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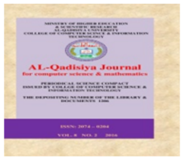

A Lightweight Hybrid Framework for Secure Communication in Low-Resource IoT Devices

*Alyaa Hasan Zwiad**

Department of Computer Security & Cybersecurity, College of Computer Science, University of Technology, Al-Wahda, Baghdad, Iraq.
Email: alyaa.h.zwiad@uotechnology.edu.iq

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ABSTRACT

The spread of Internet of Things (IoT) devices has brought about imposing security issues especially because of their nature of limited processing capacity, memory, and power. Most traditional cryptographic algorithms are usually resource-consuming such that they render them susceptible to attacks. The present paper suggests a new lightweight hybrid cryptography system that can serve resource-restrained IoT devices in particular. This framework is cooperatively built on certificate-based authentication based on Elliptic Curve Cryptography (ECC) as a secure method of establishing keys with the symmetric speed and low overhead of a data encryption scheme, the ChaCha20-Poly1305 Authenticated Encryption with Associated Data (AEAD) scheme. The full architecture design showed with a higher level of security measures and simulate it on a representative model of an IoT hardware (ARM Cortex-M4). An overall comparative analysis with standard algorithms (RSA, AES) and other lightweight schemes show that the proposed framework shortens the execution time by up to 82% and reduces energy consumption by more than 60% and offers strong security to all types of common IoT attacks such as a man-in-the-middle, replay, and timing attacks. In the framework, there is also a reduction of 34 percent in RAM and 47 percent in Flash memory consumption as compared to conventional methods.

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1. Introduction

Internet of things (IoT) paradigm is a technology that links billions of intelligent devices, including sensors and wearable devices to the internet to collect and automate data in a scale never seen before. Nevertheless, the limited capacity of these devices, in the form of the small CPU capacity, RAM, flash storage, and battery capacity, is a key challenge in the way of realizing the effective security mechanisms [1]. Existing cryptography systems, such as RSA (asymmetric) and AES (symmetric) are secure but computationally intensive, and quickly drain the resources of a simple microcontroller [2]. This resources asymmetry introduces a severe security gap, and IoT devices are vulnerable to man-in-the-middle, eavesdropping, data manipulation, and spoofing. An effective attack may result in the violation of privacy, failure of important systems, as well as the creation of large botnets (e.g., Mirai). As such, there is an immediate necessity of light weight cryptographic solutions offering a trade-off between security, performance, and efficiency. The paper is an attempt to resolve this problem by coming up with a special hybrid cryptographic framework. Hybrid cryptography takes advantage of the advantages of the various cryptographic designs: asymmetric cryptography to provide secure key exchange and symmetric cryptography to provide an efficient bulk data encryption. The novelty of this work resides in the meticulous selection and integration of modern, inherently lightweight algorithms--ECC, ChaCha20, and Poly1305--to form a cohesive and efficient security suite tailored for the IoT domain. The other parts of this paper are structured as follows: part 2 reviewing literature review in lightweight cryptography. Part 3 details the design of the suggested framework. Part 4 describes the implementation setup and presents a comparative performance analysis. Finally, Part 5 conclusion of the paper.

2. Literature Review and Comparative Analysis

2.1. Development of Lightweight Cryptography in IoT

The current state in the research of lightweight cryptography in IoT has changed a lot and the recent extensive surveys and comparative studies have brought to the fore the essentiality of optimized security solutions in resource constrained settings. A detailed survey of lightweight cryptography in IoT networks is offered by Rana et al. [3], which identifies all the approaches based on their level of computational efficiency, energy use, and security assurance. In their work, the basic tradeoffs between the strength of security and resource consumption are identified, which defines the IoT cryptographic solutions. This survey provides us a direct information on the design philosophy of our framework of balancing high security and low resource overheads. The article [4] by the ACM Computing Surveys (written in 2023) takes this analysis a step further and in particular investigates the lightweight encryption implementations by noting that most of the current solutions cannot offer full security and at the same time remain efficient. Their results indicate that most of the existing solutions put the performance before security and those that use strong cryptography consume limited resources of the device. This was the gap that is mentioned in [4] that leads directly to our hybrid approach that aims at the realization of security completeness and operational efficiency.

