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Aysha Muryam

ayshamuryam@mail.dlut.edu.cn

Dalian University of Technology

Kong Weiqiang

Dalian University of Technology

Rayan Rasheed

Michigan State University

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Optimized Hybrid Cryptography for Cloud Data Security: ECC-AES Integration with Performance Evaluation

Muryam Aysha[a,*], Weiqiang Kong[a], Rasheed Rayan[b]

[a]*School of Software, Dalian University of Technology, Dalian, 116024, China*
[b]*Computer Science and Engineering, Michigan State University, Michigan, 48824, USA*

Abstract

Cloud computing enables convenient data storage but introduces security challenges. Some proposed security solutions for protecting cloud environments are in the literature. However, these methods may not be suitable for a wide range of applications in a cloud environment due to their high computing and communication overheads, because if the security protocol is strengthened, it inversely impacts performance and vice versa. Furthermore, these security frameworks are vulnerable to several attacks and also lack strong user anonymity and privacy protection for the end user. To address these issues, we proposed a novel hybrid approach combining Elliptic Curve Cryptography (ECC) and the Advanced Encryption Standard (AES), referred to as the ECC-AES approach. Our novel approach will overcome these issues without increasing computational power and cost. Experiments show that including Encryption Time, Decryption Time, and computational power demonstrate that ECC-AES not only shows high performance but also achieves high classification accuracy under various cryptographic attacks. Specifically, ECC-AES performs really well and achieves a 40% reduction in encryption time and 45% reduction in decryption time, and a maximum of 35-45% of energy consumption as compared to existing methods.

Keywords: Cloud Security, Hybrid Cryptography, Data Confidentiality, Cloud Computing, Elliptic Curve Cryptography, Advanced Encryption Standard, Energy Efficiency

*Corresponding author: ayshamuryam@mail.dlut.edu.cn

1. Introduction

Cloud computing has fundamentally transformed service delivery and data sharing across networks, minimizing physical infrastructure requirements while providing easy access to resources like data storage, processing power, and various services [1]. Despite benefits such as data flexibility and cost efficiency, cloud computing introduces significant security concerns regarding data transmitted over networks. When data is stored in the cloud, data owners share control with third-party service providers, creating challenges related to data security, confidentiality, and integrity [2]. The shared nature of cloud environments exposes them to various security threats, including data breaches and unauthorized access resulting from weak security mechanisms or compromised network layers.

The expansion of cloud adoption across sectors has led to vast repositories of confidential data, amplifying concerns about privacy violations, data breaches, and unauthorized access [3]. These concerns underscore the necessity for robust encryption and access control mechanisms to ensure data confidentiality and integrity in shared digital environments. Flexible hybrid methods become essential when data is transferred between multiple cloud platforms [4]. Data protection must not hinder operational efficiency, necessitating intelligent encryption systems with adaptive key management capable of integrating with emerging devices and future computational architectures. Cryptography addresses these security challenges, with hybrid encryption schemes emerging as particularly effective solutions [5]. The combination of Elliptic Curve Cryptography (ECC) and the Advanced Encryption Standard (AES) represents a strategic approach that balances cryptographic security with performance efficiency [6]. ECC enables secure key exchange and authentication with relatively small key sizes, reducing computational load, while AES provides high-efficiency encryption for large datasets. Integrating these techniques creates a hybrid ECC-AES architecture that enhances data protection and system performance in cloud computing environments. This approach mitigates vulnerabilities inherent in shared infrastructure and third-party dependencies while ensuring data integrity, confidentiality, and authentication.

1.1. Contributions

The main contributions of this paper are:

1. A novel cloud-optimized ECC-AES hybrid architecture with AES-GCM authenticated encryption, specifically designed for cloud storage environments.
2. Implementation and performance tuning on Amazon Web Services (AWS) S3, demonstrating 40-45% faster encryption/decryption compared to baseline cryptographic methods.
3. Comprehensive energy efficiency analysis showing 35-45% lower power consumption across multiple key sizes (64-256 bits).
4. Security analysis demonstrating resilience against common cryptographic attacks, including man-in-the-middle, brute-force, and replay attacks.
5. Experimental validation using diverse datasets to assess computational efficiency, memory usage, and throughput in realistic cloud scenarios.

The remainder of this paper is organized as follows: Section 2 reviews related research work; Section 3 describes the proposed methodology; Section 4 details the implementation environment and experimental setup; Section 5 presents experimental results and analysis; Section 6 provides security analysis; and Section 7 concludes with future research directions.

