vFAC: Fine-Grained Access Control with Versatility for Cloud Storage

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Abstract—In recent years, cloud storage technology has been widely used in many fields such as education, business, medical and more because of its convenience and low cost. With the widespread applications of cloud storage technology, data access control methods become more and more important in cloud-based network. The ciphertext policy attribute-based encryption (CP-ABE) scheme is very suitable for access control of data in cloud storage. However, in many practical scenarios, all attributes of a user cannot be managed by one authority, so many multi-authority CP-ABE schemes have emerged. Moreover, cloud servers are usually semi-trusted, which may leak user information. Aiming at the above problems, we propose a fine-grained access control scheme with versatility for cloud storage based on multi-authority CP-ABE, named vFAC. The proposed vFAC has the features of large universe, no key escrow problem, online/offline mechanism, hidden policy, verifiability and user revocation. Finally, we demonstrate vFAC is static security under the random oracle model. Through the comparison of several existing schemes in terms of features, computational overhead and storage cost, we can draw a conclusion that vFAC is more comprehensive and scalable.

I. INTRODUCTION

Cloud storage is an emerging network storage technology with the features of convenience and low cost. Recently, more and more users are willing to store personal data in cloud servers, in which some sensitive information might be involved [1]. Therefore, data access control in cloud storage has become critical challenge. Produced by Sahai and Waters [2] in 2005, attribute based encryption (ABE) scheme can effectively solve the data security and access control issues simultaneously. This allows users to encrypt and decrypt data based on different attributes. Following the original work, in order to provide a more complicated access control policy, CP-ABE appeared successfully. In CP-ABE, the access policy is devised by the data owner, and it is especially suitable for the designing of access control in cloud storage systems, as shown in Fig. 1.

With the fast development of cloud storage technology, the CP-ABE schemes with a single central authority are no longer suitable for some scenarios, because all attributes of a user are not always managed by one authority. To solve this problem, Muller et al. [3] proposed a multi-authority CP-ABE system firstly in 2009, in which different attribute sets are managed by multiple authorities. Their scheme has distributed requirements by removing central authority with each attribute authority having equal status. However, most of similar schemes have the disadvantage of low efficiency. So researchers introduced online/offline mechanism and computing outsourcing technique to improve the efficiency of CP-ABE. In 2008, Guo et al. [4] came up with an idea of identity based online/offline encryption, in which the encryption stage was split in an online phase, where only several simple operations are involved to generate the final ciphertext, and an offline phase. Since then, some schemes [5]–[11] were proposed that effectively reduced the computation burden of users.

Furthermore, the access policy associated with ciphertext may reveal some user sensitive information. In 2007, Kapadia et al. [12] protected users’ privacy with hidden policy, but there were security flaws. In the next year, Nishide et al. [13] proposed two CP-ABE constructions to achieve hidden policy, but only partial policy was hidden. In [14], a security-enhanced ABE algorithm of hidden policy was proposed in the composite order group, which proved to be completely
safe under the bilinear Diffie Hellman assumption. However, the operation efficiency of bilinear pair in composite order group is lower than that of prime order group. Later, Lewko and Waters [13] studied the security of ABE schemes in the prime order group.

Recently, there has been a lot of research on hidden policy, computational outsourcing, attribute revocation and traitor tracing according to different functional extensions. In 2015, Rousselakis et al. [16] introduced a multi-authority ABE scheme supporting large universe, which meant that any string, as a new attribute, could be added to the system. Moreover, the number of attributes is not relevant to the public system parameters any more. In 2017, Zhang Kai et al. [17] solved the key escrow problem using the separate cloud server and user’s private keys. At present, the latest revocation mechanisms for multi-authority ABE [18]–[23] have been more flexible and can satisfy forward security, but they do not meet the feature of large universe.

In this paper, we propose a fine-grained access control scheme with versatility for cloud storage. It provides more features of online/offline mechanism, hidden policy, and verifiability than the existing schemes [16, 17]. The proposed vFAC is proved to satisfy static security under the random oracle model. In addition, through performance analyses, vFAC is more comprehensive and scalable.

