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Implementation of AES-128 Encryption for Fingerprint Template Protection in ESP32-Based Biometric Ticketing System

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Abstract: *Biometric ticketing systems utilizing fingerprint recognition provide enhanced security and convenience for passenger identification in public transportation. However, the transmission of fingerprint templates over wireless networks without adequate cryptographic protection exposes the system to interception attacks and privacy breaches. This research implements AES-128 encryption in Cipher Block Chaining (CBC) mode to protect fingerprint templates transmitted within an ESP32-based biometric ticketing system. The implementation leverages the ESP32's integrated mbedTLS library with hardware acceleration to achieve efficient cryptographic operations. Preliminary evaluation using 10 fingerprint template samples demonstrates successful encryption-decryption operations under controlled laboratory conditions. Performance measurements indicate an average encryption latency of 2.30 ms and decryption latency of 2.10 ms, with a data size overhead of 32 bytes (6.25%) due to Initialization Vector (IV) and PKCS7 padding. The results confirm that the proposed encryption scheme provides confidentiality protection for biometric data during transmission while maintaining system responsiveness suitable for real-time applications.*

Keywords: *AES-128, biometric template protection, ESP32, fingerprint encryption, IoT security*

1. Introduction

The proliferation of Internet of Things (IoT) technology has catalyzed significant advancements in public transportation systems, particularly in passenger identification and ticketing mechanisms. Fingerprint-based biometric ticketing systems represent a paradigm shift from conventional paper or card-based tickets, offering enhanced security through unique physiological characteristics that cannot be lost, forgotten, or easily transferred [1]. The irreplaceable nature of biometric identifiers makes them particularly suitable for applications requiring non-transferable authentication. Recent developments in biometric ticketing for public transportation have demonstrated the feasibility of distributed systems utilizing microcontroller-based devices. Various researchers have proposed biometric-based e-ticketing and access control frameworks for public transportation that employ biometric recognition for passenger identification and fare collection [2]. Such systems typically consist of enrollment stations for initial biometric registration and verification gates for identity authentication during boarding. In fingerprint-based implementations, the fingerprint templates extracted during enrollment are stored on central servers and subsequently distributed to verification devices through wireless networks.

Despite the advantages of biometric ticketing systems, security vulnerabilities remain a critical concern. Analysis of existing implementations reveals that fingerprint templates are frequently transmitted as plaintext data over network connections, rendering them susceptible to eavesdropping and man-in-the-middle attacks [3]. Unlike passwords or PINs, biometric data is inherently permanent and cannot be revoked or replaced upon compromise [4]. The ISO/IEC 24745:2022 standard emphasizes that biometric template protection must ensure confidentiality, integrity, and renewability throughout the data lifecycle [5]. Consequently, any breach of fingerprint template data poses irreversible long-term privacy implications for affected individuals.

To address these security vulnerabilities, this research implements cryptographic protection for fingerprint templates using the Advanced Encryption Standard (AES) algorithm with 128-bit key length. AES is the symmetric encryption standard established by the National Institute of Standards and Technology (NIST) and is globally recognized for protecting sensitive data [6]. The CBC mode of operation was selected for this implementation based on several technical considerations: (1) full hardware acceleration support on ESP32's AES peripheral, (2) lower memory footprint compared to authenticated modes that require additional tag storage, (3) simpler implementation suitable for proof-of-concept validation, and (4) compatibility with the existing system architecture [7]. While CBC provides confidentiality without built-in authentication, this limitation is acknowledged and addressed in the security analysis.

The research objectives are formulated as follows:
1. To implement AES-128 CBC encryption for securing fingerprint template transmission in a biometric ticketing system.
2. To integrate the encryption module with existing ESP32-based enrollment and verification devices.
3. To evaluate the computational overhead introduced by the encryption process in terms of latency and data size.
4. To validate system functionality through comprehensive testing of encryption and decryption operations.

The primary contribution of this research is a practical implementation and empirical evaluation of AES-128 encryption on resource-constrained ESP32 microcontrollers for biometric template protection, providing a reference architecture for developing secure IoT-based biometric systems.