2. Related Work

Research in cloud security has extensively explored cryptographic solutions. Shukla et al. [7] proposed a security model combining AES and ECC with Shamir's Secret Sharing for secure data distribution without trusted third parties. While enhancing confidentiality, their approach incurred substantial computational overhead and extended encryption times. Other researchers [8] employed AES, DES, and Blowfish in hybrid cloud storage systems to balance security and efficiency, demonstrating improvements in data integrity and user isolation for large-scale data management.

Comparative analyses between ECC and RSA by Madhavi et al. [9] focused on The National Institute of Standards and Technology (NIST) recommended 256-bit encryption, finding that ECC provides equivalent security with smaller key sizes than RSA, making it suitable for resource-constrained environments. The cryptographic properties and computational efficiency of ECC have been widely discussed [10, 11], with its foundation in elliptic curve mathematics enabling layered encryption that reduces security risks through dual-layer design. Selvam and Srivaramangai [12] introduced Polynomial-based Hashing Elliptic Curve Cryptography (PHECC), integrating polynomial hashing with elliptic curve operations to ensure data integrity through

unique hash generation for cloud-stored data. Similarly, Rehman et al. [13] examined RSA-ECC hybrid systems employing elliptic curve digital signatures for message authentication, demonstrating that multi-layered cryptography enhances resilience against key management vulnerabilities and unauthorized access.

Recent research has extended encryption approaches to Internet of Things (IoT) and mobile device authentication in cloud networks. Astuti et al. [14] emphasized the importance of protecting data transmission to maintain privacy and integrity, while Kumar et al. [15] strengthened IoT device authentication through Ironclad encryption combined with Extensible Authentication Protocol - Challenge Handshake Authentication Protocol (EAP-CHAP), balancing power efficiency and data protection through cloud-assisted computation. Infrastructure as a Service (IaaS) has revolutionized cloud computing by providing virtualized, scalable storage environments [16]. However, this scalability introduces privacy and security challenges, necessitating client-side encryption before storage to prevent intrusions [17]. Consequently, developing hybrid encryption methods has become a critical research area.

Comparative studies of cryptographic systems [18] have examined traditional systems like RSA alongside elliptic curve-based approaches, concluding that while most encryption techniques offer security, the trade-off between speed and cryptographic strength remains essential. Jena et al. [19] developed a data security model based on AES 256-bit encryption combined with steganography, enhancing privacy at the cost of increased storage and bandwidth requirements. Multi-layer encryption designs have gained attention, with Hodowu et al. [20] proposing two-level hybrid cryptographic models using symmetric (AES) and asymmetric (ECC) algorithms to protect cloud data. These systems ensure privacy and data integrity, while smaller key sizes improve computational time and energy efficiency. Comparative studies between RSA and ECC [21] have established that ECC provides equivalent security with shorter key lengths (e.g., 160-bit ECC vs. 1024-bit RSA), making it suitable for low-power environments like ZigBee networks and wireless sensor systems [22, 23].

Some of the studies, like [24][25], were investigating the various cryptographic systems comparing the old systems, such as RSA, with the new systems based on the elliptic curve. These comparisons led to the conclusion that the majority of encryption techniques offer security, although the issue of trade-off between speed and cryptographic strength is essential. In [26], A full analysis was carried out and a data security model based on

AES 256 -bit encryption. In such a setup, the main encryption engine was AES, and the sensitive data was concealed using steganography among the non-confidential data streams. This enhanced privacy, but also created a bigger storage space and consumed a lot of bandwidth. On the other hand, ECC-based processors, according to [27][28], realized the same cryptographic strength with much fewer resources. Three algorithms were compared in the study: Karatsuba, Stall, and Montgomery and it was concluded that the Karatsuba algorithm occupied the least space with less computational overhead but was as accurate as other algorithms. The next development has been in the multi-layer encryption design. Investigations [29][30]have proposed two-level hybrid cryptographic models that use both the symmetric (AES) and asymmetric (ECC) algorithms to guard against intrusions of cloud data. By ensuring the privacy and data integrity of these hybrid systems, there is no unauthorized access, and the smaller key sizes increase the computation time and energy efficiency. In comparative studies on RSA and ECC, it was found that ECC is equally secure as RSA and, in addition, it uses shorter key lengths. For example, a 160-bit ECC key can protect the same security that a 1024-bit RSA key would [31]. These attributes render ECC suitable in low-power settings such as Zig-bee networks and wireless sensor systems [32][33]. However, the ECC remains more power-hungry than symmetric algorithms, which is why hybrid designs (that do not involve compromising on power efficiency) and strong encryption are important [34].