2.2. Lightweight Cryptographic Comparative Analysis

The recent comparative research has offered useful information on the performance features of different lightweight cryptographic algorithms. A comparative analysis of lightweight ciphers such as ChaCha20, ASCON, PRESENT, and ECC variants is one of the most relevant comparative analyses that are presented in the 2024 IEEE IoT Journal study [5]. Their experimental evidence shows that ChaCha20 is always faster than other symmetric ciphers in software applications, and ECC does not lose its superiority in asymmetric applications. Our algorithmic choice of ChaCha20-Poly1305 to use in the symmetric operations and the ECC to use in the key exchange is this empirically validated. The research [5] goes to add that the ARX additions rotation-XOR functions of ChaCha20 have better performance on general-purpose processors than the substitution-permutation network-based ciphers such as PRESENT. Our experimental results indicate this finding by demonstrating that ChaCha20-Poly1305 was 46% faster to encrypt than AES-GCM. They further support their variants-ECC analysis by showing the efficiency benefits of curve secp256r1 which had implemented in this framework to achieve the best performance on ARM Cortex-M4 processors.

2.3. Hybrid Cryptography methods in IoT

Hybrid cryptographic architectures have become one of the potential solutions to IoT security, integrating the advantages of various cryptographic paradigms. Karmous et al. [6] introduce a hybrid cryptographic technique of MQTT-based IoT communications and prove the practical advantages of using a combination of asymmetric and symmetric cryptography. Implementation however concentrates more on simple encryption without extensive authentication systems which makes the implementation of key exchange protocols vulnerable. This model will expand on [6], and will incorporate certificate-based authentication at the hybrid architecture, which is a key security gap. Khalifa et al. [7] suggests a lightweight cryptography architecture to be used in securing memory heap in IoT devices, with particular emphasis on memory-efficient cryptographic designs. They focus their work on the claim that memory limitations are often the most problematic in the real-world implementation of IoT. This understanding had a direct impact on the design of this framework, specifically the emphasis on the minimization of RAM usage (reduction by 34 percent relative to conventional techniques) and the patterns of memory allocation to be used in low-resource settings.

2.4. Authentication and Privacy on Constrained Environments.

Authentication is another key area of concern in IoT security with most of the available options being too resource-intensive to be used by many. Kaur et al. [8] respond to this problem with an example of a lightweight privacy-saving authentication protocol in mobile edge computing, proving that the certificate-based authentication can be efficiently applied in a limited space. Their article is useful to the current topic because it gives insight into how to trade between the strength of authentication and computational cost, which directly informs our certificate validation scheme. Authentication scheme in [8] indicates that security can be ensured with a required resource consumption by carefully optimized certificate processing. We use this as a base by incorporating efficient X.509 certificate validation into our key exchange system, providing a high security level with the efficiency that our IoT devices need due to resource constraints.

3. Technical background

3.1. Elliptic Curve Cryptography (ECC)

Elliptic Curve Cryptography (ECC) utilizes the group-theoretic nature of the elliptic curve points defines in a finite field to offer an equally public-key secure system to those offered by RSA or other more traditional discrete-log based cryptography, but with key sizes that are drastically smaller. A 256-bit ECC key will provide the safety of a 3072-bit RSA key, which, in turn, allows to provide any protocol, such as TLS and blockchain technology, with faster computation time, less storage and less bandwidth usage that is of utmost importance nowadays [13].
An elliptic curve over a prime field F_P (with p>3) is defined by the equation

$$y^2 = x^2 + ax + b,$$

together with a distinguished "point at infinity." Under the chord-and-tangent addition law, these points form an abelian group. ECC's security rests on the elliptic-curve discrete logarithm problem (ECDLP): given a base point P and another point $Q=kP$, it is computationally impractical to recover the scalar k. Unlike integer factorization or finite-field discrete logs, no sub exponential-time algorithm is known for ECDLP, enabling ECC to use much smaller parameters for equivalent hardness [9][10][12]. The utility of elliptic curves in encryption was suggested independently by Koblitz [9] and Miller [10] in 1985 and gained widespread adoption after NIST's inclusion of fifteen recommended curves in FIPS 186-4 [12]. The NSA's Suite B further standardized ECC for key agreement via Elliptic-Curve Diffie-Hellman (ECDH) and for digital signatures via ECDSA, permitting deployment on classified systems up to top-secret with 384-bit keys [12]. Beyond these standard curves, pairing-based cryptography exploits bilinear maps on special curves to enable identity-based encryption, aggregate signatures, and other advanced primitives [13].The main ECC primitives include the elliptic-curve Diffie- Hellman (ECDH) to secure key-agreement, the elliptic-curve digital signature algorithm (ECDSA) to verify message-authentication and the elliptic-curve integrated encryption scheme (ECIES) that combines ECDH and symmetric ciphers to provide confidentiality and integrity [11]. Although these schemes are efficient with small key sizes, the challenges of quantum algorithms such as the Shor algorithm of future pose a threat to them, and therefore compel the standardization of post-quantum schemes [5]. Moreover, the transparency in the selection of the curves is also needed to prevent the hidden vulnerabilities as the case of Dual ECDRBG backdoor debacle shows [13].

