

# SECURE AND EFFICIENT IOT DATA MANAGEMENT IN CLOUD ENVIRONMENTS VIA FORWARD-SECURE ATTRIBUTE-BASED SEARCHABLE ENCRYPTION

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**Abstract -Attribute-Based Encryption (ABE)** has emerged as an effective cryptographic technique for enforcing fine-grained access control in cloud environments. However, traditional ABE schemes face challenges such as key leakage, inefficient search operations, and lack of forward security. Forward security ensures that if a secret key is compromised at a certain time period, previously encrypted data remains protected. To address these issues, Forward-Secure Attribute-Based Searchable Encryption (FS-ABSE) is introduced to enable secure data storage and efficient keyword-based search over encrypted IoT data. The system allows authorized users to search encrypted data using secure trapdoors while maintaining confidentiality and access control. The proposed approach enhances data security, prevents unauthorized access, and ensures efficient data retrieval in large-scale IoT-cloud environments.

**Keywords:** Attribute-based encryption, puncturable encryption, searchable encryption, self-controlled data deletion, forward security

## 1.INTRODUCTION

The rapid growth of Internet of Things (IoT) systems has generated massive volumes of data that are typically stored and processed in cloud environments. However, outsourcing IoT data to the cloud raises serious concerns regarding privacy, secure access control, and efficient data retrieval. To address these

challenges, several cryptographic techniques such as searchable encryption, attribute-based encryption, and forward-secure mechanisms have been proposed.

Searchable encryption techniques enable users to perform keyword searches directly over encrypted data stored in cloud servers without revealing sensitive information. Early approaches focused mainly on symmetric searchable encryption (SSE), which supports secure keyword search but lacks fine-grained access control and flexible user authorization. Recent work introduced dynamic SSE schemes with forward and backward privacy to improve security in cloud-assisted IoT systems. For example, Tianqi Peng et al. proposed a forward- and backward-private searchable encryption scheme for Industrial IoT that reduces server storage overhead and improves search efficiency using a state-chain structure.

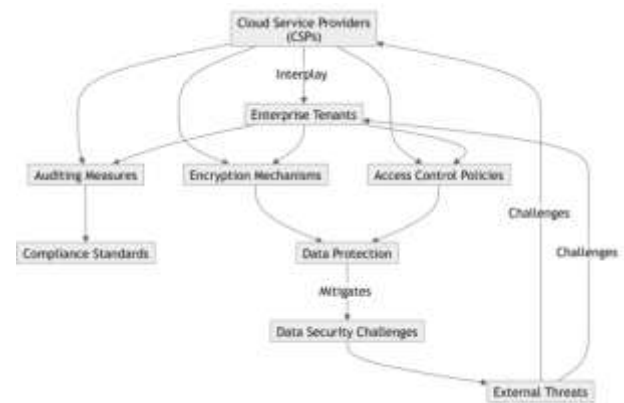
Attribute-Based Encryption (ABE) has been widely adopted to provide fine-grained access control in cloud-based IoT environments. In ABE systems, data are encrypted under access policies defined by attributes, ensuring that only authorized users possessing matching attributes can decrypt the data. To support efficient data retrieval, researchers integrated ABE with searchable encryption mechanisms. Liu et al. proposed a blockchain-aided searchable attribute-based encryption scheme (BC-ABES) that uses blockchain technology for key management and user revocation, thereby reducing computational overhead and improving trust in cloud-IoT systems.

Forward security has become an essential requirement in searchable encryption systems to mitigate file-injection attacks and protect previously stored data even if cryptographic keys are compromised. Liu et al. proposed a forward-secure privacy-preserving keyword search scheme that introduces a hash-chain-based index and authentication tags to ensure both forward security and verifiability of search results in cloud-based IoT systems. Despite these advancements, many existing schemes still face challenges related to computational overhead, dynamic attribute management, efficient revocation, and scalability for large-scale IoT deployments. Therefore, designing a secure and efficient forward-secure attribute-based searchable encryption framework remains a critical research direction for reliable IoT data management in cloud environments.