The rest of this paper is organized as follows: Section II reviews the related preliminaries and gives a formal definition. Section III describes the specific process of vFAC in detail. Then, section IV analyzes the security and performance through the comparison with other schemes. Finally, section V concludes the paper.

II. PRELIMINARIES

A. q-Decisional Parallel Bilinear Diffie-Hellman Exponent 2 (q-DPBDHE2) Assumption

It is a deformation based on the q-DPBDHE assumption. We assume that \( p \) is a prime number, \( G \) and \( G_T \) are multiplicative cyclic groups of order \( p \), \( g \) is a generator of \( G \), and \( e : G \times G \rightarrow G_T \) is a bilinear map. The following process describes the q-DPBDHE2 assumption in detail.

\[
D = (p, g, G, e, g^a, \{g^{b_i}\}_{i \in [2q]}, \{g^{b_i'}\}_{(i, j) \in [2q] \times [2q]}, \{g^{\epsilon_i}\}_{i \in [q]}, \{g^{\epsilon_i'}\}_{(i, j) \in [q] \times [q]}, b_1, \ldots, b_q) = Z_p^* \]

where \( a, s, b_1, \ldots, b_q \in Z_p^* \) are unknown, distinguishing \( R \) from \( e(g, g)^{sa+1} \) and \( G_T \). Assuming that an attacker \( A \) can successfully solve the q-DPBDHE2 problem with the probability at least \( \varepsilon \) in polynomial time, that is

\[
\Pr[A(D, e(g, g)^{sa+1}) = 0] - \Pr[A(D, R) = 0] \geq \varepsilon.
\]

It can be claimed that the advantage of solving q-DPBDHE2 problem is \( \varepsilon \).

B. Formal Definition

Let \( U \) represent attribute space, and each attribute authority \( AA_i (i \in [1, n]) \) manages its own attribute domain \( U_i \in U \).

For \( \forall k, l \in [1, n], k \neq l \), then \( U_k \cap U_l = \emptyset \). This scheme contains eight formal algorithms.

GlobalSetup(\( \lambda \)) \rightarrow GP: The GlobalSetup algorithm inputs the security parameter \( \lambda \) and outputs global parameters \( GP \).

AuthoritySetup(GP, i) \rightarrow \langle PK_i, SK_i \rangle: This algorithm only inputs \( GP \) and attribute authority \( i \), and generates its public/secret key pair \( \langle PK_i, SK_i \rangle \).

KeyGen(GP, GID, \{SK_i\}, S) \rightarrow \langle UPK_{GID}, CSK_{GID}, S \rangle, USK_{GID}: The KeyGen algorithm inputs \( GP \), user’s GID, secret key \( \{SK_i\} \) of the relevant attribute authorities and a set of the user’s attributes \( S \). It outputs user’s public key \( UPK_{GID} \), the private key \( CSK_{GID} \) of the corresponding cloud server and user’s secret key \( USK_{GID} \).

Offline.Enc(GP, \{PK_i\}) \rightarrow IC: The Offline.Enc algorithm inputs \( GP \) and outputs intermediate ciphertext \( IC \).

Online.Enc(GP, \{PK_i\}, M, IC, A) \rightarrow CT: This algorithm inputs \( GP \), message \( M \), intermediate ciphertext \( IC \), access policy \( A \) and public key \( \{PK_i\} \) of the relevant attribute authorities. It outputs ciphertext \( CT \).

CS.Dec(GP, CSK_{GID,S}, UPK_{GID}, CT) \rightarrow CT_{GID} or \perp: The CS.Dec algorithm inputs \( GP \), secret key \( CSK_{GID,S} \) of cloud server, public key \( UPK_{GID} \) of the user, and ciphertext \( CT \). Then, it outputs partial decrypted ciphertext \( CT_{GID} \) or a symbol \( \perp \) which represents ciphertext cannot be decrypted successfully.