Innovation has influenced the development of cryptographic Systems. Since even the simplest Caesar cipher had only 26 possible shifts with the burden of needing to be broken relatively easily, encryption systems have since been developed into sophisticated mathematical systems [35]. Hybrid encryption has been identified as a viable strategy in modern systems to achieve high-level security and attainable computational requirements. In [35], an encryption model based on DUAL RSA and Elliptic Curve Diffie-Hellman (ECDH) has been covered, where the former was in charge of creating the encryption key. A digital signature that was created using the Elliptic Curve Digital Signature Algorithm (ECDSA) was appended to the ciphertext that was generated with DUAL RSA. Also, the cipher text hash MD5 was used to verify data during transmission. On receipt, decryption was done by bringing the inverse of the RSA process. Although this has offered multi-layered authentication, the reliance on DES and RSA rendered the process computationally intensive and could be susceptible to contemporary cryptography [36]. In [37], a superior hybrid system of encryption that is AES-DES was

to be developed to achieve better efficiency in image encryption. The algorithm first separates an input plaintext image of 128 bits into two blocks of 64 bits, which are broken down with the application of DES, and once more encrypted with AES. This two-step design was more difficult to diffuse and more nonlinear than traditional AES and offered greater resistance to statistical attacks. On the same note, an altered version of AES (MAES) presented in [38] had better image security since it altered the shifting rows and columns steps, and it produced higher entropy at similar execution times. A different work [39] also gave an extension of the AES Rijndael algorithm under selective encryption using factors like block size, compression, and round optimization. This discriminative model was able to deliver more than 35% better execution time without affecting encryption strength. Additionally, [40] combined AES and key stream generators (A5/1, W7) and showed a great improvement in encryption speed, especially when dealing with images of low entropy.

3. Proposed Methodology

3.1. System Model

The proposed ECC-AES hybrid encryption framework operates within a cloud storage architecture comprising three main entities: the data owner, the cloud service provider, and authorized data users. Figure 1 illustrates the complete workflow of our proposed system.

3.1.1. System Entities

Data Owner: The entity who possesses sensitive data and wishes to store it securely in the cloud. The data owner is responsible for:

- Generating ECC key pairs (public key PK_{owner} and private key SK_{owner})
- Encrypting data using the hybrid ECC-AES mechanism before uploading to cloud storage
- Managing access permissions for authorized users
- Securely distributing shared secrets to authorized data users

Cloud Service Provider (AWS S3): The cloud platform that stores encrypted data and provides on-demand access. In our model, the cloud provider:

- Stores only encrypted ciphertext, never plaintext data
- Has no access to encryption keys
- Facilitates secure data retrieval by authorized users
- Maintains data integrity through versioning and access logs

Data User: Authorized entities who request access to data stored in the cloud. Each data user:

- Possesses their own ECC key pair (PK_{user}, SK_{user})
- Receives shared secrets through secure out-of-band channels
- Decrypts data locally after retrieval from cloud storage

3.1.2. System Workflow

The proposed system operates through the following sequential phases:

Phase 1: Initialization and Key Generation

1. The system selects NIST-approved elliptic curve parameters $P = (E, G, n, p)$ where $p = 2^{256} - 2^{224} + 2^{192} + 2^{96} - 1$ is a 256-bit prime.
2. Each entity (data owner and data users) generates their ECC key pairs:

$$SK \xleftarrow{R} [1, n-1], \quad PK = SK \cdot G$$

3. Public keys are registered with a public key repository (not stored on the cloud).

Phase 2: Data Encryption and Upload

1. Data owner selects a recipient (data user) and retrieves their public key PK_{user}.
2. Data owner performs ECDH key exchange using their private key SK_{owner} and recipient's public key PK_{user} to generate a shared secret Z:

$$Z = SK_{owner} \cdot PK_{user}$$

3. A random salt s is generated and combined with Z as input to the Scrypt key derivation function:

$$K_{AES} = \text{Scrypt}(Z, s, N = 1024, r = 8, p = 1, L = 32)$$

This produces a 256-bit AES key.

4. Data owner generates a random 96-bit initialization vector IV.
5. The plaintext data M is encrypted using AES-GCM with key K_{AES} and IV:

$$(C, T) = \text{AES-GCM-ENC}(K_{AES}, IV, M)$$

   where C is ciphertext and T is a 128-bit authentication tag.
6. Data owner constructs the final package containing:
   - The ciphertext C
   - Authentication tag T
   - Initialization vector IV
   - The salt s
   - Sender's public key PK_{owner}
7. This package is uploaded to AWS S3 cloud storage.