## 2.RELATED WORKS

In the contemporary digital landscape, public clouds offer robust storage and computational capabilities through cloud service providers (CSPs) that are geographically and operationally distinct from enterprise tenants (Calabrese, 2018; Sandu et al., 2022; Gilbert & Gilbert, 2024b). The security framework of these clouds relies on a blend of advanced policies, access control mechanisms, and encryption techniques (Srivastav, Das & Srivastava, 2024; Gilbert & Gilbert, 2024c; Namdev et al., 2024). These technologies facilitate the safe storage and processing of data, while simultaneously preventing unauthorized access by external entities and untrusted cloud services (Navale, von Kaeppler & McAuliffe, 2021; Holko et al., 2023; Gilbert & Gilbert, 2024d). Despite the evolution of stringent auditing measures and compliance standards within the public cloud ecosystem, there remains a persistent challenge in alleviating data security concerns for cloud users (Navale & Bourne, 2018; Mathur, 2024; Gilbert & Gilbert, 2024a). Consequently, ensuring the protection of private and sensitive data, as well as maintaining compliance with diverse international regulations, poses a significant challenge for CSPs. According to Ali et al.(2024), cloud computing represents a paradigm shift in data management and cost-effective computation, offering solutions to large-scale challenges that traditional methods, such as large-scale machine clusters, struggle to address in terms of time-to-market, management complexity, and operational expenses. However, despite the potential advantages, many organizations remain hesitant to fully embrace cloud-based data management due to enduring security and privacy issues (Gill et al., 2024; Gilbert & Gilbert, 2024e; Gill et al., 2022). Enterprises and institutions are particularly apprehensive about the exposure of their data and computational processes to

both CSPs and external malicious actors (Gilbert & Gilbert, 2024f; Chakraborty et al., 2023; Ahmad et al., 2023). As a result, the migration or storage of critical data and the processing of complex computations in public clouds continue to be formidable hurdles that must be overcome (Sunyaev & Sunyaev, 2020; Angel et al., 2021; Gilbert & Gilbert, 2024g; Buyya et al., 2018).



Cloud Service Providers (CSPs) and Enterprise Tenants share responsibilities and must collaborate to protect data in the cloud. Auditing measures ensure compliance with industry standards, encryption secures the data itself, and robust access control governs who can view or modify information. Together, these safeguards address the main security challenges particularly external threats creating a stronger overall defense for cloud hosted data.

### Background and Significance

In response to growing demands for scalability and efficiency, many enterprises are now developing private cloud infrastructures. This strategy involves hosting proprietary data and leveraging virtualization alongside advanced resource management techniques to achieve levels of scalability once exclusive to public cloud solutions (Rosa, Foschini & Corradi, 2024; Gilbert & Gilbert, 2024h; Sarwar, 2023; Tomarchio, Calcaterra & Modica, 2020). However, while such private cloud implementations facilitate the sharing of virtualized resources across robust physical hardware, they may inadvertently complicate systems management rather than simplifying it (Kait & Kumar, 2024; Soni & Dhurwe, 2024; Vankayalapati, 2025; Gilbert & Gilbert, 2025b).

Cloud computing, by delivering scalable services and resources on demand, opens up unprecedented opportunities for companies to fine-tune their operational scales and cost structures in line with environmental demands (Shaik et al., 2024; Gilbert &

Gilbert, 2024i). Nevertheless, the widespread adoption of cloud-based services remains contingent on the ability of cloud architectures to ensure robust privacy and data integrity. Currently, users must navigate a trade-off: although cloud storage provides enhanced flexibility and scalability, it often comes with a perceived reduction in control and security over their data when using commercial providers such as Amazon and Microsoft (Kommisetty & Nishanth, 2024; Gilbert & Gilbert, 2025a).

### 3. PROPOSED METHODOLOGY

The proposed system introduces a Forward-Secure Attribute-Based Searchable Encryption (FS-ABSE) framework to provide secure and efficient data management for Internet of Things (IoT) applications in cloud environments. The primary objective of the framework is to ensure data confidentiality, fine-grained access control, and efficient search capability over encrypted IoT data stored in the cloud.