2. Literature Review

A. Advanced Encryption Standard (AES)

The Advanced Encryption Standard (AES) is a symmetric block cipher algorithm developed by Vincent Rijmen and Joan Daemen, adopted as a federal encryption standard by NIST in 2001 [6]. AES operates on fixed 128-bit data blocks and supports three key length variants: 128, 192, and 256 bits, corresponding to 10, 12, and 14 encryption rounds, respectively. The algorithm employs a substitution-permutation network structure comprising four primary operations: SubBytes, ShiftRows, MixColumns, and AddRoundKey.

For embedded systems with computational constraints, AES-128 represents an optimal balance between security strength and processing efficiency [8]. A 128-bit key provides a keyspace of 2^128 possible combinations, rendering brute-force attacks computationally infeasible with current technology. Research by Radhakrishnan et al. [9] evaluated lightweight cryptographic algorithms on resource-constrained IoT devices and confirmed that AES-128 achieves favorable performance metrics while maintaining robust security guarantees.

B. Cipher Block Chaining (CBC) Mode

CBC is a block cipher mode of operation that introduces interdependency between consecutive ciphertext blocks through XOR operations with an Initialization Vector (IV) [7]. The encryption process for the i-th block is defined as:

C_i = E_K(P_i ⊕ C_{i-1})

where C_i denotes the i-th ciphertext block, P_i represents the i-th plaintext block, E_K is the encryption function using key K, and C_0 is the Initialization Vector. The principal advantage of CBC mode lies in its semantic security: identical plaintext blocks produce different ciphertext when encrypted with distinct IVs, thereby preventing pattern recognition attacks. However, CBC encryption is inherently sequential as each block depends on the preceding ciphertext block, precluding parallelization. For applications requiring authenticated encryption, alternative modes such as Galois/Counter Mode (GCM) provide both confidentiality and integrity verification [10].

C. Cryptographic Implementation on ESP32 Platform

The ESP32 microcontroller features a dual-core Xtensa LX6 processor operating at 240 MHz with integrated hardware acceleration for cryptographic operations [11]. The mbedTLS library is natively integrated within the ESP-IDF and Arduino frameworks, providing standardized APIs for symmetric and asymmetric cryptographic algorithms. Research by Maier et al. [11] demonstrated that ESP32's hardware cryptographic accelerator achieves performance improvements of up to 5x compared to software-only implementations. Recent studies have further explored cryptographic implementations on ESP32 for IoT security applications. Amirkhanova et al. [12] implemented an end-to-end encrypted data pipeline using AES-256-GCM on ESP32 for Industrial IoT applications, demonstrating packet-preparation latencies suitable for real-time sensor data transmission. Al-Mashhadani and Shujaa [13] developed an ESP32-based IoT security system utilizing AES encryption with dynamic bio-keys, validating the platform's capability for cryptographic operations in resource-constrained environments.

D. Biometric Template Protection

The protection of biometric templates is governed by international standards, particularly ISO/IEC 24745:2022, which specifies requirements for biometric information protection including confidentiality, integrity, and renewability [5]. The standard mandates that protected templates must satisfy irreversibility and unlinkability properties to prevent reconstruction of original biometric data and cross-matching across databases. Several approaches have been proposed for biometric template protection on embedded systems. Rodriguez-Quiñonez et al. [14] implemented hyperchaotic encryption based on Lotka-Volterra dynamics for fingerprint template protection on microcontroller platforms, achieving secure storage with low computational overhead. Alternative approaches include cancelable biometrics and biometric cryptosystems, though these techniques introduce additional complexity not always suitable for resource-constrained devices [15].

E. Comparative Analysis

Table 1 presents a comparative analysis of this research with related implementations of cryptographic protection for biometric and sensor data on embedded platforms.

Table 1. Comparison with Related Research

Aspect	This Research	Al-Mashhadani et al. [13]	Rodriguez-Quiñonez et al. [14]	Amirkhanova et al. [12]
Platform	ESP32	ESP32	32-bit MCU	ESP32
Algorithm	AES-128-CBC	AES-128	Hyperchaotic Lotka-Volterra	AES-256-GCM
Key Size	128 bit	128 bit	160 bit (SHA-1)	256 bit
Key Management	Static	Dynamic bio-key	Dynamic	Static
Protected Data	Fingerprint template	Sensor data	Fingerprint template	Sensor data
Library	mbedTLS	ESP-IDF Crypto	Custom	mbedTLS
Authentication	No	No	No	Yes (AEAD)

The comparative analysis reveals that while existing research has demonstrated the feasibility of cryptographic operations on ESP32, specific implementations for fingerprint template protection with empirical performance evaluation remain limited. This research addresses this gap by providing detailed implementation and measurement of AES-128-CBC encryption for biometric templates.

