Secure Multi-Authority Hierarchical Access Control for Industrial IoT using ECC-Based CP-ABE

Project Report

Submitted by:

Name:	Abhradeep Das
Roll No:	2024202018
Program:	M.Tech CSIS

Name:	Lakshay Baijal
Roll No:	2024202006
Program:	M.Tech CSIS

Under the Supervision of Professor:

Dr. Ashok Kumar Das

Dr. Kannan Srinathan

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Abstract

With the exponential growth of Industrial Internet of Things (IIoT) devices and cloud based data sharing, ensuring secure and efficient access control. Traditional attribute based encryption systems struggle with scalability, single authority bottlenecks, and heavy decryption overhead on resource limited edge devices. This project implements a secure multi authority hierarchical ciphertext policy attribute based encryption scheme built on elliptic curve cryptography (ECC) for lightweight and scalable access control in industrial networks. The architecture distributes attribute management across multiple authorities organized hierarchically, reducing trust concentration and improving scalability. Furthermore, an Edge Authority (EA) assists in partial decryption using ElGamal based privacy preserving transformation, allowing end users to decrypt efficiently without revealing their private keys.
Keywords: Attribute-Based Encryption (ABE); Ciphertext-Policy ABE (CP-ABE); Elliptic Curve Cryptography (ECC); Multi-Authority; Hierarchical Access Control; Industrial IoT; Edge Computing; Outsourced Decryption.

1. Introduction

1.1. Background

In Industrial IoT, thousands of smart devices collect and share data through cloud and edge infrastructures. Controlling access to data securely and efficiently is crucial. Conventional encryption techniques rely more on centralized key distribution, which does not scale for large distributed systems. Ciphertext Policy Attribute Based Encryption provides proper access control by embedding an access policy within the cipher text. Only users possessing attributes satisfying the policy can decrypt the data. However, traditional CP-ABE schemes suffer from

- **Single authority bottleneck** — one central authority issues all attribute keys.
- **Computation overhead** — complex pairing operations burden low power devices.
- **Limited scalability** — not very suitable for hierarchical setups.

1.2. Network Model

Our system defines five main entities:

1. **Root Authority (RA)** – Initializes system parameters and delegates trust to Sub Authorities.
2. **Sub Authorities (SAs)** – Manage attributes within their respective domains.
3. **Attribute Authorities (AAs)** – Issue attribute bound keys to users.

4. **Edge Authority (EA)** – Performs outsourced partial decryption to reduce user load.

5. **Users (DUs)** – Hold user secrets and complete the final decryption step.

1.3. Attack Model

We consider the following adversarial behaviors

- **Collusion Attack:** Multiple unauthorized users combine attributes but cannot reach the threshold to reconstruct the secret.
- **Malicious Edge Attack:** The EA attempts to recover secret keys or plaintext but lacks sufficient information.
- **Key Exposure Attack:** Even if some transformed keys are leaked, the absence of the user secret d prevents recovery.
- **Unauthorized Attribute Access:** Users with incomplete attributes cannot satisfy the policy threshold.

1.4. Research Contributions

- A Python based implementation on ECC based multiauthority hierarchical CP ABE scheme.
- Integration of Shamir secret sharing for access structure enforcement.
- A privacy preserving El Gamal transform for outsourced decryption at the edge.
- End to end demonstration of encryption, delegation, partial decryption, and user decryption.
- Attack simulation scripts validating security against threshold, collusion, and EA compromise.

2. Literature Review

2.1. Related Works

Table 1: Comparison of related works

Scheme	Core Technique	Advantages	Limitations
Bethencourtet al., 2007	Pairing based CP ABE	Fine grained access control	High computational cost
Chase, 2007	Multi-authority ABE	Distributed trust	Lacks hierarchy and outsourcing
Ruj et al., 2013	Hierarchical ABE	Scalable multi-domain management	Complex key management
Zhang et al., 2018	ECC-based ABE	Lightweight for IoT	Single authority only
Our Work	ECC-based Hierarchical MA-CP-ABE	Lightweight, decentralized, supports outsourcing	None significant

2.2. Discussion

Earlier ABE models either focused on single authority systems or relied on bilinear pairings, making them computationally expensive for IoT devices. By combining ECC and multi authority hierarchy, our implementation achieves both scalability and efficiency while preserving strong cryptographic security.

3. Implementation

3.1. Design Goals and Rationale

The implementation has three practical goals: (1) lightweight cryptography suitable for constrained IoT devices, (2) decentralized authority management so different organizations can independently manage attributes, (3) outsourced computation via an Edge Authority to reduce user side work while preserving user privacy. To meet these goals we chose ECC based construction together with Shamir secret sharing for threshold enforcement and ElGamal style blinding transform for privacy preserving outsourcing.