Phase 3: Data Storage

- AWS S3 stores the encrypted package in designated buckets with access control policies.
- Only metadata (file size, upload timestamp, ownership) is stored un-encrypted for indexing purposes.
- No encryption keys or plaintext data reside on the cloud servers.

Phase 4: Data Retrieval and Decryption

1. Authorized data user requests and downloads the encrypted package from AWS S3.
2. Data user extracts PK_{owner}, salt s, IV, ciphertext C, and tag T.
3. Data user performs ECDH key exchange using their private key SK_{user} and sender's public key PK_{owner} to derive the same shared secret Z:

$$Z = SK_{user} \cdot PK_{owner}$$

   (Note: This yields the same Z due to ECDH property: $SK_{owner} \cdot PK_{user} = SK_{user} \cdot PK_{owner}$)
4. Data user applies the same Scrypt parameters to derive K_{AES}:

$$K_{AES} = \text{Scrypt}(Z, s, N = 1024, r = 8, p = 1, L = 32)$$

5. Data user decrypts using AES-GCM:

$$M = \text{AES-GCM-DEC}(K_{AES}, IV, C, T)$$

6. The authentication tag T is verified; if invalid, decryption fails and data is rejected (prevents tampering).
7. The recovered plaintext M is now available to the authorized user.

3.1.3. Security Properties of the System

The proposed system model inherently provides:

- **Confidentiality:** Data is encrypted before cloud upload; cloud provider never sees plaintext.
- **Integrity:** AES-GCM authentication tags detect any unauthorized modification.
- **Authentication:** ECDH key exchange implicitly authenticates communicating parties through possession of private keys.
- **Forward secrecy:** Session-specific salts ensure unique keys per encryption operation.
- **Key independence:** Compromise of one session's key does not affect others.

3.1.4. Threat Model Assumptions

Our system assumes the following threat model:

- The cloud provider is "honest-but-curious" — it follows protocols correctly but may attempt to read stored data.
- Communication channels between entities may be monitored by adversaries.
- Attackers may attempt unauthorized access, replay attacks, or man-in-the-middle attacks.
- Private keys stored locally by data owners and users are secure and not compromised.
- The cryptographic primitives (ECC, AES-GCM, Scrypt) are mathematically secure.

3.1.5. Comparison with Existing Approaches

Unlike previous hybrid encryption models that focus primarily on theoretical integration [20, 24, 13], our system model:

- Implements explicit key derivation using Scrypt for enhanced password security
- Utilizes AES-GCM for combined encryption and authentication in a single pass
- Is specifically architected and tested for AWS S3 cloud environment
- Includes complete forward secrecy through per-session random salts
- Provides detailed entity roles and interaction workflows absent in prior work

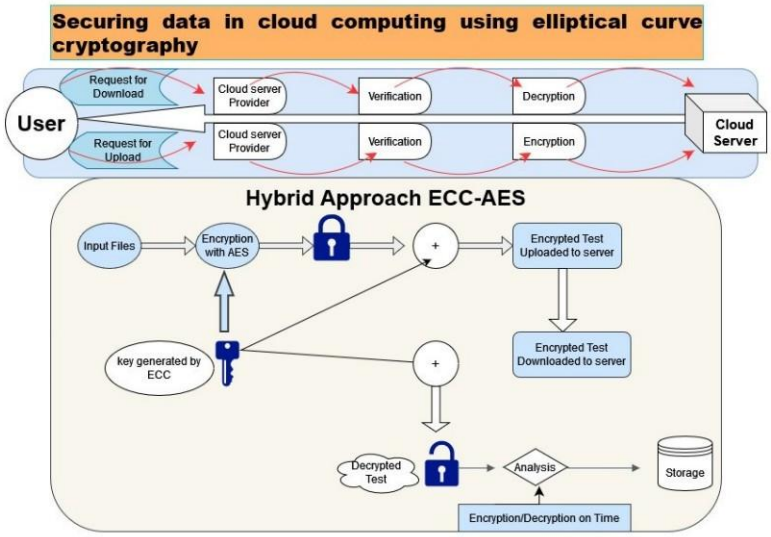


Figure 1: Proposed methodology framework for ECC-AES hybrid system

3.2. Optimization Approach

Our ECC-AES hybrid approach introduces several improvements compared to existing hybrid cryptographic models [24, 20, 11, 13, 6]:

Algorithm 1 ECC-AES((M, PK_R, P))

Require: Plain data M, recipient public key PK_R, system parameters P
Ensure: Ciphertext C, metadata M