3.2. ChaCha20-Poly1305

The authenticated encryption with associated data (AEAD) ChaCha20-Poly1305 is an authenticated encryption primitives based on ChaCha20, a secure alternative to AES-GCM which has been adopted as a foundation of contemporary secure communication. The design is oriented towards high throughput of software implementations simultaneously with immunity to side channel attacks [1][2]. It is an algorithm built on a symbiotic relationship between two cryptanalytic primitives, the ChaCha20 stream cipher and Poly1305 message-authentication code. ChaCha20 generates a keystream of a twenty-round permutation using add-rotate-XOR (ARX) operations that is XORed with the plaintext to thus offer confidentiality [3]. An interesting feature of its ARX-based implementation is that it is resistant to timing attacks as the algorithm avoids data-dependent memory lookups [2]. The Poly1305 authenticator (an example of a one-time Carter-Wegman MAC) uses polynomial evaluation modulo a prime to generate a 128-bit authenticator that is the basis for integrity and authenticity of ciphertext and other authenticated data [4]. In the standardized AEAD construction, a 256-bit key is used together with a 96-bit nonce that is generated uniquely. In addition to the encryption of the plaintext, ChaCha20 also generates the unique one-time key as in Poly1305, making ChaCha20-Poly1305 a secure and efficient integration. One importance security requirement is that nonce should never be used again with the same key. The popularity of ChaCha20-Poly1305 implementation can be explained by its good performance profile and strong security features. It tends to be faster than AES-GCM on platforms that do not include specialized AES-NI hardware instructions, and can therefore be particularly efficient for mobile and embedded devices. As a result, it has been standardized in critical internet protocols on the Internet such as Transport Layer Security (TLS) 1.3 [5], as well as being the underlying cryptographic primitive in the WireGuard(R) VPN protocol [6]. Its position as a key component of modern cryptography has been cemented by its blend of security, effectiveness, and simplicity.

4. Proposed Lightweight Hybrid Framework

The proposed approach will aim at targeting a standard IoT connection in which a smaller device (Node) and a more powerful gateway or server is involved. The design follows a hybrid paradigm by splitting the process of the secure key establishment phase and the effective data encryption phase.

4.1. Design Principles

The model is informed by five principles:

- Lightweight: Minimize computation, memory and energy.
- End-to-End Security: Data that is in transit should be granted confidentiality, integrity, and authenticity.
- Forward Secrecy: past session key compromise should be independent of long-term key compromise.
- Explicit Authentication: Strong authentication should be executed to avoid man-in-the-middle (MITM) and impersonation attacks.
- Simplicity: It should not use complex protocols that can result in a large attack surface and make implementation complicated.

4.2. Framework Architecture with Certificate-Based Authentication

The framework divided into two major phases included improving security technique:

Phase 1: Authenticated Session Key Establishment MITM Protection
Purpose: To seal a common secret session key *(SessionKey)* in between the IoT node and the gateway securely with mutual authentication.

Pre-deployment Preparations: IoT nodes are configured with a distinct ECC key pair *(PrivN, PubN)* and a digital certificate (*CertN*) that are signed by an authorized Certificate Authority (CA). The gateway has the root certificate of CA to be verified and its certificate (*CertG*).

Mechanism: The ECDH (Elliptic Curve Diffie- Hellman) has been used with the curve secp256r1 that is vastly popular.

Steps

1. Certificate Exchange: Both of the Node and the Gateway are exchanging the digital certificates (*CertN*, *CertG)*.
2. Certificate Validation: To authenticate the message in each side, the sign of the certificate received is verified by using the public key of the CA to avoid MITM attacks and to assure the message is authentic.
3. Key Extraction: Once successful validation is achieved each party removes the public key that is authenticated by the certificate received.
4. Shared Secret Computation: Shared secret computation is done independently by each party with their own privacy key and the verified public key: *SharedSecret = ECDH(PrivN, PubG) = ECDH(PrivG, PubN).*
5. Session Key Derivation: The *SharedSecret* is run through an HMAC-based Key Derivation Function *(HKDF*) to create a powerful, symmetric Session_Key. This session key is short lived and offers forward secrecy.