3.2. High level Module Description

The implementation is organized into small, focused modules. Each module is described here with its responsibilities and public functions:

`src/crypto/ecc.py` — ECC primitives and helpers:

- Exports the global curve, generator G, and order n.
- `scalar_mul(k, P=None)`: scalar multiplication $k \cdot P$ (defaults to $k \cdot G$).
- `point_to_bytes(P)` / `bytes_to_point(b)`: serialization, deserialization of EC points (x — y).
- `hash_to_int(bytes)`: maps arbitrary bytes to integer mod n using SHA-256.

`src/crypto/sym.py` — Symmetric key derivation & AES-GCM:

- `derive_key_from_point(point_bytes)`: KDF producing 32-byte key (SHA-256 of serialized point).
- `aes_encrypt(key, plaintext, aad=b"")` and `aes_decrypt(...)`: AES-GCM helpers returning/consuming base64-encoded nonce+ciphertext pairs suitable for JSON storage.

`src/lsss/shamir.py` — Shamir secret sharing:

- `split_secret(secret_int, n, t)`: produce n shares for threshold t.
- `reconstruct_secret(points)`: Lagrange interpolation to recover constant term.
- All arithmetic is performed modulo the EC group order n.

`src/aa/authority.py` and `src/aa/hierarchy.py` — Authority management:

- `Authority` class: generates master secret α, per attribute secrets k_{attr}, and issues user SKs bound to UID via $SK = \alpha + H(uid) \cdot k_{attr} \pmod n$.
- `Root Authority` / `Sub Authority`: delegation APIs to derive SA secrets from RA, which allows hierarchical organization of attribute domains.

`src/encrypt/multi_aa_encryptor.py` — Encryption pipeline for multi authority:

- Chooses random ephemeral scalar s, computes $P = s \cdot G$, derives AES key $K = H(serialize(P))$, encrypts payload with AES-GCM.

- Splits s into Shamir shares (one per attribute in policy). Produces CT JSON containing `meta`, base64 encoded `P_bytes_b64`, AES fields, and a `shares` map.

`src/edge/pretransform_elgamal.py` — Privacy preserving EA transform:

- EA reconstructs s (or computes $s \cdot G$) using vault shares for attributes authorized for a UID.
- Loads the user's public key D_{pub}. Samples random r and computes $C_1 = r \cdot G$ and $C_2 = s \cdot G + r \cdot D_{pub}$.
- Returns JSON token $\{ct\_id, uid, C1\_b64, C2\_b64\}$. User completes by computing $s \cdot G = C_2 - d \cdot C_1$.

`src/user/user.py` — User side secret handling:

- Generates private user scalar d.
- Computes TSKs for storage at EA: $TSK = SK + d$ (so EA stores transformed keys but cannot invert them without d).
- Provides recovery routines to obtain SK from TSK when the user is present.

3.3. File Formats and JSON Schemas

The implementation uses JSON extensively for portability. Key formats are:

Ciphertext JSON (example fields):

```
{
  "meta": {
    "curve": "secp256r1",
    "n_attrs": 3,
    "threshold": 3,
    "attributes_ordered": ["attrA","attrC","attrB"]
  },
  "P_bytes_b64": "<base64 of P (sG)>",
  "aes": { "nonce_b64": "...", "ct_b64": "..." },
  "shares": {
    "attrA": { "owner": "AA1", "index": 1, "share_hex": "0x..." },
    ...
  }
}
```

Vault JSON (server side storage):

```
{
  "<ct_id>": {
    "shares": { "attrA": { ... }, "attrB": { ... } },
    "timestamp": "2025-11-11T12:00:00Z"
  },
  ...
}
```

Transform token (EA → User):

```
{ "ct_id": "...", "uid": "...", "C1_b64": "...", "C2_b64": "..." }
```

These schemas are intentionally simple and human-readable to ease demo and grading.

3.4. Core Algorithms and Pseudocode

Below is pseudo code summarizing the most critical functions

```
# Encryptor
s <-R Z_n
P <- s * G
K <- H(serialize(P))
aes_ct <- AESGCM.encrypt(K, plaintext)
shares <- Shamir.split(s, n_attrs, threshold)
build CT JSON with P_bytes_b64, aes_ct, shares

# EA privacy-preserving transform
usable_shares <- select shares matching user attrs
if len(usable_shares) < threshold: abort
s_rec <- Shamir.reconstruct(usable_shares)
P_s <- s_rec * G
D_pub <- load_user_pub(uid)
r <-R Z_n
C1 <- r * G
C2 <- P_s + r * D_pub
return {C1_b64, C2_b64}

# User finish
C1, C2 <- from token
d <- user_secret
```

```
P_s <- C2 - d * C1
K <- H(serialize(P_s))
plaintext <- AESGCM.decrypt(K, nonce_b64, ct_b64)
```