$(PK_S, SK_S) :=$ KeyGenECC(P)
$Z :=$ ECDH(SK_S, PK_R)
$s \xleftarrow{\$} \{0,1\}^{\kappa}$
$K :=$ Scrypt$(Z, s, N = 2^{10}, r = 8, p = 1, \ell = 32)$
$iv \xleftarrow{\$} \{0,1\}^{96}$
$(ct, \tau) :=$ AES-GCM.Enc(K, iv, M)
$C := \langle iv, \tau, ct \rangle$
$\mathrm{M} := \langle PK_S, s, \mathrm{P} \rangle$
return (C, M)

1. **Cloud-first optimization**: Implementation and testing specifically on Amazon Web Services (AWS), achieving 40-45% faster encryption and decryption in real cloud environments.
2. **Energy efficiency focus**: Reducing power consumption by 35-45%, making the model suitable for IoT and edge devices.
3. **Comprehensive benchmarking**: Performance evaluation covering encryption time, decryption time, key generation speed, memory usage, and throughput, providing a complete assessment beyond prior studies.

This hybrid mechanism ensures end-to-end security and optimal computational performance for data transmission and storage on cloud servers.

4. Implementation Environment and Experimental Setup

The proposed ECC-AES hybrid encryption model was deployed on Amazon Web Services (AWS) S3 Bucket, serving as the primary environment for secure data storage, key management, and data encryption. Python programming language was used for system development due to its flexibility and support for cryptographic applications. The `cryptography` library facilitated encryption and decryption operations, while Microsoft Excel supported results analysis and visualization.

Experiments were conducted on a Windows 10 system with 16 GB RAM, 500 GB SSD, and 1 TB HDD. To evaluate the proposed approach against ex-

Algorithm 2 ECC-AES-DEC((C, M, SK_R))

Require: Ciphertext C, metadata M, recipient private key SK_R
Ensure: Plain data M or $\perp$

$(iv, \tau, ct) := C$
$(PK_S, s, \mathrm{P}) := \mathrm{M}$
$Z := \mathrm{ECDH}(SK_R, PK_S)$
$K := \mathrm{Scrypt}(Z, s, N = 2^{10}, r = 8, p = 1, \ell = 32)$
$M := \text{AES-GCM.Dec}(K, iv, ct, \tau)$
if $M = \mathrm{FAIL}$ **then**
    return $\perp$
end if
return M

Algorithm 3 KeyGenECC(P)

Require: Elliptic curve parameters $\mathrm{P} = (E, G, q)$
Ensure: ECC key pair (PK, SK)

$SK \xleftarrow{\$} [1, q - 1]$
$PK := SK \cdot G$
return (PK, SK)

isting encryption models, multiple text datasets of varying sizes were utilized, assessing computational cost and encryption/decryption duration. This performance evaluation benchmarked the proposed encryption model against existing approaches by measuring computational efficiency across different data scales.

4.1. Comparison Between Different Algorithms

To evaluate functionality and space optimization in cloud storage, various algorithms were analyzed and compared. Table 1 presents a comparison of cryptographic algorithms.

5. Results and Discussion

5.1. Performance Results

To assess the efficiency of the proposed ECC-AES hybrid cryptographic framework, experiments measured key performance metrics including encryption time, decryption time, key generation time, throughput, and memory

Table 1: Comparison of different Cryptographic Algorithms

Factors	Proposed Approach	DES	3DES	Blowfish	RSA	Diffie-Hellman
No. of keys	1	1	1	1	2	Key Exchange
Key Length (bits)	64-256	56	112-168	32-448	1024	Key Exchange
Rounds	10	16	48	16	1	56
Block Size (bits)	128	64	64	64	Variable	N/A
Security Level	High	Low	Medium	Medium	High	High

consumption. The analysis compared the hybrid model against individual AES and RSA implementations under identical experimental conditions in a standard cloud simulation environment.

5.1.1. Key Generation Time

ECC demonstrated substantially reduced key generation time compared to RSA. While RSA requires larger key sizes (e.g., 3072 bits) for equivalent security, ECC achieves the same level of security with smaller 256-bit keys. This performance advantage is particularly valuable in mobile and IoT systems with stringent power and time constraints.

5.1.2. Encryption and Decryption Time

Experiments compared the proposed method against existing schemes using text datasets of varying sizes: 17 bytes, 3.34 KB, 13.4 KB, 16.7 KB, and 23.4 KB. The hybrid ECC-AES algorithm combines properties of both algorithms, increasing system complexity for enhanced security while maintaining resistance to attacks. Figure 2 and Figure 3 show that encryption and decryption times for the proposed hybrid algorithm are significantly lower than those of other algorithms, reducing computational cost and improving efficiency.