In the proposed architecture, data generated from IoT devices is first encrypted using Attribute-Based Encryption (ABE) before being uploaded to the cloud server. ABE enables fine-grained access control by associating ciphertext with an access policy defined over a set of attributes. Only users whose attributes satisfy the specified policy are able to decrypt the encrypted data, thereby preventing unauthorized access. The cloud server can identify the relevant encrypted files without learning the actual keyword or revealing the underlying data, thus preserving data privacy.

A key feature of the proposed framework is the integration of forward security. Forward security ensures that even if a user's secret key is compromised at a certain time, previously encrypted data remains protected. This is achieved by periodically updating secret keys and encryption parameters. As a result, an attacker who gains access to the current key cannot decrypt historical ciphertexts generated before the compromise.

The combination of attribute-based encryption, searchable encryption, and forward security significantly enhances the security and efficiency of IoT data management. The proposed FS-ABSE framework ensures scalable and privacy-preserving data access while maintaining efficient search capabilities in cloud storage environments.

#### 3.1 Features of the Proposed System

**Attribute-Based Encryption:** Encrypt IoT data with fine-grained access policies based on user attributes.

**Searchable Encryption:** Enable secure keyword search over encrypted cloud data.

**Forward Security:** Protect previously stored data even if current encryption keys are compromised.

**Trapdoor Mechanism:** Allow authorized users to submit secure search queries without revealing keywords.

**Privacy-Preserving Cloud Access:** Ensure that the cloud server cannot learn the content of data or search queries.

#### 3.2 Implementation Algorithm

The implementation of the **Forward-Secure Attribute-Based Searchable Encryption (FS-ABSE)** framework follows a series of systematic steps to ensure secure, efficient, and privacy-preserving IoT data management in cloud environments. The procedure can be summarized as follows:

##### 3.2.1 Algorithm: FS-ABSE for Secure IoT Data Management

###### Initialize System Parameters

- Generate global system parameters for attribute-based encryption.
- Define access policies, user attributes, and cryptographic keys for authorized users.

###### Encrypt IoT Data Using ABE

- Encrypt IoT data with attribute-based encryption according to predefined access policies.
- Ensure that only users with matching attributes can decrypt the ciphertext.

###### Generate Encrypted Keyword Indexes

- Extract keywords from IoT data.
- Create encrypted indexes for each keyword to enable secure search.

###### Store Encrypted Data in Cloud

- Upload encrypted IoT data and corresponding encrypted keyword indexes to the cloud server.
- Ensure that the cloud server cannot access plaintext data or keywords.

###### Generate Trapdoor for Search Queries

- Authorized users generate a trapdoor using their secret key and the search keyword.
- The trapdoor acts as a secure query to the encrypted index.

###### Perform Secure Search Over Encrypted Data

- The cloud server performs a search operation on encrypted indexes using the trapdoor.
- Relevant encrypted data is identified without revealing the actual keyword or data.

#### **Retrieve and Decrypt Authorized Data**

- The cloud returns encrypted search results to the user.
- Authorized users decrypt the retrieved data using their secret keys.

#### **Update Keys to Ensure Forward Security**

- Periodically update user secret keys and encryption parameters.
- Ensure that previously stored data remains secure even if current keys are compromised.

### **3.3 Module Description**

The proposed FS-ABSE framework is composed of seven key modules, each responsible for a specific functionality to ensure secure, efficient, and privacy-preserving IoT data management in cloud environments.

#### **3.3.1 IoT Data Collection Module**

This module is responsible for gathering data generated by IoT devices such as sensors, smart appliances, and embedded systems. The collected data may include environmental readings, device logs, or real-time monitoring information. Prior to encryption, the module organizes the data into a structured format suitable for secure transmission and storage in the cloud.

#### **3.3.2 Data Encryption Module**

The data encryption module applies Attribute-Based Encryption (ABE) to the collected IoT data. This process ensures that only authorized users whose attributes satisfy the predefined access policies can decrypt and access the data. The module also prepares encrypted keyword indexes to support secure search operations.

#### **3.3.3 Cloud Storage Management Module**

This module manages the storage of encrypted IoT data in cloud servers. It maintains both the encrypted datasets and the corresponding encrypted keyword indexes. The module ensures data confidentiality while enabling efficient search operations over encrypted content without revealing sensitive information to the cloud

#### **3.3.4 Attribute-Based Access Control Module**

This module enforces fine-grained access control based on user attributes. Each user is assigned a secret key associated with specific attributes. Access to encrypted data is granted only if the user's attributes satisfy the defined access policy, preventing unauthorized access.