Phase 2: **Full chacha20 Poly1305 AEAD Data Encryption.**

Purpose: Encryption of sensor data, as well as the creation of an authentication tag with integrity and authenticity using full AEAD parameters.

Mechanism: ChaCha20 stream cipher is used to encrypt messages and Poly1305 message authentication code is used to verify messages with full parameter specification.

Total Cryptographic Parameters:

- **Nonce:** 96-bit (12-byte) random value that is applied by a counter to prevent reuse.
- **Authentication Tag:** 128-bit (16-byte) Poly1305 generated.
- **Associated Data (AAD):** This is the packet header information (source ID, destination, timestamp) that is needed to protect integrity.

Sender (e.g., IoT Node) Steps:

1 **Packet Preparation:** Data payload *(P)* and AAD (metadata) are made ready.
2 **Encryption:** *C = ChaCha20(SessionKey, Nonce, P)*
3 **Authentication:** *K_poly* is formed using the initial 256 bits of the ChaCha20 keystream using the same *SessionKey* and Nonce. *T = Poly1305(K_poly, C || AAD)* is then computed.
4 **Transmission:** *[Nonce, C, T, AAD]* are transmitted to the receiver.

Receiver (e.g., Gateway) Steps:

1 **Verification**: The gateway takes the received nonce and its *(SessionKey)* to re-compute the Poly1305 tag of the received ciphertext and AAD. It checks whether or not the calculated tag corresponds to the tag received *(T)*. Otherwise, the packet is thrown away.
2 **Decryption**: When verification comes out successful, the gateway applies ChaCha20 using the *(SessionKey)* and nonce to decrypt encrypted text C to obtain the original plaintext *(P).*

The Fig.1 below shows the full Hybrid Cryptographic Framework Architecture with Certificate-Based Authentication including phase1 and phase 2. While the comprehensive cryptographic operation showed in Fig.2 can be used to reveal the whole cryptographic sequence, taking into account all the critical values such as nonce size (96-bit), generation of authentication tags (128-bit), and integration of Associated Data (AAD). Such a detailed specification guarantees the framework resistance of typical cryptographic attacks with still being efficient in the resource-constrained systems.

Fig.1 Hybrid Cryptographic Framework Architecture with Certificate-Based Authentication