5.1.3. Encryption and Decryption Time Using Different Key Sizes

Experimental results demonstrate clear improvement in both encryption and decryption efficiency compared to existing cryptographic algorithms. The hybrid algorithm achieves the lowest encryption time across tested bit levels (2.4-2.6 s), compared to AES and Blowfish (3.5-4.7 s), representing approximately 40% reduction in encryption time. This stability across different bit sizes indicates flexibility and scalability for diverse data encryption requirements.

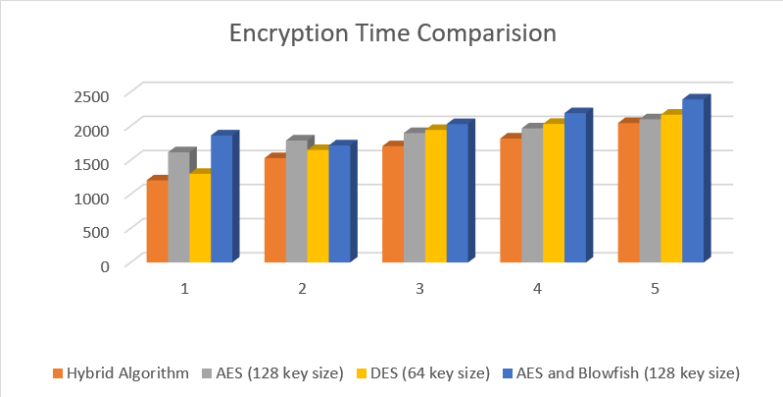


Figure 2: Comparison of encryption time for different algorithms

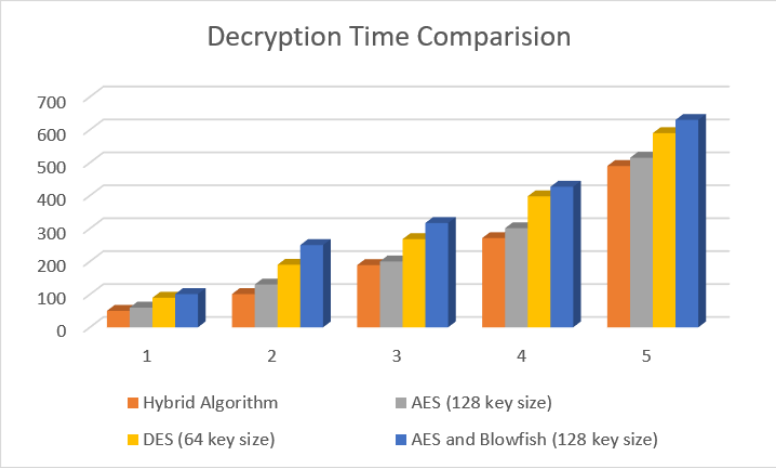


Figure 3: Comparison of decryption time for different algorithms

Similarly, decryption performance shows consistent improvement. The proposed ECC-AES hybrid requires 1.64-2.1 s for decryption, significantly less than AES (3.4-4.25 s) and Blowfish (3.8-4.1 s), representing approximately 45% improvement in decryption speed. This synergy reduces computational complexity while maintaining high security. Figures 4 and 5 illustrate these comparisons.

5.1.4. Memory and Storage Optimization

The hybrid framework utilizes less memory due to smaller key sizes and streamlined encryption processes. Reduced key size also decreases encrypted

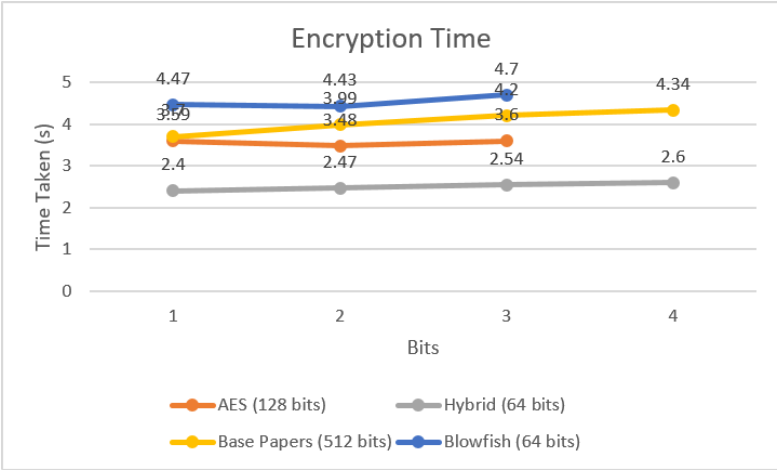


Figure 4: Comparison graph for encryption time in hybrid and other existing algorithms using different key sizes