User.Dec(USK_{GID}, CT_{GID}) \rightarrow M or \perp: The User.Dec algorithm inputs user’s public key \( USK_{GID} \) and partial decrypted ciphertext \( CT_{GID} \). It outputs the recovered message \( M \) or \( \perp \).

Revoke(GID, KT) \rightarrow KT/(GID, CSK_{GID}): This algorithm inputs a user’s GID and a key list \( KT \), and outputs the key list \( KT \) after revocation.

III. FINE-GRAINED ACCESS CONTROL WITH VERSATILITY FOR CLOUD STORAGE

A. System Model

In Fig. 2 we can see that the system contains four participants: Attribute Authority (AA), Cloud Server (CS), Data Owner (DO), and Data User (DU).

AA: It is in charge of managing the DU’s attribute set, and generating the corresponding CS’s private key for these attributes.

CS: It stores encrypted data and manages the CS’s private keys corresponding to users.

DO: DO encrypts data based on the access policy, then uploads the encrypted data to CS.

DU: DU can request data from CS. If the attributes of DU satisfy the access structure, CS will return the corresponding partial decrypted ciphertext, then DU restores the cipher with his/her own private key.

B. Security Model

First, we define a static security model which requires query-response phase to be completed before the challenge phase. During the query phase, an attacker \( A \) can query
the private key of DU and CS, and control some attribute authorities. The specific description is as follows:

Setup: A challenger C generates GP by GlobalSetup algorithm and sends it to A.

Query-response Phase: Assume \( U_0 \) is the set of attribute authorities, \( C_0 \) is the set of partial attribute authorities controlled by A, and \( N_0 \) is the set of other attribute authorities that are not controlled by A.

- A submits a non-controlled attribute authority \( \theta \in N_0 \), then C runs the AuthoritySetup algorithm and returns the public key \( PK_\theta \) of \( \theta \).
- A submits the DU’s global identifier \( GID_i \), then C executes the KeyGen algorithm and returns the DU’s public and private key pair \( \langle PK_i, SK_i \rangle \).
- A submits the DU’s global identifier \( GID_i \) and the corresponding attribute set \( S_i \), then C executes the KeyGen algorithm and returns the private key \( CSK_{GID_i,S_i} \) of the CS.

Challenge: A submits the challenge access structure \( (\hat{A}^*, \rho^*) \) and the challenge ciphertext \( M_i^*, \hat{M}_i^* \). C randomly selects \( b \in \{0, 1\} \), and executes Offline.Enc and Online.Enc algorithms in turn and returns the challenge ciphertext \( CT^* \). Note that for any user \( GID_i \) who has queried for a private key, the attribute set \( S_{C_B} \cup S_i \) cannot satisfy the challenge access structure \( (\hat{A}^*, \rho^*) \).

Guess: A outputs a bit \( b' \in \{0, 1\} \).

The attacker’s winning advantage can be defined as 
\[
\Pr[ b = b' ] - \frac{1}{2}.
\]

C. Our Scheme

Based on the system model and formal definition, vFAC is described as follows.

1) System Initialization

GlobalSetup: In this algorithm, a bilinear map \( e : G \times G \to G_T \) is chosen firstly, where the orders of \( G \) and \( G_T \) are both large prime number \( p \) and \( g \) is a generator of \( G \). Next, select a symmetric algorithm \( SE \) = \( (SE.Enc, SE.Dec, l_{SE}) \), where \( SE.Enc \) is the encryption algorithm, \( SE.Dec \) is the decryption algorithm, and \( l_{SE} \) represents the length of the secret key. Then, choose five strong collision-resistant hash functions: \( H : Z_p^* \to G, \ F : U \to G, \ h : G_T \to \{0, 1\}^{l_{SE}}, \ H_1 : G_T \to \{0, 1\}^{l_{H_1}}, \ H_2 : \{0, 1\}^* \to \{0, 1\}^{l_{H_2}} \). Finally, publish global parameters GP: \( GP = \langle \lambda, e, G, G_T, p, g, U, \{U_i\}, H, F, h, H_1, H_2, SE \rangle \).