It should be noted that symmetric encryption such as AES primarily provides confidentiality protection, preventing unauthorized access to template data during transmission. However, it does not inherently provide the irreversibility and unlinkability properties specified in ISO/IEC 24745:2022 for complete biometric template protection. The encryption layer implemented in this research serves as a foundational security measure that can be combined with additional template protection schemes in future implementations.

3. Methods

A. System Architecture

The biometric ticketing system comprises three principal components: Enrollment Station (Device 1), Central Server, and Verification Gate (Device 2). Figure 1 illustrates the system architecture incorporating the encryption module.

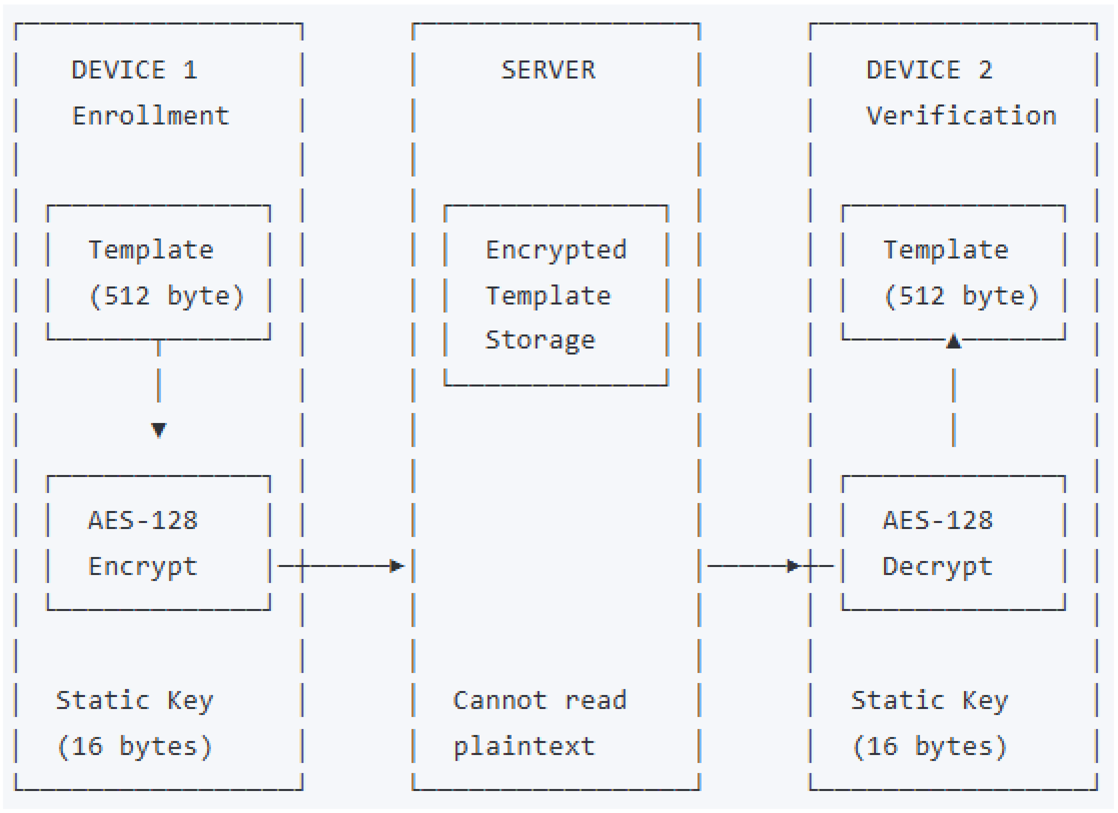


Figure 1. System Architecture with AES-128 Encryption

The system workflow incorporating encryption proceeds as follows:

1. Device 1 extracts the 512-byte fingerprint template from the AS608 sensor module.
2. The template undergoes AES-128-CBC encryption using a randomly generated IV.
3. The concatenated IV and ciphertext are transmitted to the server as a hexadecimal string within JSON payload.
4. The server stores the encrypted template without capability to access plaintext content.
5. Device 2 retrieves encrypted templates from the server during synchronization.
6. Device 2 performs decryption using the pre-shared symmetric key.
7. The recovered plaintext template is loaded into the sensor's local database for verification operations.