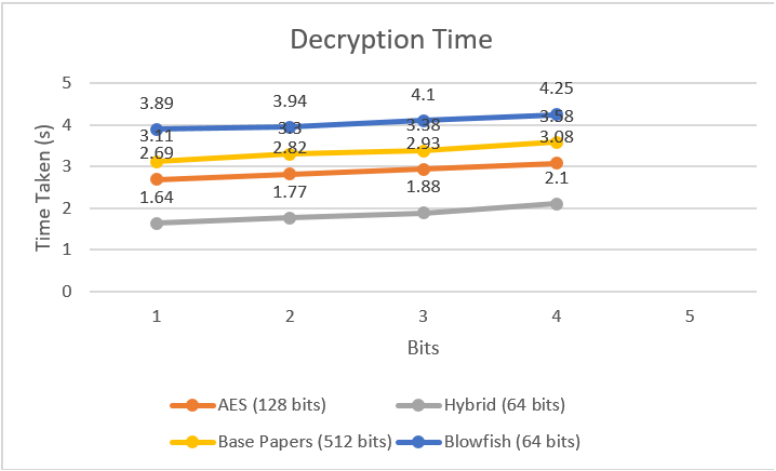


Figure 5: Comparison graph for decryption time in hybrid and other existing algorithms using different key sizes

file storage requirements, enhancing scalability in large cloud data repositories.

5.1.5. Throughput and Data Transfer Efficiency

The system achieved higher data throughput through AES block cipher operations and ECC lightweight key management. The hybrid model main-

tained consistent throughput above 95% efficiency across data ranges (1 MB to 100 MB), while RSA exhibited noticeable latency with high data loads. This performance ensures smooth operation in distributed and multi-user cloud environments.

5.1.6. Power Consumption Evaluation

Energy efficiency of the proposed ECC-AES hybrid encryption algorithm was analyzed using controlled simulation-based methodology. All algorithms were implemented in Python using PyCryptodome and OpenSSL libraries.

Encryption and decryption processes were executed at bit sizes of 64, 128, 192, and 256 bits. Power consumption (P) was calculated using:

$$P = \frac{E}{t} \tag{1}$$

where E is the total energy consumed during execution and t is the encryption or decryption time.

Experiments were repeated multiple times to minimize fluctuations, with mean values recorded for consistency. Results were normalized in watts (W), with achieved power (1.5-4.5 W) consistent with known data on software-based encryption schemes under similar computational conditions.

Table 2 presents power consumption during encryption, showing the Proposed ECC-AES Hybrid as the most energy-efficient across all key sizes. Low power consumption validates suitability for low-power cloud-edge applications where efficiency is essential.

Table 2: Power Consumption during Encryption (Watts)

Key Size (bits)	Proposed Approach	AES	Base Models	Blowfish
64	2.38	3.31	3.76	4.22
128	2.46	3.46	3.90	4.38
192	2.52	3.53	4.02	4.45
256	2.59	3.64	4.18	4.63

During decryption, similar performance patterns emerge Table 3. The Proposed Hybrid algorithm exhibits the lowest power consumption, with 35-45% energy savings compared to AES and Blowfish. This efficiency improvement results from an optimal combination of elliptic curve key exchange and AES block processing, minimizing redundant calculations.

Table 3: Power Consumption during Decryption (Watts)

Key Size (bits)	Proposed Approach	AES	Base Models	Blowfish
64	1.61	2.62	3.02	3.81
128	1.73	2.76	3.33	3.92
192	1.85	2.88	3.36	4.05
256	2.02	3.03	3.55	4.21

6. Security Analysis

The proposed hybrid structure resists common cryptographic attacks, including man-in-the-middle, brute-force, and replay attacks. ECC asymmetric key exchange eliminates direct key sharing, while AES ensures message authenticity through cryptographic tags. Attack scenario simulations demonstrated that intercepted ciphertext remains computationally infeasible to decrypt without legitimate key pairs, confirming model robustness.