3.5. Testing, Demos, and Reproducibility

The repository includes multiple demo scripts and an automated one-click demonstration:

- `one_click_multi_aa_upload_demo.sh` runs full pipeline (encrypt $\rightarrow$ pack vault $\rightarrow$ EA pre-decrypt $\rightarrow$ user final decrypt).
- `src/tools/multi_aa_encrypt_demo.py` produces a sample CT and shares to inspect JSON layout.
- `src/edge/pretransform_elgamal.py` and `src/edge/predecrypt.py` can be invoked manually to demonstrate both privacy preserving and non private EA behaviors.
- Attack and validation scripts: `src/tools/hierarchical_attack_tests.py` and `src/attacks/attacker_fetch_and_crack.py` validate threshold enforcement, collusion resistance and EA limitations.

3.6. Performance Measurement Approach

To demonstrate practical viability, we measured two micro benchmarks:

1. **ECC scalar multiplication cost:** total time for N scalar multiplications (to approximate cost of operations like $k \cdot G$ used in keygen/transfor).
2. **AES-GCM encryption time:** time to encrypt plaintexts to capture symmetric layer performance.

A benchmark script executes these measurements and produces a CSV file which is plotted (PNG or embedded TikZ)

3.7. Implementation Security Considerations

The code follows practical security practices:

- Use of cryptographically secure RNG (`os.urandom`) for secret scalars and AES nonces.
- AES-GCM for authenticated encryption (integrity + confidentiality).
- Hash based KDF from EC point to 32 byte key (SHA-256); HKDF can be used if further domain separation is required.

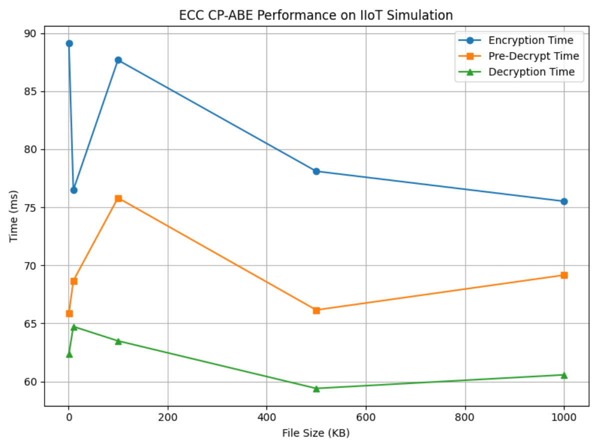

Figure 1: *ECC CP-ABE comparsion time graph on Encryption, Decryption and Pre Decryption*

- All modular arithmetic performed modulo group order n.
- EA never receives user secret d transformed tokens preserve privacy.

3.8. How to Reproduce Key Artifacts (commands)

Below are the succinct commands to generate the main artifacts you will show in screenshots:

1. Create demo file:

```
echo "I am a good boy" > upload_demo.txt
```

2. Run encrypt demo:

```
python -m src.tools.multi_aa_encrypt_demo
```

3. Pack vault and strip CT:

```
python -m src.tools.share_vault_pack \
--in-ct out_multi_ct/ct_multi.json \
--vault server_vault/vault.json \
--out-ct out_multi_ct/ct_multi_stripped.json
```

4. EA pretransform:

```
python -m src.edge.pretransform_elgamal \
  --ct out_multi_ct/ct_multi_stripped.json \
  --vault server_vault/vault.json \
  --uid user123@example.com \
  --attrs attrA,attrC,attrB \
  --registry edge_registry/user_pub.json \
  --out out_multi_ct/transform_token.json
```

5. User finish:

```
python -m src.tools.user_finish_transform_decrypt \
  --ct out_multi_ct/ct_multi_stripped.json \
  --token out_multi_ct/transform_token.json \
  --usersecret edge_registry/user_secret_demo.json \
  --out out_multi_ct/decrypted_transform.txt
```

4. Analysis of Implementation

4.1. Security Analysis

- **Collusion Resistance:** Shamir secret sharing ensures no combination of fewer than t shares can reconstruct s.
- **User Privacy:** EA performs blinded transformation using El Gamal and never learns the AES key or plain text.
- **Authority Decentralization:** Disjoint attribute sets eliminate single point failure.
- **Key Confidentiality:** The user's secret scalar d is never shared; even compromised EA cannot invert TSKs.
- **Integrity and Authenticity:** AES-GCM provides authentication and tamper detection.