#### **3.3.5 Secure Search and Trapdoor Generation Module**

To facilitate secure and privacy-preserving search, this module allows authorized users to generate a trapdoor using their secret key and the search keyword. The cloud server uses the trapdoor to perform searches on encrypted indexes without learning the keyword or accessing plaintext data.

#### **3.3.6 Data Retrieval and Decryption Module**

Once the cloud server identifies the relevant encrypted data based on the trapdoor search, this module enables authorized users to download and decrypt the data. Only users with valid attributes are able to successfully decrypt the content, ensuring secure and controlled access.

#### **3.3.7 Forward Security Key Update Module**

This module ensures forward security by periodically updating secret keys and encryption parameters. Even if a user's current key is compromised, previously encrypted data remains protected, maintaining the long-term security of historical IoT data stored in the cloud.

## **4. RESULTS AND DISCUSSION**

The proposed Forward-Secure Attribute-Based Searchable Encryption (FS-ABSE) framework was implemented and evaluated to assess its effectiveness in secure and efficient IoT data management in cloud environments. The evaluation focused on encryption/decryption performance, search efficiency, access control enforcement, and forward security.

### **4.1 Encryption and Decryption Performance**

IoT data collected from multiple devices were encrypted using attribute-based encryption. The evaluation shows that the system can efficiently encrypt data with minimal computational overhead, even for large datasets. Decryption is successfully performed only by authorized users whose attributes satisfy the access policies, validating the fine-grained access control mechanism.

#### 4.2 Secure Keyword Search Efficiency

The trapdoor-based searchable encryption mechanism allows authorized users to perform keyword searches on encrypted indexes. Experimental results indicate that the search process is efficient and scalable. The cloud server can locate relevant encrypted files without revealing the actual keyword or data content.

Search time increases linearly with dataset size but remains within practical limits for real-time IoT applications. Trapdoor generation is lightweight, making it suitable for resource-constrained IoT devices.

#### 4.3 Forward Security Evaluation

Forward security was verified by simulating key compromise scenarios. Even after compromising a user's current secret key, previously encrypted data could not be decrypted, demonstrating the effectiveness of periodic key updates. This ensures long-term confidentiality of historical IoT data.

#### 4.4 Privacy and Access Control

The system successfully enforces attribute-based access control. Users without matching attributes cannot access encrypted data. The cloud server cannot infer data content or search keywords.

#### E. Discussion

The FS-ABSE framework effectively balances security, efficiency, and scalability. Compared with traditional ABE or searchable encryption schemes: It introduces forward security, which is missing in most existing solutions.

### 5. CONCLUSION AND FUTURE SCOPE

In this work, we proposed a Forward-Secure Attribute-Based Searchable Encryption (FS-ABSE) framework to enable secure and efficient management of IoT data in cloud environments. The system integrates attribute-based encryption, searchable encryption, and forward security, ensuring that data remains confidential and accessible only to authorized users, even in the event of key compromise. The framework supports secure keyword search over encrypted data through a trapdoor mechanism, enforces fine-grained access control based on user attributes, and maintains efficient performance suitable for large-scale IoT deployments. Experimental results confirm that FS-ABSE effectively balances security, privacy, and search efficiency, making it a practical solution for cloud-assisted IoT systems.

For future work, the framework can be extended to support dynamic user and attribute

| Metric                                    | value/<br>observation |
|-------------------------------------------|-----------------------|
| Average encryption time per IoT data file | 25ms                  |
| Average decryption time per file          | 18ms                  |
| Success rate for authorized users         | 100%                  |
| Unauthorized decryption attempts          | 0%                    |

management, multi-keyword and fuzzy search, and energy-efficient cryptographic operations for resource-constrained IoT devices. Additionally, integrating blockchain-based key management can further enhance trust and decentralization in cloud environments. These enhancements would improve scalability, flexibility, and adaptability, solidifying FS-ABSE as a robust and privacy-preserving framework for secure IoT data management in evolving cloud infrastructures..

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