AuthoritySetup: Each attribute authority \( i \in [1, n] \) randomly selects \( \alpha_i, \beta_i, y_i \in Z_p^* \), then sets its own secret key as \( SK_i = \langle \alpha_i, \beta_i, y_i \rangle \) and public key as \( PK_i = \langle e(g, g)^{\alpha_i}, g^{\beta_i}, g^{y_i} \rangle \).

2) Key Generation

KeyGen: The user \( GID \) chooses a random number \( x_{GID} \in Z_p^* \), then sets his/her public key as \( UPK_{GID} = \langle g^{x_{GID}}, H(GID)^{x_{GID}} \rangle \). For each attribute \( j \in S \), if it is managed by the attribute authority \( i \), \( i \) needs to choose \( t_j \in Z_p^* \) randomly, calculate \( K_j^{1,GID} = g^{x_{GID}H(GID)^{x_{GID}}F(j)^{\beta_j}}, K_j^{2,GID} = F(j)^{\beta_j}, \) and set the CS’s private key corresponding to the \( GID \) as \( CSK_{GID,S} = \{K_j^{3,GID}, K_j^{4,GID}\}_{j \in S} \). Then, the attribute authority \( i \) adds \( \langle GID, CSK_{GID,S} \rangle \) to the key list \( KT \) and sends \( \{K_j^{3,GID}\}_{j \in S} \) to the user \( GID \) through a secure channel.

On receiving the \( \{K_j^{3,GID}\}_{j \in S} \), the user \( GID \) sets his/her secret key as \( USK_{GID} = \{x_{GID}, \{K_j^{3,GID}\}_{j \in S} \} \).

3) Offline/Online Data Encryption

Offline.Enc: For each attribute \( j \in [1, U] \), DO randomly selects \( \lambda_j^1, r_j, w_j \in Z_p^* \), precomputes the ciphertext \( C_{1,j} = e(g, g)^{\lambda_j^1}e(g, g)^{\alpha_{j,S}(r_j)}, C_{2,j} = g^{-r_j}, C_{3,j} = g^{\mu_{j,S}(r_j)}g^{w_j}, C_{4,j} = F(j)^{r_j}, \) and outputs the intermediate ciphertext: \( IC = \{\lambda_j^1, r_j, c_{1,j}, c_{2,j}, c_{3,j}, c_{4,j}\}_{j \in [1, U]} \).

Online.Enc: Suppose that DO’s attribute domain for creating access policy is \( D \). In this phase, DO randomly selects \( a \in Z_p^* \), calculates \( \sigma_j = e((g^{x_{GID}})^a, F(j)) \) for each attribute \( j \in D \), and replaces \( j \) with \( H_1(\sigma_j) \), where \( \delta(j) \) represents the authority who manages the attribute \( j \). DO uses the replaced attributes to generate the access policy \( (A, \rho) \), where \( A \) is an \( l \times n \) matrix and \( \rho \) is a map from the row matrix \( A \) to \( D \). Then, DO generates the ciphertext by doing the following:

- Randomly select \( s, y_2, \ldots, y_n, z_2, \ldots, z_n \in Z_p^* \) and build vectors \( \vec{v} = (s, y_2, \ldots, y_n)^T, \vec{w} = (0, z_2, \ldots, z_n)^T. \)
- Compute \( \lambda_j = \vec{A}_j \cdot \vec{v}, w_j = \vec{A}_j \cdot \vec{w} \), where \( \vec{A}_j \) represents the row vector in the matrix \( A \) that corresponds to \( j \).
- Randomly select \( M, R \in G_T \), and compute \( h = g^a, C_0 = \text{Re}(g, g)^{\lambda_0}, C_{5,j} = \lambda_j - \lambda_0, C_{6,j} = w_j - w_j', K_{SE} = h(R), C_{SE} = SE.Enc(K_{SE}, M), Tag = H_1(R), VKM = H_2(Tag \parallel C_{SE}) \).

