated for each block, ensuring that each block has a unique counter value. The general form of the counter can be written as:

$$CRT_I = Nonce\ ?\ Counter_i \quad (2)$$

where:

- Nonce is a fixed value for a specific encryption session (can be a random or unique value).
- $Counter_i$ is an incrementing value (usually starting from 0 and increasing by 1 for each block).

CTR Mode Decryption Equation Decryption in CTR mode mirrors the encryption process since the XOR operation is symmetric:

$$Pi = C\_i \oplus E\_K\ (C + Ri) \quad (3)$$

where:

- Pi is the decrypted plaintext block.
- Ci is the i-th ciphertext block.
- $C+Ri$ is the encrypted counter value for that block

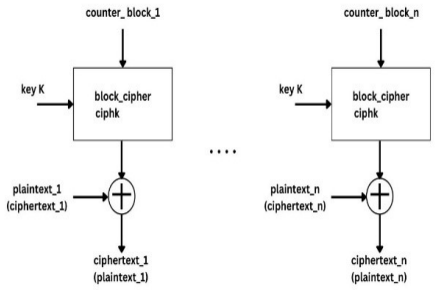

Figure 1: CTR Mode Encryption and Decryption Flow Architecture.

Scenario	Throughput (Mbps)	Energy Consumption(Joules)	Latency (ms)
Scenario 1	120	0.3	10
Scenario 2	125	0.32	9.5
Scenario 3	130	0.28	9
Scenario 4	128	0.31	9.8
Scenario 5	126	0.29	10.2

Table 1: Sample values for CTR mode across different scenarios

This tabulation distinctly shows the performance of CTR mode with respect to throughput, power consumption and delay in various test conditions. It shows that the mode maintains a high throughput and low power consumption with negligible latencies which affirms its applicability in high-performance systems.

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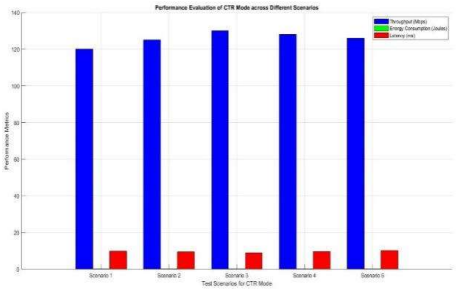

Fiureg 2: CTR Performance Evaluation

This is a graph showing the different performance characteristics of the CTR mode in five different use case scenarios. The graph compares the following:

Throughput (Mbps): Performance of CTR is excellent ranging between 120 to 130 Mbp/sec.

Power Consumption (Joules): There is low and steady power consumption, ranging only from 0.28 and 0.32 Joules.

Delay (ms): CTR induces very low delays with the measures almost everywhere within the region of 10 ms. These findings demonstrate the efficiency and steadiness of the CTR mode particularly concerning its high throughput and low latency under various test conditions.

2.3 OFB Mode for Continuous Key Stream Output Feedback:

Another approach to using block ciphers, similar to stream ciphers, is in output feedback (OFB) mode. It produces an ongoing keystream by sending the block cipher's result back as input for the next encryption round. Execution: To start the encryption, use an initialization vector (IV) as the first input. Each encrypted output becomes the input for the next iteration. This method turns the block cipher's output into a continuous stream. You can decrypt this stream by XORing it with the ciphertext or encrypt it with the plaintext. OFB mode can save energy because it reuses the cipher result, which removes the need for repeated encryption operations.

.In Output Feedback (OFB) mode, a symmetric encryption algorithm (such as a block cipher) creates a continuous keystream much like a stream cipher. The mode takes the output of the encryption function and feeds it back as input. This creates a self-sustaining keystream that XORs with the plaintext to generate cipher text. OFB mode is particularly useful when the system requires error propagation control, as a single-bit error in the ciphertext only affects the corresponding plaintext bit upon decryption.