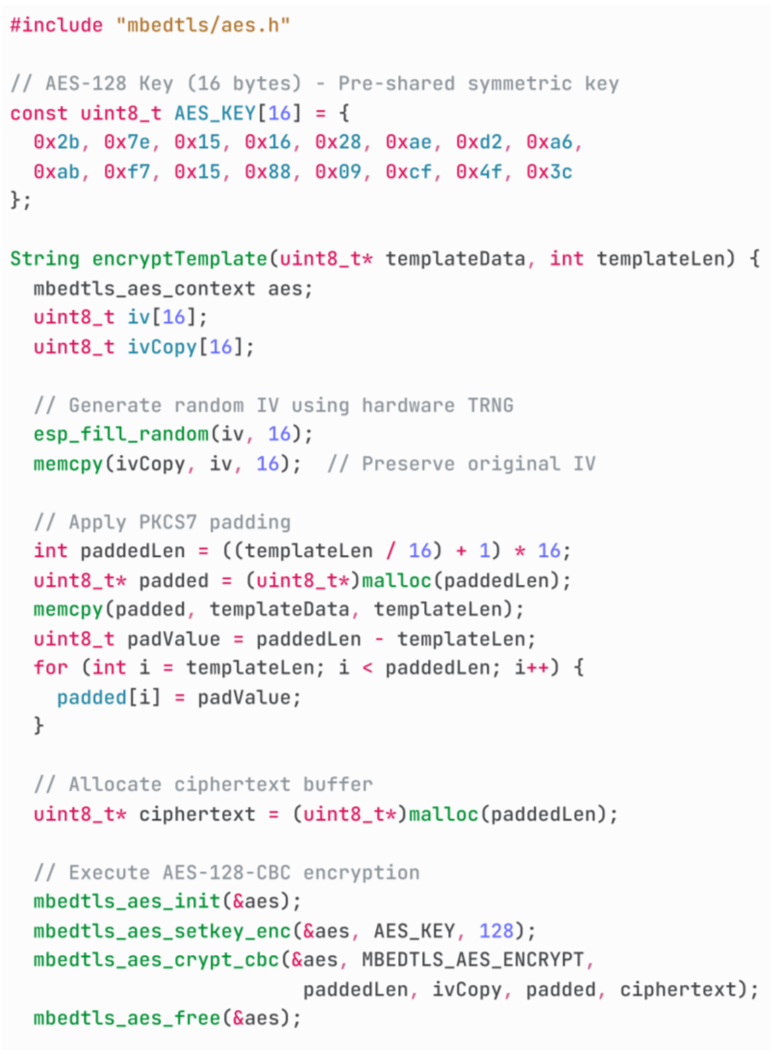
B. Encryption Algorithm

The fingerprint template encryption process comprises the following sequential operations:

1. IV Generation: A 16-byte Initialization Vector is generated using the ESP32's hardware True Random Number Generator (TRNG), ensuring cryptographic randomness for each encryption operation.
2. PKCS7 Padding: Padding bytes are appended to achieve data length as a multiple of the 16-byte AES block size. For the 512-byte template (already block-aligned), 16 bytes of padding with value 0x10 are added per PKCS7 specification.
3. AES-128-CBC Encryption: The padded plaintext is encrypted using the 16-byte symmetric key and generated IV through the mbedTLS library's CBC implementation.
4. IV Prepending: The IV is concatenated with the ciphertext to enable decryption without separate IV transmission.
5. Hexadecimal Encoding: The binary encrypted output is converted to hexadecimal string representation for JSON-compatible transmission.