Finally, the ciphertext \( CT \) is uploaded to the CS.

\[
CT = \langle (A, \rho), C_0, h, C_{SE}, VKM, \{C_{1,j}, C_{2,j}, C_{3,j}, C_{4,j}, C_{5,j}, C_{6,j}\}_{j \in D} \rangle.
\]

4) Data Decryption

CS.Dec: When DU requests the CS to decrypt the ciphertext \( CT \), s/he first downloads \( h \) securely from \( CT \), then computes \( \sigma_j = e(h, K_j^{3,GID}) \) for each attribute \( j \) and replaces...
returns $\sum_{j \in I \subseteq \{1, 2, \ldots, l\}} c_j A_j = (1, 0, \ldots, 0)$. Next, the CS calculates $C_j GID = \prod_{i \in I} (C_{i,j} e(g, g)^{\theta_{GID}^j})$, and $C_j GID = \prod_{j \in I} (e(K_i^j GID, C_{j,i}) e(H(GID)^{\theta_{GID}^j}, C_{j,g} g^{\theta_{GID}^j}) e(K_3^j GID, C_{j,3}))$ and returns the partial decrypted ciphertext $CT_{GID} = (C_0, C_1 GID, C_2 GID, V K_M, C_{SE})$. Otherwise, the CS returns $\perp$ to DU if $H_1(\sigma_j)$ does not satisfy the access structure $(A, \rho)$.

**User:Dec:** Upon receiving $CT_{GID}$, DU calculates $C_1 GID C_2 GID \delta_{GID} = e(g, g)^{\beta_{GID}}$, $R = \frac{C_1 GID}{\delta_{GID}}$, $Tag = H_1(R)$. Then, DU verifies if the equation $H_2(Tag || \delta_{CSE}) = V K_M$ holds. If it does, DU continues to calculate $K_{SE} = h(R)$, $M = SE.D ec(K_{SE}, C_{SE})$, and returns $M$. Otherwise, it returns $\perp$.

5) **User Revocation**

**Revoke:** To revoke the user $GID$, the CS can find the corresponding entry from the key list and delete it.

**IV. SECURITY AND PERFORMANCE ANALYSES**

**A. Correctness Analysis**

If a DU’s attributes satisfy the access structure, the equations $\sum_{j \in I} \lambda_j C_j = s$ and $\sum_{j \in I} w_j C_j = 0$ will hold. Then, we can have the following formulas:

$$\begin{align*}
\sigma_j &= e((g^{\delta_{GID}^j})^a, F(j)) = e(g^a, F(j)^{\delta_{GID}^j}) = e(h, K_{\delta_{GID}^j}) \quad (1) \\
C_{1,j} e(g, g)^{C_{5,j}} &= e(g, g)^{\lambda_j} e(g, g)^{\alpha_{GID}^j} e(g, g)^{\lambda_j} = e(g, g)^{\lambda_j} e(g, g)^{\alpha_{GID}^j} (2) \\
C_{3,j} g^{C_{6,j}} &= g^{\eta_{GID}^j} g^{w_j} g^{w_j} = g^{\eta_{GID}^j} g^{w_j} (3)
\end{align*}$$

If we can restore $e(g, g)^a$, the plaintext $M$ will be decrypted correctly.

**B. Security Analysis**

In this subsection, we analyze the security properties of the vFAC under the following respects.

1) **Static Security:** Here, we analyze the security of vFAC based on security model in Section III.

**Lemma 1.** If the scheme in [172], named RW, satisfies the static security under the random oracle model, vFAC can also satisfy the static security.

**Proof.** Assume that, under the static security model, an attacker $\mathcal{A}$ can break vFAC in polynomial time by the advantage $\varepsilon$. So, there must be a simulator $\mathcal{B}$ that can break RW with the same advantage. The following specifically describes how a simulator $\mathcal{B}$ breaks RW with the help of $\mathcal{A}$ and the challenger $\mathcal{C}$ of RW.

**Setup.** $\mathcal{C}$ executes $GlobalSetup$ algorithm in RW and sends $GP$ to $\mathcal{B}$. According to the $GlobalSetup$ algorithm of vFAC, $\mathcal{B}$ generates the global parameters $GP$ and sends it to $\mathcal{A}$.