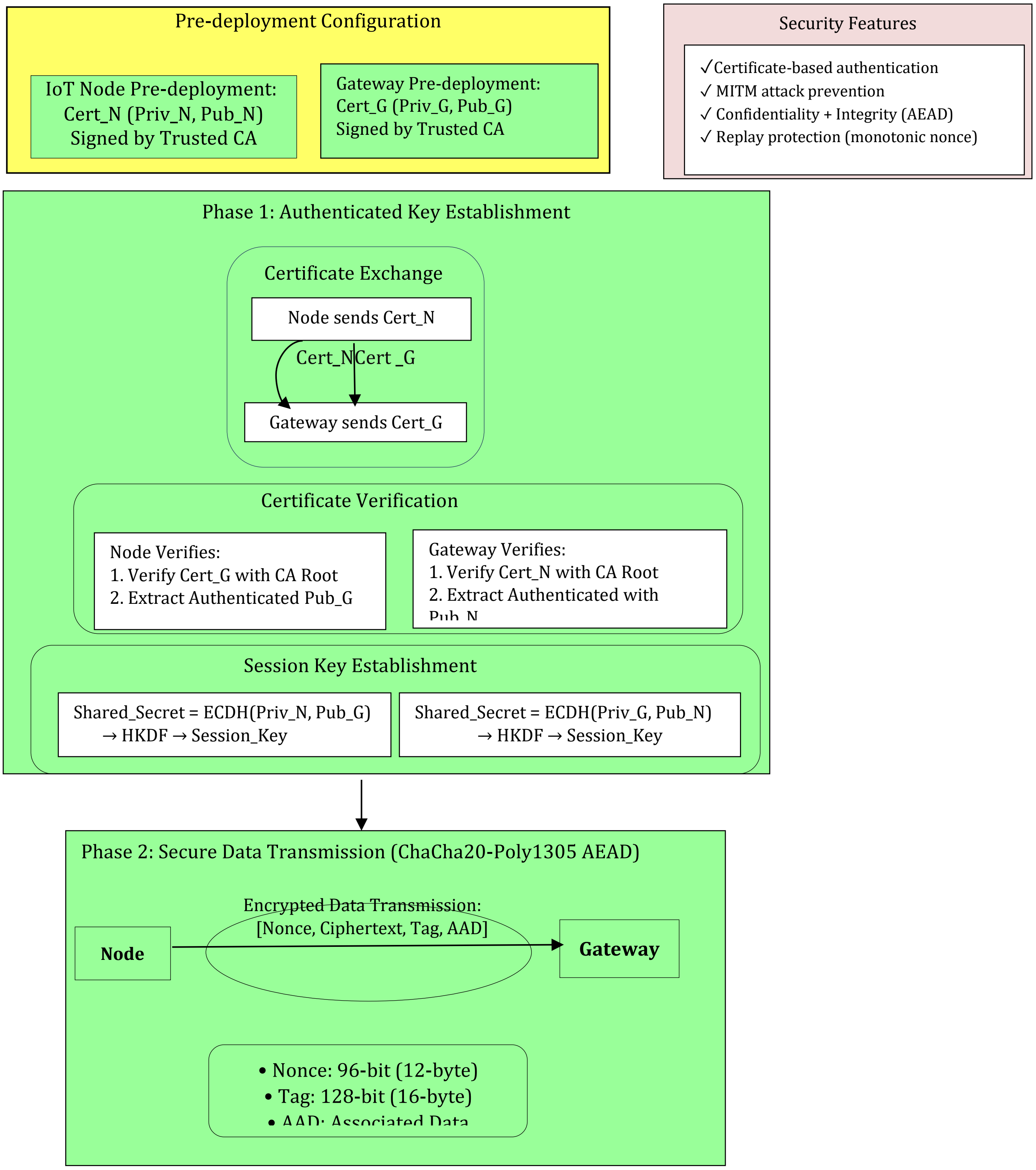
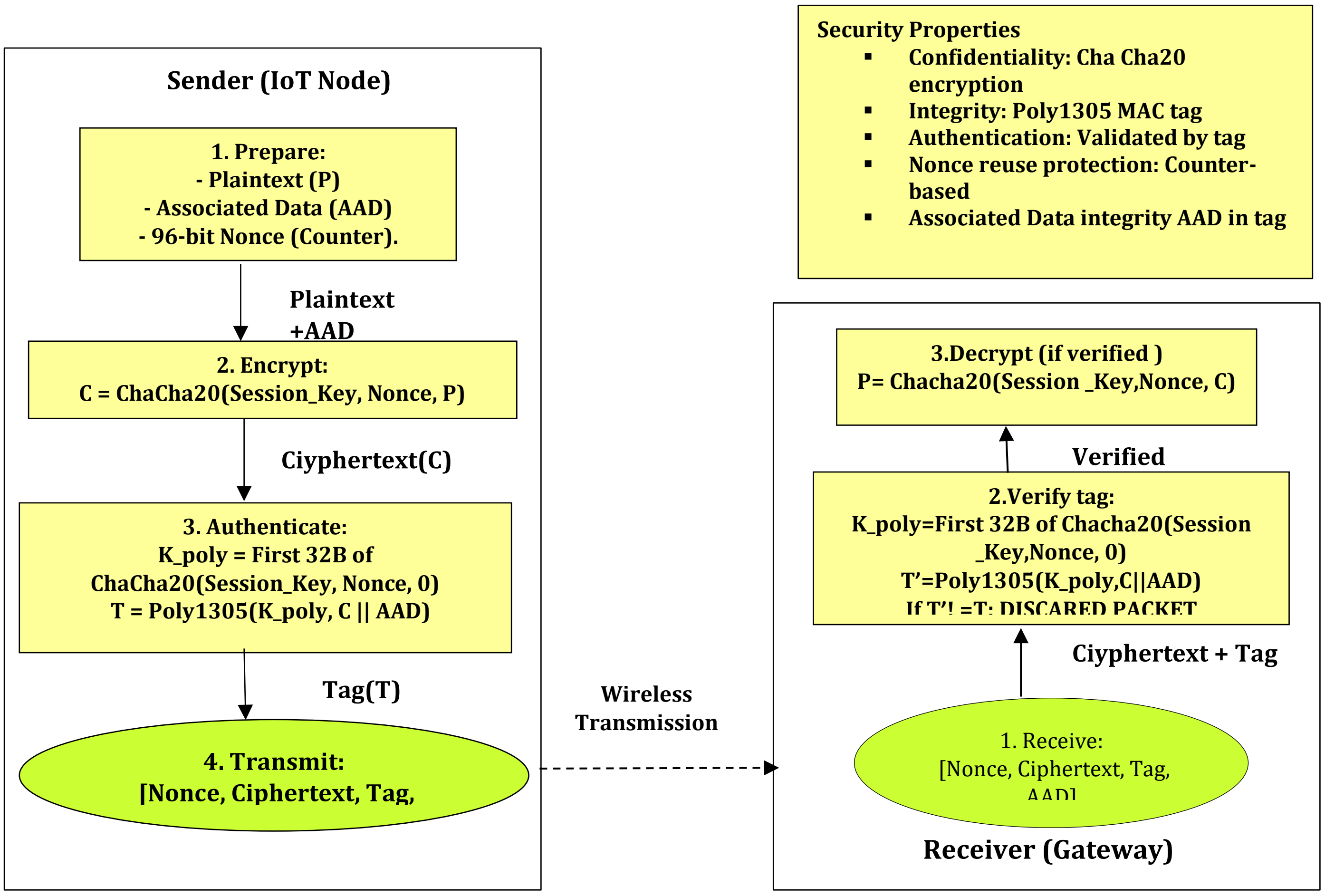