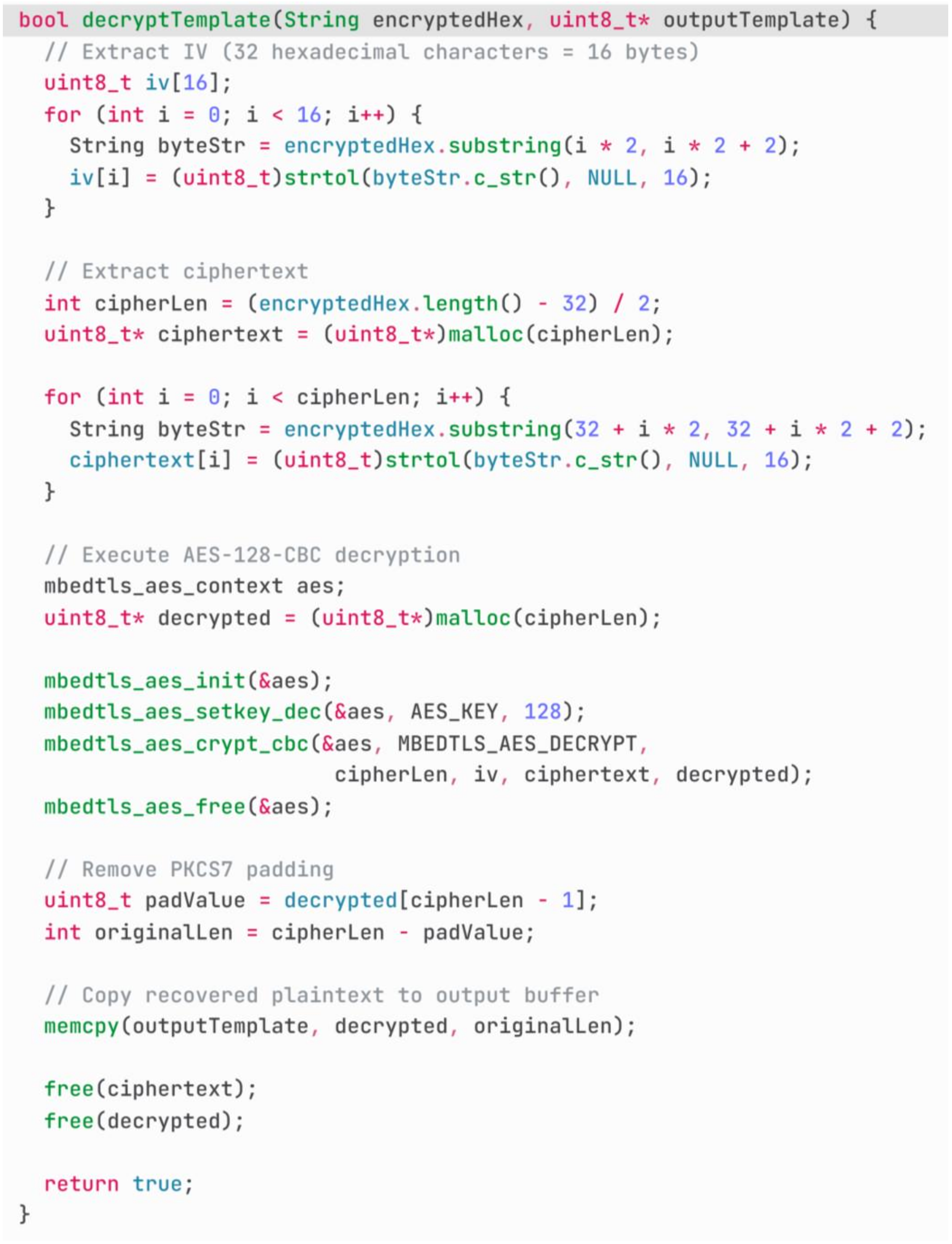
C. Encryption Implementation on Device 1