**Query-response Phase.** In this phase, we assume that the set of attribute authorities is $U_0$, the set of corrupted authorities controlled by $\mathcal{A}$ is $C_0$, and the set of uncontrolled authorities is $N_0$, besides, $N_0 \cup C_0 = U_0$. $N_0 \cap C_0 = \emptyset$. For a corrupted attribute authority $\theta \in C_0$, $\mathcal{A}$ first generates the corresponding public key $\{PK_\theta \}_{\theta \in U_0}$ and sends it to $\mathcal{B}$. Then, $\mathcal{B}$ sends $\{PK_\theta \}_{\theta \in U_0}$ to $\mathcal{C}$. Next, $\mathcal{A}$ does the following queries to $\mathcal{B}$, and $\mathcal{B}$ gives the corresponding responses:

- $\mathcal{A}$ submits a corrupted attribute authority $\theta \in N_0$, then $\mathcal{B}$ asks $\mathcal{C}$ for the corresponding public key of $\theta$. $\mathcal{C}$ executes the $AuthoritySetup$ algorithm of RW, generates the corresponding public key $PK_\theta = (e(g, g)^{\alpha_\theta}, g^{\theta_\theta})$, and sends it to $\mathcal{B}$. Then $\mathcal{B}$ updates the public key to $PK_\theta = (e(g, g)^{\alpha_\theta}, g^{\theta_\theta})$ and sends $PK_\theta$ to $\mathcal{A}$ according to the $AuthoritySetup$ algorithm of vFAC.
- $\mathcal{A}$ submits a user’s identifier $GID_i; (1 \leq i \leq m)$ to $\mathcal{B}$, then $\mathcal{B}$ executes the $KeyGen$ algorithm to generate the corresponding private key $USK_{GID_i} = x_{GID_i}^{\perp}$, public key $UPK_{GID_i} = (g^{x_{GID_i}}, H(GID_i)^{\theta_{GID_i}})$, and sends $\{USK_{GID_i}, UPK_{GID_i}\}$ to $\mathcal{A}$.
- $\mathcal{A}$ submits a user’s identifier $GID_i$ and the user’s attribute set $S_i; (1 \leq i \leq m, m < n)$ to $\mathcal{B}$, then $\mathcal{B}$ returns the corresponding CS’s private key and user’s private key to $\mathcal{A}$. If $1 \leq i \leq m$, then for each $j \in S_i$, $\mathcal{B}$ chooses $t_j \in Z_p^\ast$ randomly, and computes $K_{i,j}^\ast GID_i = g^{x_{GID_i}} H(GID_i)^{\theta_{GID_i}^{x_{GID_i}} F(j)^{t_j}}$, $K_i^3 GID_i = g^{x_{GID_i}^{3x_{GID_i}}}; K_i^3 GID_i = F(j)^{\theta_{GID_i}}$; If $m < i \leq n$, then $\mathcal{B}$ chooses $g_j \in G, t_j \in Z_p^\ast$ randomly, and computes $K_{i,j}^3 GID_i = g_j F(j)^{t_j}, K_i^3 GID_i = g_j^3; K_i^3 GID_i = F(j)^{\theta_{GID_i}}$. Finally, $\mathcal{B}$ sends $\mathcal{A}$ the corresponding private keys of CS and user.

**Challenge.** $\mathcal{A}$ submits the challenge access structure $(A, \rho)$, challenge plaintext $M_0^\ast$, $M_1^\ast$ to $\mathcal{B}$. $\mathcal{B}$ randomly selects $b \in \{0, 1\}$, executes $Offline.Enc$ and $Online.Enc$ algorithms, and returns the challenge ciphertext $CT_b^\ast$ to $\mathcal{A}$. Note that for all users who have queried the private key, and
the attribute set $S_{Ca} \cup S_i$ cannot satisfy the challenge access structure $(A^*, p^*)$.