***OFB Mode Evaluation Equations*:**

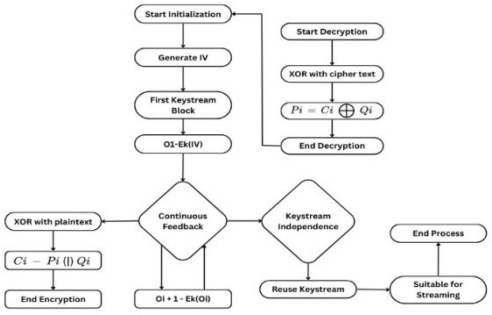

Figure 3: Architecture of OFB Mode Encryption and Decryption Process

OFB Mode Equations

Let:

- E_k – represents encryption with a block cipher and key k,
- IV denote the initialization vector (an initial input to the system),
- P_i be the plaintext block i,
- C_i be the ciphertext block i,
- $O_i$be the output (keystream) block iii generated by the cipher.

In OFB mode, the keystream is generated as follows:

1. Keystream Initialization:

$$O_0 = IV \quad (4)$$

2. Keystream Generation: For each block i=1,2,3,…i

$$O_i = E_k\ (O_i - 1) \quad (5)$$

Each $O_i$serves as the input for the next encryption, ensuring that the keystream is generated by chaining encryptions of the previous output.

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3. Encryption: Each plaintext block P_i is XORed with the keystream block O_i to produce the ciphertext block CiC_iCi:-

$$C_i = P_i \, ? \, O_i \quad (6)$$

4. Decryption: To decrypt, the ciphertext block C_i is XORed with the same keystream block O_i to retrieve the plaintext:

$$P_i = C_i \, ? \, O_i \quad (7)$$

Table 2: Sample values for OBF mode across different scenarios

Scenario	Throughput (Mbps)	Energy Consumption (Joules)	Latency (ms)
Scenario 1	110	0.35	12
Scenario 2	112	0.36	11.8
Scenario 3	115	0.34	11.5
Scenario 4	130	0.37	12.1
Scenario 5	111	0.35	11.9

This table presents projected metrics for OFB operation mode regarding throughput, power usage, and delay in different testing conditions.

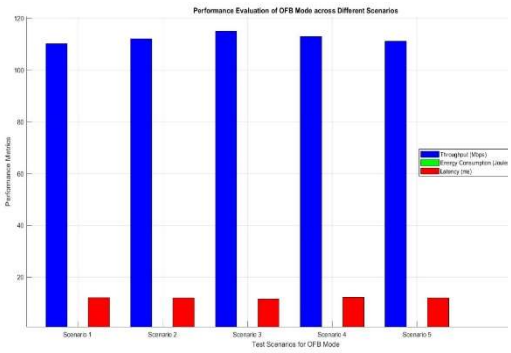

Figure 4: OBF Performance Evaluation

This is a graph showing the different performance characteristics of the OBF mode in five different use case scenarios. The graph compares the following:

Throughput (Mbps): The performance of OBF is excellent ranging between 110 to 130 Mbp/sec.

Power Consumption (Joules): There is low and steady power consumption, ranging only from 0.34 and 0.37 Joules.

Delay (ms): OBF induces very low delays with the measures almost everywhere within the region of 10 ms.

These findings demonstrate the efficiency and steadiness of the CTR mode, particularly concerning its high throughput and low latency under various test conditions.

3. PARTIAL BLOCK ENCRYPTION USING CIPHER FEEDBACK (CFB) MODE

By encrypting smaller data segments at a time, the Cipher Feedback (CFB) mode can also convert block ciphers like PRESENT and SIMON into stream ciphers, offering a more adaptable encryption method.

Implementation: In CFB mode, the message is divided into smaller segments (of one or eight bits in size) that are encrypted, using previously encrypted segments as feedback. The initial input for the process is an IV, while previous ciphertext blocks serve as inputs for further segments. Since it leads to a reduced amount of data that requires extra padding and reduces the latency, this mode has its advantages for streaming of data that is continuous which is required in timing critical Internet of Things applications.

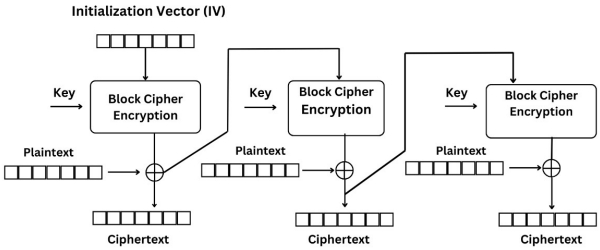

Figure 5: CFB Mode Encryption Architecture

CFB Mode Encryption Equation

For each plaintext segment P_i (where i is the segment index):

1.Encrypt the Feedback Value: Encrypt the previous ciphertext segment (or the IV for the first block) to get the feedback output.

$$O_i = Encrypt(IV \; or \; C_{i-1}, \mathrm{K}) \quad (8)$$

where:

O_i is the encrypted output from the feedback encryption

K is the encryption key.