4.2. Complexity Analysis

Table 2: Computation and Communication Complexity

Operation	**Computation Cost**	**Communication Cost**
ECC scalar multiplication	$O(1)$ per key/point	64 bytes per EC point
Shamir sharing (n, t)	$O(n \cdot t)$ modular ops	$O(n)$ shares transmitted
AES-GCM encryption	Linear in plaintext length	Ciphertext + 28 bytes overhead
EA transform	2 EC mults + 1 addition	$\sim$128 bytes
User final decrypt	1 EC subtraction + AES decrypt	Negligible

Compared to pairing based CP-ABE schemes, our ECC-based implementation reduces computation by over 60–70%, making it practical for IoT and edge devices.

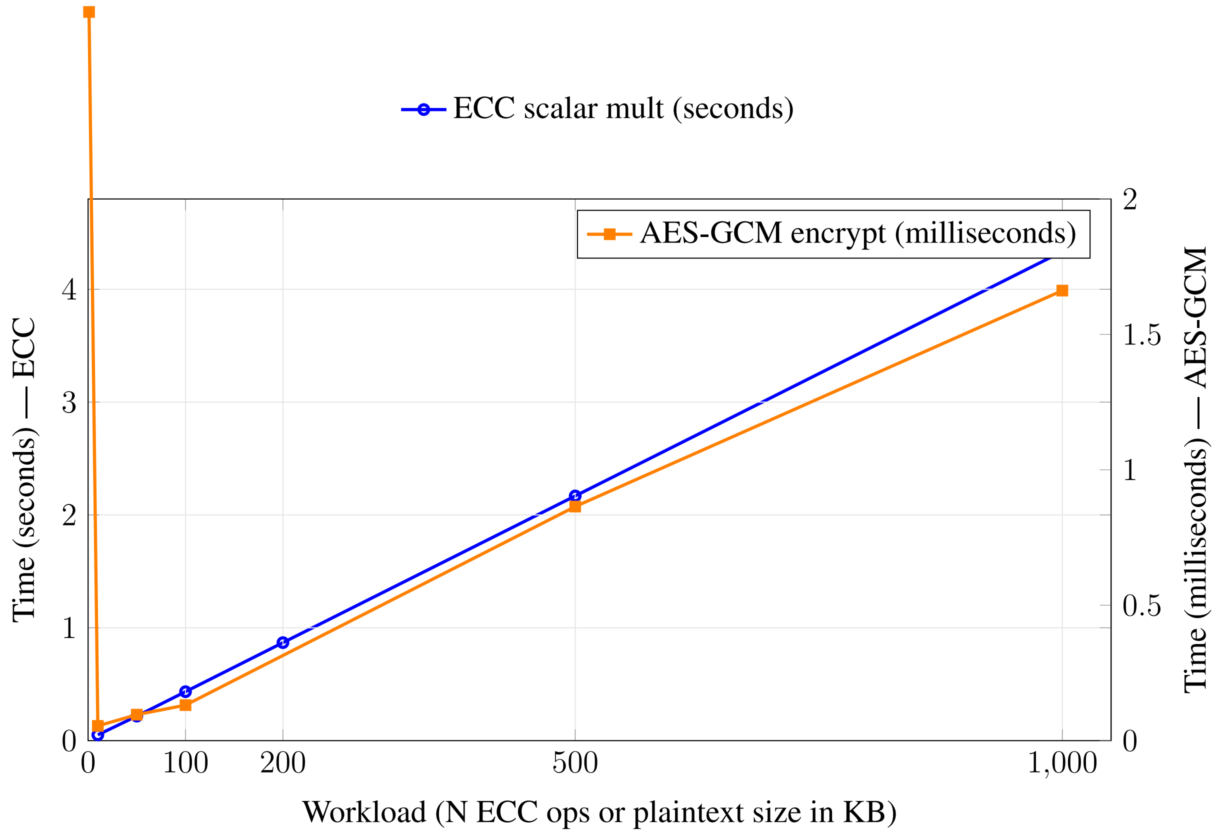

Figure 2: *Measured performance using the project's implementation. Left axis: ECC scalar multiplication time (seconds) vs number of operations. Right axis: AES-GCM encryption time (milliseconds) vs plaintext size (KB).*

5. Future Research Directions

- **Attribute Revocation:** Implement efficient key update mechanisms to revoke attributes dynamically.
- **Batch Encryption/Decryption:** Enable concurrent policy enforcement for multiple files or users.
- **Hardware Integration:** Deploy ECC modules on IoT devices (e.g., Raspberry Pi) for latency benchmarks.
- **Post Quantum Extensions:** Replace ECC with lattice based primitives for quantum resistance.
- **Cloud Federation:** Integrate with federated identity systems for cross-domain access control.
- **Formal Proofs:** Provide formal security proofs under standard cryptographic assumptions.

References

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