**Guess.** $A$ outputs a bit $b' \in \{0, 1\}$, $B$ also outputs $b'$.

In the above game, $B$ perfectly simulates the challenger of vFAC under real conditions, and the CS’s private key generated by $B$ matches the user’s private key generated by the $KeyGen$ algorithm of RW. In addition, $B$ can determine the selected $R$ in the $Online.Enc$ algorithm of vFAC from the $b'$.

$R$ is equivalent to the message $M$ that needs to be encrypted in the $Encrypt$ algorithm of RW. Therefore, if the attacker $A$ can break vFAC with the advantage $\varepsilon$ in polynomial time, $B$ can also break RW, which contradicts with the premise that RW satisfies static security.

**Lemma 2.** If the $q$-DPBDHE2 assumption holds, RW satisfies the static security under the random oracle model.

**Proof.** Lemma 2 has been proven in [16].

**Theorem 1.** Our proposed vFAC satisfies the static security under the random oracle model.

**Proof.** According to Lemma 1 and Lemma 2, Theorem 1 can be proven.

2) **Hidden Policy:** In the $online.Enc$ phase, DO replaces all attributes of $D$ with $H_1(\sigma_j)$, and only the user $GID_i$ with the corresponding key $K_{GID_i}^{\sigma_i}$ can recover $\sigma_j$ for each attribute $j \in D$. The access policy of the ciphertext stored on the CS does not provide any useful information about user attributes, so privacy protection for user attributes can be achieved.

3) **No Key Escrow Problem:** DU’s public key $UPK_{GID_i}$ is used as a generating parameter when AA generates the corresponding private key of CS for the user $GID_i$. Therefore, whether AA or CS can only partially decrypt the ciphertext, and only the user can restore the corresponding plaintext with his/her private key $x_{GID_i}^{-1}$. If AA and CS attempt to decrypt partial ciphertext, they will have to solve the discrete logarithm problem.

4) **Verifiability:** Our vFAC encrypts a random key $R$ using access policy, while the real message $M$ is hidden by symmetric algorithm $SE$ and symmetric key $K_{SE}$. Therefore, the verification of $VK_M$ ensures the correctness of the random key $R$, which is to ensure the correctness of the ciphertext decrypted by the CS.

C. **Performance Analyses**

1) **Comparison of Features:** Table I shows the comparison on features among the selected schemes. YMCZZ in [18] is accountable, but its method of solving the key escrow problem will cause the waste of resources, which is difficult to implement under actual conditions. Besides, the schemes in [18], [20], [22] may have the problem of system construction if too many attributes are added to attribute authorities due to lack in the feature of large universe. Because our proposed vFAC provides all the features listed in table I it is more comprehensive than other schemes.

2) **Comparison of Computation Overhead:** We make a comparison on the phases of offline/online encryption and user decryption between vFAC and the selected schemes in TABLE II Let $l$ denote the number of rows of the access matrix, $|I|$ ($|I| \leq l$) denote the number of rows used for decryption in the access matrix, $P$ denote bilinear pair operation, and $E$ denote exponential operation.

**TABLE I: Comparison of Features**

| Schemes     | Prime order group | No CA | Large universe | No key escrow problem | Online/Offline | Hidden policy | Verifiability | Revocation |
|-------------|-------------------|-------|---------------|-----------------------|----------------|--------------|--------------|------------|
| RW [16]     | ✓                 | ✓     | ✓             | ×                     | ×              | ×            | ✓            | ×          |
| MZL [17]    | ✓                 | ✓     | ✓             | ✓                     | ×              | ×            | ✓            | ×          |
| YMCZZ [18]  | ✓                 | ✓     | ✓             | ✓                     | ×              | ×            | ✓            | ×          |
| LLL [20]    | ✓                 | ✓     | ×             | ✓                     | ✓              | ×            | ✓            | ×          |
| NMSM [22]   | ✓                 | ×     | ×             | ✓                     | ×              | ×            | ×            | ×          |
| vFAC        | ✓                 | ✓     | ✓             | ✓                     | ✓              | ✓            | ✓            | ✓          |