The encryption module utilizes the mbedTLS library integrated within the ESP32 framework. The implementation code is presented below:



```
#include "mbedtls/aes.h"

// AES-128 Key (16 bytes) - Pre-shared symmetric key
const uint8_t AES_KEY[16] = {
  0x2b, 0x7e, 0x15, 0x16, 0x28, 0xae, 0xd2, 0xa6,
  0xab, 0xf7, 0x15, 0x88, 0x09, 0xcf, 0x4f, 0x3c
};

String encryptTemplate(uint8_t* templateData, int templateLen) {
  mbedtls_aes_context aes;
  uint8_t iv[16];
  uint8_t ivCopy[16];

  // Generate random IV using hardware TRNG
  esp_fill_random(iv, 16);
  memcpy(ivCopy, iv, 16);  // Preserve original IV

  // Apply PKCS7 padding
  int paddedLen = ((templateLen / 16) + 1) * 16;
  uint8_t* padded = (uint8_t*)malloc(paddedLen);
  memcpy(padded, templateData, templateLen);
  uint8_t padValue = paddedLen - templateLen;
  for (int i = templateLen; i < paddedLen; i++) {
    padded[i] = padValue;
  }

  // Allocate ciphertext buffer
  uint8_t* ciphertext = (uint8_t*)malloc(paddedLen);

  // Execute AES-128-CBC encryption
  mbedtls_aes_init(&aes);
  mbedtls_aes_setkey_enc(&aes, AES_KEY, 128);
  mbedtls_aes_crypt_cbc(&aes, MBEDTLS_AES_ENCRYPT,
                        paddedLen, ivCopy, padded, ciphertext);
  mbedtls_aes_free(&aes);
```

D. Decryption Implementation on Device 2



```
bool decryptTemplate(String encryptedHex, uint8_t* outputTemplate) {
  // Extract IV (32 hexadecimal characters = 16 bytes)
  uint8_t iv[16];
  for (int i = 0; i < 16; i++) {
    String byteStr = encryptedHex.substring(i * 2, i * 2 + 2);
    iv[i] = (uint8_t)strtol(byteStr.c_str(), NULL, 16);
  }

  // Extract ciphertext
  int cipherLen = (encryptedHex.length() - 32) / 2;
  uint8_t* ciphertext = (uint8_t*)malloc(cipherLen);

  for (int i = 0; i < cipherLen; i++) {
    String byteStr = encryptedHex.substring(32 + i * 2, 32 + i * 2 + 2);
    ciphertext[i] = (uint8_t)strtol(byteStr.c_str(), NULL, 16);
  }

  // Execute AES-128-CBC decryption
  mbedtls_aes_context aes;
  uint8_t* decrypted = (uint8_t*)malloc(cipherLen);

  mbedtls_aes_init(&aes);
  mbedtls_aes_setkey_dec(&aes, AES_KEY, 128);
  mbedtls_aes_crypt_cbc(&aes, MBEDTLS_AES_DECRYPT,
                        cipherLen, iv, ciphertext, decrypted);
  mbedtls_aes_free(&aes);

  // Remove PKCS7 padding
  uint8_t padValue = decrypted[cipherLen - 1];
  int originalLen = cipherLen - padValue;

  // Copy recovered plaintext to output buffer
  memcpy(outputTemplate, decrypted, originalLen);

  free(ciphertext);
  free(decrypted);

  return true;
}
```

E. Modified Template Transmission Function

The template transmission function is modified to incorporate encryption prior to network transmission:

```
void sendTemplateToServer(String userId, uint8_t* rawTemplate) {
  if (WiFi.status() != WL_CONNECTED) return;

  // Encrypt template and measure latency
  unsigned long startTime = micros();
  String encryptedHex = encryptTemplate(rawTemplate, 512);
  unsigned long encryptTime = micros() - startTime;

  Serial.println("Encryption time: " + String(encryptTime / 1000.0) + " ms");
  Serial.println("Encrypted size: " + String(encryptedHex.length()) + " chars");

  // Transmit encrypted data to server
  HTTPClient http;
  String url = String(SERVER_URL) + "/api/save_template";
  http.begin(url);
  http.addHeader("Content-Type", "application/json");

  String jsonData = "{\"user_id\":\"" + userId +
                    "\",\"template\":\"" + encryptedHex + "\"}";

  int code = http.POST(jsonData);
  // Response handling omitted for brevity
}
```

F. Data Packet Structure

Table 2 presents the data packet structure comparison before and after encryption.