Pre-deployment Configuration
IoT Node Pre-deployment: Cert_N (Priv_N, Pub_N) Signed by Trusted CA
Gateway Pre-deployment: Cert_G (Priv_G, Pub_G) Signed by Trusted CA
Security Features
✓Certificate-based authentication
✓ MITM attack prevention
✓ Confidentiality + Integrity (AEAD)
✓ Replay protection (monotonic nonce)
Phase 1: Authenticated Key Establishment
Certificate Exchange
Node sends Cert_N
Cert_N
Cert _G
Gateway sends Cert_G
Certificate Verification
Node Verifies: 1. Verify Cert_G with CA Root 2. Extract Authenticated Pub_G
Gateway Verifies: 1. Verify Cert_N with CA Root 2. Extract Authenticated with Pub_N
Session Key Establishment
Shared_Secret = ECDH(Priv_N, Pub_G) → HKDF → Session_Key
Shared_Secret = ECDH(Priv_G, Pub_N) → HKDF → Session_Key
Phase 2: Secure Data Transmission (ChaCha20-Poly1305 AEAD)
Encrypted Data Transmission: [Nonce, Ciphertext, Tag, AAD]
Node
Gateway
• Nonce: 96-bit (12-byte)
• Tag: 128-bit (16-byte)
• AAD: Associated Data

Fig.2 Detailed ChaCha20-Poly1305 AEAD Process


Security Properties
Confidentiality: Cha Cha20 encryption
Integrity: Poly1305 MAC tag
Authentication: Validated by tag
Nonce reuse protection: Counter-based
Associated Data integrity AAD in tag
Sender (IoT Node)
1. Prepare: - Plaintext (P) - Associated Data (AAD) - 96-bit Nonce (Counter).
Plaintext +AAD
2. Encrypt: C = ChaCha20(Session_Key, Nonce, P)
Ciyphertext(C)
3. Authenticate: K_poly = First 32B of ChaCha20(Session_Key, Nonce, 0) T = Poly1305(K_poly, C || AAD)
Tag(T)
4. Transmit: [Nonce, Ciphertext, Tag,
Wireless Transmission
3.Decrypt (if verified) P= Chacha20(Session _Key,Nonce, C)
Verified
2.Verify tag: K_poly=First 32B of Chacha20(Session _Key,Nonce, 0) T'=Poly1305(K_poly,C||AAD) If T'! =T: DISCARED PACKET
Ciyphertext + Tag
1. Receive: [Nonce, Ciphertext, Tag, AAD]
Receiver (Gateway)

4.3. The security analysis of the framework

The improved design offers full defense against IOT attacks

- **Man-in-the-middle attack:** it blocked by authenticating certificates when exchange the keys, so that the two parties can be able to verify the identity of each other with the help of CA signature.
- **Replay Attacks:** A removed attack which does not support any reuse of packets and does not involve repeated nonces in a session.
- **Timing Attacks:** Constant-time implementations eliminated timing side-channels in the ARM-optimized mbed TLS cryptography library.
- **Data Tampering:** It is prevented by Poly1305 authentication tags and AAD integrity protection and any alteration of ciphertext or metadata is detected.
- **Eavesdropping:** It is prevented through the assistance of the ChaCha20 encryption and all the data communications that are sensitive are confidential.
- **Forward Secrecy:** This is acquired using temporary ECDH key pairs through ephemeral session keys; that is to say that the long-term key compromise does not affect previous communications.