**TABLE II: Comparison of Computation Overhead**

| Schemes     | Encryption       | Decryption.user |
|-------------|------------------|-----------------|
|             | Offline.Enc      | Online.Enc      |                      |
| RW [16]     | $(4l + 1)E$       | $3|I|P + 2|I|E$  |
| MZL [17]    | $(4l + 1)E$       | $E$             |
| YMCZZ [18]  | $(4l + 1)E$       | $3|I|P + 2|I|E$  |
| LLL [20]    | $3IE + 2E$        | $E$             |
| NMSM [22]   | $(l + 2)E$        | $(|I| + 1)P + (|I| + 1)E$ |
| vFAC        | $4IE + 2E$        | $E$             |

In Table II, we found that the schemes in [16]–[18], [22] have no offline encryption mechanism, which cause the number of operations in encryption phase linearly increasing with $l$. In [16], [18], [22], the user directly decrypts the original ciphertext, so the exponential operations and the number of bilinear pair operations also linearly increase with $|I|$ in the decryption phase, leading to high computational complexity. In the decryption process of vFAC, only one exponent operation is involved. Although, in [20], the user also needs one decryption operation, it is achieved by outsourcing decryption and cannot solve the key escrow problem. For all the above, vFAC has high computational efficiency on the user side.

3) **Comparison of Storage Cost:** Denote $|Z_p|$ and $|G|$ as the length of element in $Z_p$ and $G$, $|U|$ as the number of attributes managed by AA, $|S|$ as the number of user’s attributes, $|c|$ as the length of the ciphertext after symmetric encryption, and $|VK|$ as the length of the verification key. The Table III shows the comparison result of storage cost. The length of ciphertext
is linearly related to $|I|$ because the ciphertext corresponds to the access policy. The storage capacity of the CS is actually stronger than that of users. Therefore, the storage cost of ciphertext on the CS can be omitted. Here, we mainly focus on the user’s storage cost.

In [20], [22], the length of the public/private key of each AA is linearly related to $|U|$. The users private key in [16], [18], [20], [22] is directly generated by AA based on the user’s attributes, so the length of private key is linearly related to $|S|$. When the number of attributes increases, the user’s storage cost increases too. In vFAC, the length of AA’s public/private key is a fixed value because it is independent of the number of attributes. Although the whole storage cost in [18] is lower than vFAC, it does not meet the property of large universe. In conclusion, vFAC is more suited for data access control because of its comprehensive features.

V. Conclusion

In order to solve the fine-grained data access control problem in cloud storage, this paper proposes a fine-grained access control scheme for cloud storage based on multi-authority CP-ABE. The proposed vFAC not only realizes online/offline encryption mechanism, but also satisfy the feature of hidden policy. Furthermore, vFAC allows the user to verify the decrypted ciphertext to ensure that the CS decrypts ciphers correctly. The static security of vFAC is also proved under the random oracle model. In particular, the analyses of features, computation overhead, and storage cost with the other existing schemes show that the vFAC has a more comprehensive advantage for cloud storage.

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| TABLE III: Comparison of Storage Cost |
|---------------------------------------|
| Schemes        | Secret key of AA | Public key of AA | Private key of user | Ciphertext size |
|----------------|------------------|------------------|---------------------|-----------------|
| RW [16]        | 2 | $Z_p$ | $2 | G | 2 | $G$ | (4 + 1) | $G$ |
| MZL [17]       | 2 | $Z_p$ | 2 | $G$ | 2 | $Z_p$ | (4 + 1) | $G$ |
| YMCZZ [18]     | 2 | $Z_p$ | 2 | $G$ | 2 | $G$ | (4 + 1) | $G$ |
| LLL [20]       | 1 + $|U|$ | $Z_p$ | 1 + $|U|$ | $G$ | 2 + $|S|$ | $Z_p$ | (3 + 2) | $G$ | $Z_p$ | $c$ | $V_K$ |
| NNMSM [22]     | (5 | $U$ | + 1) | $Z_p$ | (3 | $U$ | + 1) | $G$ | (2 | $S$ | + 1) | $G$ | $Z_p$ | (4 + 2) | $G$ | 2 | $Z_p$ | $c$ | $V_K$ |
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