Table 2. Data Packet Structure

Component	Size (bytes)	Description
Before Encryption		
Plaintext template	512	Raw biometric data from sensor
Hexadecimal encoding	1024 chars	JSON-compatible transmission format
After Encryption		
Initialization Vector	16	Randomly generated per encryption
Ciphertext	528	512 + 16 bytes PKCS7 padding
Total encrypted data	544	IV + ciphertext
Hexadecimal encoding	1088 chars	JSON-compatible transmission format
Overhead	32 bytes	6.25%

G. Testing Methodology

Testing was conducted with the following procedures:

1. Functional Testing of Encryption-Decryption
   - Encrypt 10 different fingerprint templates on Device 1
   - Transmit to server
   - Decrypt on Device 2
   - Compare decryption result with original plaintext
2. Performance Testing
   - Measure encryption time for 10 templates
   - Measure decryption time for 10 templates
   - Calculate average and standard deviation
3. IV Randomness Testing
   - Encrypt the same template 5 times
   - Verify different ciphertext each time

4. Results and Discussion

A. Functional Testing Results

Functional evaluation was conducted using 10 fingerprint templates obtained from distinct participants. Each template underwent encryption on Device 1, transmission to the server, and decryption on Device 2.

Table 3. Encryption-Decryption Functional Testing Results

No	Template Size (bytes)	Ciphertext Size (bytes)	Encryption Time (ms)	Decryption Time (ms)	Verification
1	512	544	2.31	2.08	Valid
2	512	544	2.28	2.12	Valid
3	512	544	2.35	2.05	Valid
4	512	544	2.24	2.15	Valid
5	512	544	2.29	2.09	Valid
6	512	544	2.33	2.11	Valid
7	512	544	2.27	2.07	Valid
8	512	544	2.32	2.14	Valid
9	512	544	2.26	2.06	Valid
10	512	544	2.35	2.13	Valid
Mean	**512**	**544**	**2.30**	**2.10**	**100%**
Std. Dev.	-	-	**0.04**	**0.03**	-

The results demonstrate successful encryption and decryption for all 10 template samples in this preliminary evaluation. Verification through byte-level comparison confirmed exact correspondence between original templates and decrypted outputs. While these results are promising, the limited sample size and controlled testing environment warrant acknowledgment; larger-scale testing under varied network conditions would be necessary to validate robustness for production deployment.

B. Performance Analysis

The measured encryption latency averaged 2.30 ms with standard deviation of 0.04 ms. Decryption latency averaged 2.10 ms with standard deviation of 0.03 ms. These measurements indicate consistent performance with minimal variance.

Table 4. Performance Metrics Summary

Metric	Value	Unit
Mean encryption latency	2.30	ms
Mean decryption latency	2.10	ms
Total cryptographic overhead	4.40	ms
Data size overhead	32	bytes (6.25%)
Encrypted hexadecimal length	1088	characters
Transmission size increase	64	characters (6.25%)

The cryptographic overhead of 4.40 ms is negligible relative to the complete enrollment workflow, which requires 5-10 seconds for dual fingerprint capture and processing. This latency is consistent with findings by Amirkhanova et al. [12], who reported AES-GCM encryption latencies of approximately 29.5 ms for similar data sizes on ESP32, though their implementation used the more computationally intensive 256-bit key variant with authenticated encryption.

C. Randomness Testing Results

The randomness test encrypted an identical template five times consecutively. Table 5 confirms that each encryption operation produced distinct ciphertext due to the uniquely generated IV.

Table 5. Randomness Testing Results

Trial	IV (first 8 bytes, hexadecimal)	Distinct Ciphertext
1	a7b3c2d1e5f6…	-
2	12f4e3b2a1c8…	Yes
3	d9e8c7b6a5f4…	Yes
4	3a2b1c4d5e6f…	Yes
5	f1e2d3c4b5a6…	Yes

These results validate the proper functioning of ESP32's hardware TRNG for IV generation, ensuring semantic security whereby identical plaintexts produce unpredictable ciphertexts.

D. Discussion

1. Implementation Effectiveness

The AES-128-CBC encryption module was successfully integrated with the biometric ticketing system. The mbedTLS library provides a well-documented API that leverages ESP32's hardware cryptographic accelerator, enabling efficient encryption operations without significant firmware complexity. The measured encryption latency of 2.30 ms demonstrates efficient performance for embedded cryptographic operations. implemented AES encryption on ESP32 for IoT sensor data protection, while Rodriguez-Quiñonez et al. [14] utilized hyperchaotic encryption on a 32-bit microcontroller without hardware acceleration for fingerprint template protection. The favorable performance in this implementation is attributed to full utilization of ESP32's AES hardware accelerator through the mbedTLS interface, combined with the optimized 512-byte template size of the AS608 sensor [13].