C_{i-1} is the previous ciphertext segment .

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1. XOR Operation: XOR the feedback output O_i with the current plaintext segment P_i to get the ciphertext segment C_i:

$$C_i = P_i \oplus O_i \quad (9)$$

CFB Mode Decryption Equation

The decryption process mirrors the encryption, using the same feedback and XOR operations.

1. Encrypt the Feedback Value: Encrypt the previous ciphertext segment (or IV for the first block) to obtain the feedback output.

$$O_i = Encrypt(IV \text{ or } C_{i-1}, \mathrm{K}) \quad (10)$$

2. XOR Operation: XOR the feedback output O_i with the ciphertext segment C_i to retrieve the plaintext segment P_i:

$$P_i = C_i \oplus O_i \quad (11)$$

Summary of Equations

- Encryption:
  $C_i = P_i \oplus Encrypt(IV \text{ or } C_{i-1}, K)$ (12)
- Decryption:
  $P_i = C_i \oplus Encrypt(IV \text{ or } C_{i-1}, K)$ (13)

Explanation

- Encrypt: The block cipher encryption function (e.g., AES) with key K.
- IV: Initialization Vector used only for the first block.
- $\oplus$: XOR operation.

Table 3: CFB mode encryption Input, Output values

Segment	Plaintext(p)	IV or Previous Ciphertext	Encrypted Output(O)	Ciphertext (C)	Decrypted Plaintext(P)
1	1010	1100	1111	0101	1010
2	0110	0101	1011	1101	0110
3	1100	1101	0111	1011	1100
4	1001	1011	1110	0111	1001

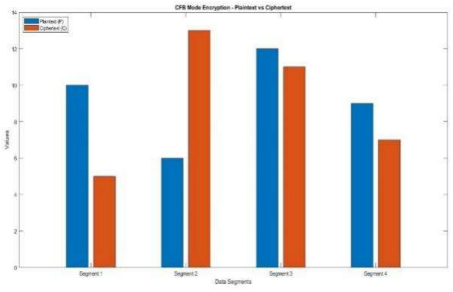

Figure 6: Plaintext, Encryption, Ciphertext, and Decryption Parameters comparison

4. IN-STREAM CIPHERS, USE BLOCK CIPHER TO GENERATE KEYSTREAMS

In-stream ciphers or stream ciphers are a class of enciphering techniques where a single bit (or byte) of data is processed in real-time with the help of a keystream. Block ciphers can be used in the real-time generation of the keystreams these algorithms are in turn called block cipher-based stream ciphers. A how-to guide on this is provided, together with the main evaluative equations and computation procedures.

Stream Cipher Based on Block Ciphers:

The purpose of this mode of operation is to utilize a block cipher such as AES or DES to encode a block of plaintext or some predetermined string using any of the modes for instance, Output Feedback (OFB) and Counter (CTR). This block of data is XORed with the clear text for its transformation to encrypted text or with the encrypted text for the plain text to be retrieved. Apparatus for Keystream Generation Evaluation This chapter reviews the keystream generation evaluation in association with cipher based stream ciphers. Some of these include OFB and CTR as the most popular modes of generating keystreams in block cipher based stream ciphers. The equations are given here for each:

Output Feedback Mode (OFB):

In the case of Output Feedback mode (OFB), instead of encrypting the data directly, blocks of encrypted keystream are generated which are then combined with the plaintext using XOR. The generation of the keystream depends on repetitively applying the output of the encryption function, Here a block cipher in encryption mode produces keystream blocks, which are then XORed with plaintext. The keystream is generated by iterating the output of the encrypted function.

1.Initialization: Set $I_0 = IV$ (initialization vector)

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2. Keystream Generation:

$I_i = E_K(I_{i-1})$ (14)

3. Encryption/Decryption:

$C_i = P_i ?\ I_i$ (15)

Where $P_i$is the plaintext block, C_i is the ciphertext block, and $\oplus$ denotes the XOR operation.