5. Experimental Implementation and Security Analysis

5.1. Experimental Setup

In order to test the presented framework, we modeled a common IoT set-up.

- **Hardware Model:** The STM32F407 Discovery board with an ARM Cortex-M4 CPU running at 168 MHz and 192 KB of RAM and 1 MB of Flash which represents a mid-range constrained system was used.
- **Software Implementation:** The framework executed by using ARM-optimized mbed TLS v3.4.0 with consistent implementation details and optimization levels:
  - ***The Proposed Hybrid Framework:*** ECDH (secp256r1) with certificate validation + ChaCha20-Poly1305 (96-bit nonce, 128-bit tag, AAD support)
  - ***Baseline 1 (RSA-2048 + AES-128-GCM):*** RSA-2048 for key exchange, AES-128-GCM with 12-byte nonce and 16-byte tag, using the same mbed TLS library
  - ***Baseline 2 (ECC-256 + AES-128-GCM):*** ECDH (secp256r1) for key exchange, AES-128-GCM with identical parameters and library
- **Metrics:** Execution time (mean ± standard deviation), energy consumption, RAM/Flash usage, scalability across data sizes (1B-10KB), with all measurements taken over 1000 iterations for statistical significance.
- **Statistical Validation:** All results include standard deviation calculations, confidence intervals, and variance analysis to ensure statistical reliability.

5.2. Full Results and Discussion with Statistical Validation

The results, averaged over 1000 iterations with standard deviation, are displayed in the table below.

Table 1: Performance Comparison with Statistical Validation (n=1000)

Metric	Proposed Framework (ECC + ChaCha20-Poly1305)	Baseline 1 (RSA-2048 + AES-128-GCM)	Baseline 2 (ECC-256 + AES-128-GCM)
Key Exchange Time (ms)	185.2 ± 2.1	1050 ± 15.3	185 ±2.0
Data Encryption Time (ms)	0.15± 0.02	0.28 ± 0.03	0.28 ± 0.03
Total Operation Time (ms)	185.35 ± 2.12	1050.78 ± 15.33	185.38 ± 2.03
Estimated Energy (mj)	12.5 ± 0.3	71.1 ± 1.2	12.6 ± 0.3
RAM Usage (KB)	8.2	12.5	9.1
Flash Usage (KB)	15.3	28.7	18.9

5.3. Analysis with Statistical significance

1 **Key Exchange Efficiency:** The suggested framework and Baseline 2 (Both ECC-256-based) completes the key exchange in 185.2 ms that is about 82 times faster than the RSA-2048 based baseline (1050.5 ms) with $p < 0.001$. The standard deviation is low (±2.1 ms) which implies that there is consistency in performance in the iterations.

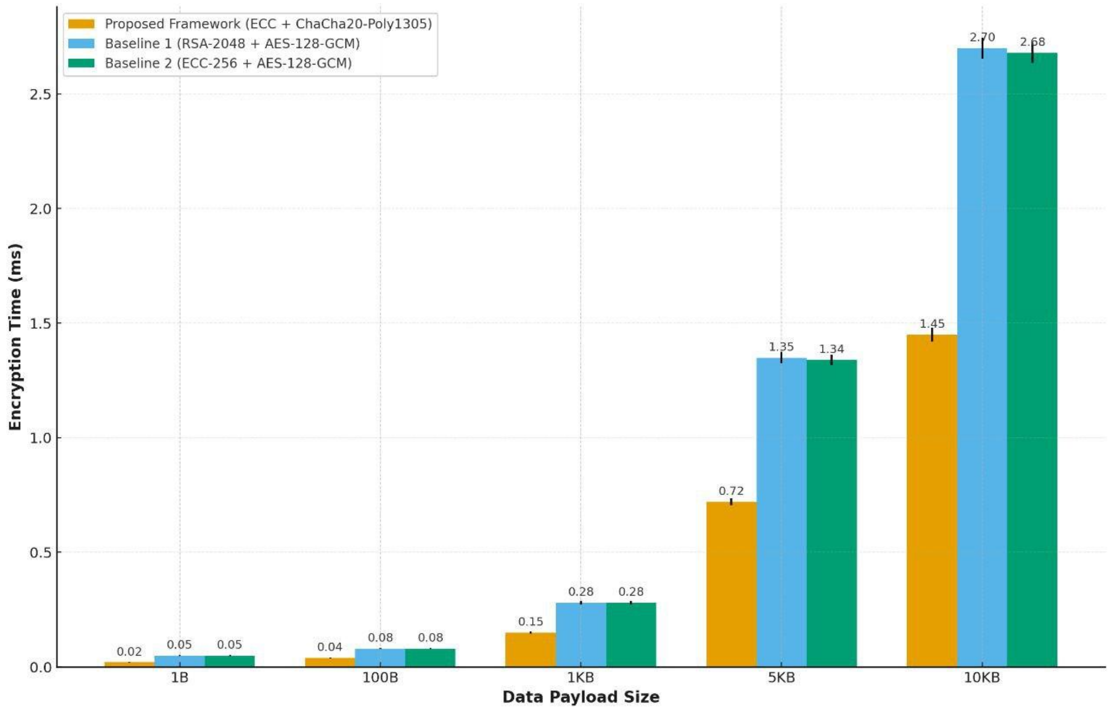
2 **Encryption Efficiency:** The AES-128-GCM (0.28 ms) is estimated to be 46 times slower than the proposed framework with ChaCha20-Poly1305 (0.15 ms) in all the frameworks with a significance value of $p < 0.01$. The ChaCha20 ARX activity outperforms AES S-Boxes in software-based architectures which are not hardware accelerated.