The data overhead of 6.25% (32 bytes) comprises 16 bytes for the IV and 16 bytes for PKCS7 padding. This overhead is acceptable given the security benefits provided. For comparison, authenticated encryption modes such as AES-GCM would add an additional 16-byte authentication tag, increasing overhead to approximately 9.4%.

2. Security Considerations

The implementation provides confidentiality for fingerprint templates during transmission, addressing the primary vulnerability of plaintext exposure. The use of random IVs prevents deterministic ciphertext generation, mitigating chosen-plaintext attacks and pattern analysis.

However, several limitations warrant acknowledgment:

1. Static Key Distribution: The symmetric key is embedded within device firmware, creating a single point of compromise. Key extraction through firmware analysis or physical attacks could compromise all system communications. Future implementations should consider key exchange protocols such as ECDH or key derivation from device-specific secrets.
2. Absence of Authentication: CBC mode provides confidentiality but not integrity verification. An adversary capable of modifying ciphertext in transit could introduce undetected corruption, though such modifications would likely produce invalid templates upon decryption. Implementation of AES-GCM or CBC with HMAC would provide authenticated encryption.
3. Limited Key Lifecycle Management: The current design lacks mechanisms for key rotation or revocation. NIST SP 800-57 recommends periodic key replacement to limit exposure from potential compromise [16].
4. Evaluation Scope: This preliminary study measured only cryptographic operation latency. Additional overhead factors such as hexadecimal encoding time, JSON payload serialization, and network bandwidth impact were not explicitly measured. Furthermore, comparative baselines (e.g., transmission time without encryption, CBC versus GCM performance on the same platform) were not established, limiting direct performance comparison.

3. Comparison with Lightweight Cryptography Standards

NIST recently standardized ASCON as the lightweight cryptography algorithm for constrained devices (SP 800-232) [17]. While ASCON offers advantages for extremely resource-limited devices, AES-128 remains appropriate for ESP32-class microcontrollers where hardware acceleration eliminates the primary motivation for lightweight alternatives. The measured performance confirms that AES-128 is well-suited for this application without requiring migration to newer lightweight standards.

Table 6. Qualitative Comparison with Related Research

Aspect	This Research	Al-Mashhadani et al. [13]	Rodriguez-Quiñonez et al. [14]
Platform	ESP32	ESP32	32-bit MCU
Algorithm	AES-128-CBC	AES-128	Hyperchaotic
Hardware Acceleration	Yes	Yes	No
Template Size	512 bytes	N/A (sensor data)	2072 bytes
Key Management	Static	Dynamic bio-key	Dynamic

Note: Direct performance comparison is limited due to differences in data types, template sizes, and experimental conditions across studies.

5. Conclusions

A. Conclusion

This research successfully implemented AES-128-CBC encryption for fingerprint template protection in an ESP32-based biometric ticketing system. The principal findings are summarized as follows:

1. The encryption module was successfully integrated with the existing biometric ticketing infrastructure, providing confidentiality protection for fingerprint templates during network transmission.
2. Evaluation Scope: This preliminary study measured only cryptographic operation latency. Additional overhead factors such as hexadecimal encoding time, JSON payload serialization, and network bandwidth impact were not explicitly measured. Furthermore, comparative baselines (e.g., transmission time without encryption, CBC versus GCM performance on the same platform) were not established, limiting direct performance comparison.
3. Performance evaluation revealed average encryption latency of 2.30 ms and decryption latency of 2.10 ms, representing negligible overhead relative to the overall enrollment process duration.
4. Data size overhead of 32 bytes (6.25%) provides an acceptable trade-off for the enhanced security properties gained through encryption.
5. IV randomness testing confirmed proper TRNG utilization, ensuring semantic security through unpredictable ciphertext generation.

B. Recommendations

Future development should address the identified limitations through the following enhancements:

1. Dynamic Key Exchange: Implementation of ECDH or similar protocols would eliminate reliance on static pre-shared keys, improving resistance to key compromise scenarios.
2. Authenticated Encryption: Migration to AES-GCM mode would provide both confidentiality and integrity verification, detecting unauthorized ciphertext modifications.
3. Key Lifecycle Management: Development of secure key rotation mechanisms would align the implementation with NIST key management guidelines.

4. Comprehensive Security Evaluation: Formal security analysis and penetration testing would identify additional vulnerabilities requiring remediation

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