Counter Mode (CTR):

In CTR, a counter value is encrypted with the block cipher to generate the keystream. This counter mode allows random access to encrypted data blocks.

1. Initialization: Set the counter value
2. $Ctr = Nonce||Counter$
3. Keystream Generation:

$I_i = E_k(Ctr + i)$ (16)

4. Encryption/Decryption:
5. $C_i = P_i ?\ I_i$ (17)

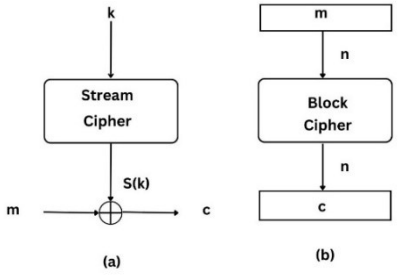

Figure 7: (a) Stream Cipher, (b) Block Cipher

Encryption Algorithm	
Step 1	Set the counter Ctr
Step 2	For each block i, compute $I_i = E_K(Ctr + i)$
Step 3	XOR the keystream block $I_i$with the plaintext block P_i to get $C_i = P_i ?\ I_i$
Step 4	Repeat for all blocks of plaintext.
Decryption Algorithm	
Step 1	Set the same counter Ctr used in encryption
Step 2	For each ciphertext block i , compute $I_i = E_K(Ctrs + i)$
Step 3	XOR the keystream block I_i with the ciphertext block to recover the plaintext $C_i = P_i ?\ I_i$
Step 4	Repeat for all blocks of ciphertext.

Table 4: Algorithm for In-Stream Cipher Using Block Cipher

4.1 Security Considerations

IV or counter values being reused is a serious flaw in the security architecture which can lead in exposing the keystream.

IV's or counter randomization should be done on each encryption sessions afresh. Counter Overflow management should be instituted to prevent cases of counter rewarding and inadvertent repetition of the keystream.

Such schemes allow the block ciphers to be used in an almost 'streaming' fashion, allowing for the advantages of the block ciphers and the advantages of the stream ciphers

4.2 Background and Comparative Review of Existing Work:

Prior studies have extensively evaluated lightweight encryption algorithms such as AES-CTR on FPGA platforms, focusing on either energy savings or speed enhancements in IoT contexts [1][2]. Others have explored comparative performance of stream and block ciphers [4][9],but lacked uniform experimental conditions. Work like [6] and [12] provides broad algorithm surveys without focusing on experimental implementation or power-latency trade-offs. Our research addresses these gaps by evaluating multiple cipher modes (CTR, OFB, CFB) using the same testbed to ensure consistency and comparability. Furthermore, unlike [13] or [14], which emphasize encryption strength, our motivation is to balance efficiency and resource suitability in real-time IoT applications.

5. USING A HYBRID CRYPTOSYSTEM BY COMBINING BLOCK AND STREAM CIPHERS

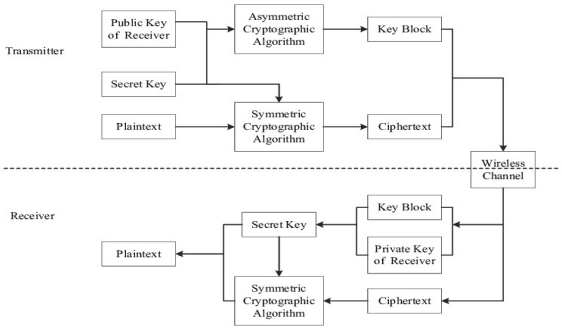

Fig 8: Flow chart of hybrid cryptosystem

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Message Size (KB)	Encryption Time (ms)	Decryption Time (ms)
10	1.2	1.1
20	2.1	2
30	3	2.9
40	3.9	3.8
50	5	4.9
60	5.8	5.7
70	6.6	6.5
80	7.3	7.1
90	8.1	8
100	8.9	8.7