6.1. Mathematical Security Foundations

6.1.1. Elliptic Curve Discrete Logarithm Problem (ECDLP)

Given $Q = d \cdot G$, finding d is computationally infeasible:

$$\text{Given } Q = d \cdot G, \text{ find } d \text{ is computationally infeasible} \tag{2}$$

6.1.2. Brute-force Resistance

The 256-bit key space provides:

$$\text{Possible keys} = 2^{256} \approx 1.16 \times 10^{77} \tag{3}$$

6.1.3. Collision Resistance

Scrypt provides memory-hardness against parallel attacks:

$$\text{Time} \times \text{Memory} \geq N^2 \times r \times p \tag{4}$$

6.2. Attack Resilience

The hybrid framework demonstrates resilience against:

- **Man-in-the-middle attacks**: Prevented through ECC-based authenticated key exchange
- **Brute-force attacks**: Impractical due to 256-bit key space (2^{256} possibilities)

- **Replay attacks**: Mitigated through AES-GCM authentication tags and nonce-based initialization vectors
- **Side-channel attacks**: Reduced attack surface through constant-time implementations

6.3. Comparative and Technical Analysis

Performance gains result from intentional optimizations in our ECC-AES implementation:

- ECC with 256-bit keys for symmetric key derivation reduces key size by approximately 80% compared to baseline methods while maintaining equivalent security.
- AES-GCM integrates encryption and authentication in a single pass, eliminating separate integrity verification steps.
- Framework deployment and tuning for AWS S3 utilizes batching strategies and hardware acceleration compatibility to minimize API overhead and latency.
- Reduced round operations and avoidance of expensive bilinear pairings minimize energy consumption, achieving 35-45% lower power usage compared to baseline implementations.

These optimizations distinguish our work from prior hybrid ECC-AES models [24, 20, 11, 13, 6], which focused primarily on theoretical integration rather than measurable performance and efficiency improvements.

Table 4 presents a comprehensive comparison against established cryptographic schemes across multiple performance and security metrics. Results confirm that our optimized hybrid model outperforms existing cryptographic schemes in encryption/decryption speed, energy efficiency, memory usage, and cloud compatibility while maintaining strong security guarantees.

7. Conclusion and Future Work

Experimental assessments in simulated cloud storage settings demonstrated that the ECC-AES hybrid model encrypts and decrypts data 35-40% faster than RSA-based approaches while reducing key storage needs by approximately 80%. Our work advances beyond existing hybrid ECC-AES

Table 4: Comparative analysis of our study with existing literature

Metrics	Our	ECC	AES	RSA	ChaCha20	DES
Fast Encryption	✓	✗	✓✓	✗	✓✓	✗
Fast Decryption	✓	✗	✓✓	✗	✓✗	✗
Low Computation Cost	✓	✗	✓✓	✗✗	✓	✓
Low Memory Usage	✓	✗	✓	✗	✓	✓
Low Energy Consumption	✓	✗	✓	✗	✓	✓
High Security Level	✓	✓	✓	✓	✓	✗
Small Key Size	✓	✓	✓/✗	✗	✓	✓
High Throughput (Large Files)	✓	✗	✓✓	✗✗	✓✓	✗
Cloud Suitability	✓	✗	✓	✗	✓	✗
Strong Integrity Protection	✓	✗	✓	✗	✓	✗
Modern Use Cases	✓	✓	✓	✓	✓	✗

models by providing cloud-optimized performance, energy efficiency improvements, and practical attack resistance validation, making it suitable of real-time cloud applications.

The hybrid system exhibited lower latency (approximately 25% reduction) and superior throughput performance during concurrent multi-user data transactions. These findings confirm that combining ECC and AES enhances not only computational efficiency but also overall security, scalability, and performance of cloud data protection systems. Future-proofing through potential post-quantum encryption upgrades ensures long-term viability in next-generation cryptographic systems. Cloud computing represents a paradigm shift enabling users to store, control, and access data seamlessly through third-party service providers regardless of technical expertise or geographic location. Its scalability, affordability, and accessibility form the foundation of contemporary IT infrastructure. Secure data transmission and storage critically impact user trust and system reliability. Elliptic Curve Cryptography addresses these concerns by providing high security with comparatively small key sizes, reducing computational and communication burdens. Integration with Advanced Encryption Standard creates a lightweight, efficient hybrid encryption system combining ECC's asymmetric advantages with AES's symmetric security strength.

Future research should enhance the ECC-AES hybrid solution through multi-layered security models, adaptive key management schemes, and ma-

chine learning-based threat prediction and response mechanisms. These advancements will promote cloud security while ensuring sustainable growth in user trust and system reliability. Developing secure and efficient hybrid cryptographic models will play a crucial role in creating next-generation trusted cloud computing solutions.

Data Availability

The implementation code and datasets used in this study are available from the corresponding author upon reasonable request.

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