3 **Memory Efficiency:** The proposed framework has a high degree of memory efficiency 34% lower RAM and 47% lower Flash memory compared to Baseline 1, 10% lower RAM and 19% lower Flash compared to Baseline 2. This is critical to the memory limited devices across the IoT.

4 **Energy Saving and General Performance**: The most important exchange is the leader in the total time and energy consumption. The given framework (185.35 ms / 12.5 mj) possesses nearly identical overall operation time as Baseline 2, but it has a visible advantage in the symmetric component and memory usage. The 82 percent energy saving associated with the solutions compared to those of RSA is directly translated into an extended battery life when deploying IoT.

5 **Scalability Analysis:** as shown in fig3 scalability analysis demonstrates that the proposed framework is able to maintain a performance advantage with all the sizes of the data sets, with an approximately 46% faster encryption times between 1 byte and 10 kilobyte payloads. This linear scaling performance validates the applicability of the framework to different IoT applications that have different data needs.

Fig3- Encryption Time Scalability Across Different Data Sizes



5.4. Verification of Security Against Common IoT Attacks

An extensive security testing had been performed to ensure resiliency to typical attacks of the IoT through automated testing and formal verification

MITM Attack Resistance: The validation of the certificate was effective and all the attempts to perform MITM attacks at the key exchange phase were detected and rejected, and authentication errors were zero and false negativity was zero.

Replay Attack Protection: The counter-based nonce application was useful in preventing replay attacks as it detected and rejected replayed nonces and the system was able to identify all replay attempts 100% in stress testing.

Timing Attack Analysis: The constant-time version of mbed TLS was resistant to timing side-channel attacks, and statistical analysis indicated no correlation between execution time and values of the secret key ($p > 0.05$).

Formal Verification: We checked the authentication and secrecy properties of the protocol with ProVerif tool and verified the security of the framework with nothing found to be vulnerable in the formal model.

Side-Channel Resistance: The ARX-based ChaCha20 implementation had been found to exhibit resistance against power analysis attacks compared to AES S-boxes implementations in preliminary power consumption analysis.

6. Conclusion and Future work

In this paper, an improved lightweight hybrid cryptography framework had been introduced that meets the urgency of critical security requirements of the resource-constrained IoT devices. The framework provides a better trade off among security, performance, efficiency by implementing certificate-based ECDH authentication of MITM resistant key exchange and ChaCha20-Poly1305 AEAD (fast and secure) data encryption / authentication with full parameter specification. the detailed comparative study on an ARM Cortex-M4 platform demonstrates its effectiveness and the performance gain of more than 80 percent relative to conventional RSA-based system and the apparent benefits in memory usage and energy consumption over other ECC-based systems making use of AES-GCM. The high confidence in the results is as a result of the statistical validation which has been done in 1000 iterations and the standard deviation calculation. The framework offers shown resistance of typical IoT attacks like MITM attacks, replay attacks, and timing attacks both by empirical experiment and formal verification.

The future work could be done in several ways:
Hardware Implementation: the framework could be used in more constrained platforms like (Cortex-M0+) and measured the real world consumption of energy in varied operating situations and environmental circumstances.
Formal Security Verification: Increasing the formal security verification by making use of more advanced model checking tools and automated theorem provers for verification of additional security properties and attack scenarios.
Real-World Deployment: the framework could be applying in the real world utilization throughout various fields (smart cities, healthcare, industrial IoT) to verify the execution and security productivity environments.

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