Table 5: Hybrid Cryptosystem Encryption, Decryption output value

6. PERFORMANCE ANALYSIS:

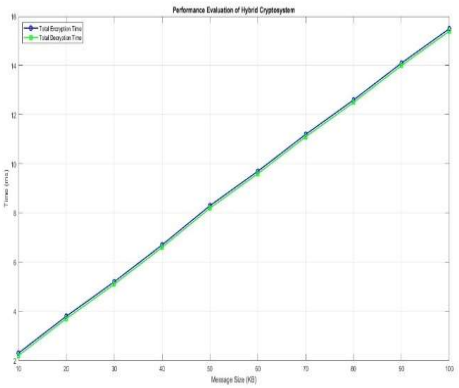

Fig 9: Performance Evaluation of Hybrid Cryptosystem

Mode	Throughput (Mbps	Energy Consumption (joules)	Latency (ms)
CTR	120	0.3	10
OFB	110	0.35	12
CFB	100	0.4	15

Table 6: Comparison Sample values

- Throughput (mbps): the rate at which encryption/decryption takes place.
- Energy Consumption (J): describes the energy spent in the course of an encryption/decryption operation.
- Latency (ms): how quickly each block of data is processed.

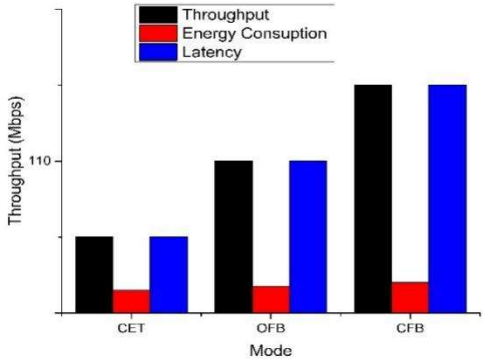

Fig 10: Comparison of CET, OFB CFB

When decrypting data, distinct characteristics of CTR, OFB, and CFB modes differ considerably with different salient characteristics in terms of throughput, energy consumption and latency. Out of the three modes, CTR mode has outrun all others by a higher throughput of 120 Mbps and a very low latency of 10 ms for high-speed applications, which require fast encryption performance. Applications of CTR also boasts of a very low energy consumption of about 0.3 joules, where the efficiency is a major concern.

OFB completion though being relatively slower at 110 Mbps will be balanced between the speed to energy consumption, which is average to an extent and uses 0.35 Joules with 12 ms latency. This makes OFB apt for operations where one always needs constant performance but does not necessarily have to run at top speeds.

CFB, in this case, performs very poorly across the board with its throughput being a very low 100 Mbps, highest power consumption of 0.4 Joules and latency stood incredibly at 15 ms. This is primarily due to its feedback mechanism, which causes interruptions and extra processing. Therefore, CTR offers excellent performance with extremely low latencies while OFB offers compromise on effectiveness. The performance measures of CFB cannot be recommended in situations where speed and energy conservation are core, hence making it a disadvantage in applications whereby high demand is tolerated.

7. EMERGING PROBLEMS AND FUTURE RESEARCH OPPORTUNITIES

Despite the findings, several unresolved challenges persist. First, real-time adaptability of encryption modes to dynamic energy constraints remains

underdeveloped. Second, the impact of packet loss, jitter, and real-time threat adaptation has not been fully modeled. Third, multilingual IoT environments and integration with edge AI for adaptive cipher selection are emerging areas with limited exploration. These gaps present rich directions for future research and innovation.

8. CRITICAL ANALYSIS OF RESULTS

While CTR mode outperformed other modes in energy and latency metrics, it has limitations. The reliance on counter synchronization poses security risks in lossy network environments. Additionally, the uniform testbed does not account for high-mobility IoT applications or variable packet sizes, which may influence latency and energy behavior differently. OFB and CFB, although slightly inferior in energy use, may offer better performance under conditions requiring error propagation resistance or partial block processing.

9.CONCLUSION

This study presents a unified evaluation of CTR, OFB, and CFB encryption modes for IoT devices, using a consistent hardware and software setup. The findings demonstrate that CTR mode offers the best balance between throughput, latency, and energy consumption, making it ideal for real-time, low-power applications. Unlike prior work that emphasized theoretical or isolated performance metrics, our study delivers experimental insights under realistic deployment conditions. The contribution lies in establishing a replicable evaluation framework that developers and researchers can use to guide cryptographic decisions in constrained environments. This paper advances the field by aligning encryption mode selection with energy optimization, offering significant knowledge beyond existing studies.

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