Secure Outsourced Attribute-Based Signatures with Perfect Anonymity in the Standard Model

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Abstract

Outsourced attribute-based signatures (OABS) enable users to sign messages without revealing specific identity information and are suitable for scenarios with limited computing power. Recently, Mo et al. proposed an expressive outsourced attribute-based signature scheme (Peer-to-Peer Networking and Applications, 11, 2017). In this paper, we show that Mo et al.’s scheme does not achieve any of the three security properties. Their scheme is incorrect. The adversary can collude with the malicious signing-cloud service provider (S-CSP) to forge valid signatures on any message and any attribute set. And the S-CSP could trace the access structures used to generate the signatures. Then, we treat the S-CSP as an adversary and present more accurate unforgeability and anonymity models for OABS to remedy the drawbacks of the previous ones. Finally, we propose a simple but significant improvement to fix our attacks. The improved scheme achieves correctness, unforgeability, and perfect anonymity while keeping the efficiency almost unchanged. We also prove the security of the improved scheme under the standard model.

1. Introduction

Attribute-based cryptography is a powerful cryptographic primitive, enabling us to design various cryptosystems with fine-grained access control in a multiuser environment [1, 2]. Attribute-based signature (ABS) is one of the leading research contents of attribute-based cryptography. ABS can provide fine-grained privacy protection for signers and finds applications in many fields, such as private access control, trust negotiations, and anonymous credentials [2, 3]. ABS may also be applied to mobile authentication and two-factor/multifactor authentication in the future [4–6]. Since it was introduced, numerous ABS schemes for different access structures have been proposed one after another [7–15].

However, with the continuous enhancement of the expressiveness of the access structure, the computational overhead of ABS is increasing, which makes it challenging to execute in devices with limited computing power. Using outsourcing technology of cloud computing, Chen et al. [16] introduced outsourced attribute-based signatures (OABS) to overcome this problem. In OABS, the signer can delegate most of his/her signing workload to a signing-cloud service provider (S-CSP). After receiving the semisignature from the S-CSP, the signer can generate the final signature by little computations. In this way, ABS can be used in resource-constrained devices.

1.1. Related Works. While introducing OABS, Chen et al. [16] proposed two concrete OABS schemes. Their schemes are signature-policy OABS schemes with threshold access structures. After, Mo et al. [17] proposed an OABS scheme and applied it to the medical cloud. Mo et al.’s scheme is a key-policy OABS scheme that supports a more expressive monotonic access structure. Sun et al. [18, 19] introduced decentralization into OABS and proposed an outsourcing decentralized multiauthority attribute-based signature scheme. Their scheme is a signature-policy scheme for
threshold access structure. In 2021, Huang et al. [20] proposed a new key-policy OABS scheme for circuits. Their scheme is a short signature scheme, and its final signature has only one element of the group.

Chen et al.’s OABS model assumes that the S-CSP is honest-but-curious, i.e., the S-CSP always runs the algorithm honestly and outputs the semisignatures correctly, but the S-CSP may forge signatures. As a remedy for the overly strong assumption of S-CSP’s honesty, Chen et al. [16] discussed the accountability of OABS, which provides an audit function for S-CSP’s honesty. Liu et al. [21] studied OABS under the concept of server-assisted anonymous attribute authentication, added the correctness verification of the semisignature to OABS, and defined the outsourcing of the semisignature to OABS, and defined the outsourcing verifiability. After that, Ren and Jiang [22] formally introduced the concept of Verifiable Outsourced Attribute-Based Signatures (VOABS) with a concrete scheme supporting threshold access structure. Unfortunately, Uzunkol [23] presented two attacks on the verifiability of Ren et al.’s scheme [22] and showed that it does not achieve any of correctness, unforgeability, and perfect anonymity while keeping the efficiency almost unchanged. We also prove its security under the standard model.

1.3. Organization. The rest of this paper is organized as follows. Section 2 presents preliminaries. Section 3 reviews Mo et al.’s EOABS scheme and analyzes its security. Section 4 presents a new definition and new security models for OABS. Section 5 proposes an improvement to fix our attacks with security proofs and performance analysis. Section 6 concludes this paper.

2. Preliminaries

Let \( a \in \mathbb{R} \) denote sampling \( a \) randomly from \( A \). Let \( [n] = \{1, 2, \ldots, n\} \) for \( n \in \mathbb{N} \). For any vectors \( v = (v_1, v_2, \ldots, v_k) \in \mathbb{Z}_p^k \) and \( w = (w_1, w_2, \ldots, w_k) \in \mathbb{Z}_p^k \), their inner product \( vw = \sum_{i=1}^{k} v_i w_i \).

2.1. Bilinear Map. Let \( G \) and \( G_T \) be prime order \( p \) multiplicative cyclic groups. Let \( e: G \times G \rightarrow G_T \) be a map satisfying the following properties:

(i) For all \( a, b \in \mathbb{R} \) and \( g_1, g_2 \in \mathbb{G} \), \( e(g_1^a, g_2^b) = e(g_1, g_2)^{ab} \).

(ii) There exist \( g_1, g_2 \in \mathbb{G} \) such that \( e(g_1, g_2) \neq 1_{G_T} \).

(iii) For all \( g_1, g_2 \in \mathbb{G} \), \( e(g_1, g_2) \) can be computed efficiently.

2.1.1. Computational Diffie-Hellman Exponent (CDHE) Problem. Given \( (g, g^a, g^{a^2}, \ldots, g^{a^n}, g^{a^{2n}}, \ldots, g^{a^{3n}}) \) to compute \( g^{a^x} \), where \( g \in \mathbb{G}, a \in \mathbb{R} \). [28]

2.2. Linear Secret Sharing Scheme. Let \( P = \{p_1, p_2, \ldots, p_n\} \) be a party set; a collection \( \mathcal{A} \) of nonempty subsets of \( P \) is defined as an access structure. A set in \( \mathcal{A} \) is an authorized set, and a set not in \( \mathcal{A} \) is an unauthorized set. An access structure \( \mathcal{A} \subseteq 2^P \) is monotone, if \( B \in \mathcal{A} \) and \( B \subseteq C \) implies \( C \in \mathcal{A} \) for all \( B, C \).

A linear secret sharing scheme (LSSS) for a monotone access structure \( \mathcal{A} \) over \( \mathbb{Z}_p \) is a matrix \( M_{l \times k} \) with a function \( \pi(i) \) indicating the \( i \) th row of \( M \) as an attribute, and it satisfies the following properties:

(i) For any authorized set \( A \in \mathcal{A} \), there are constants \( \{w_i \in \mathbb{Z}_p\}_{i \in I} \) such that \( \sum_{i \in I} w_i M_i = (1, 0, \ldots, 0) \), where \( I = \{i : \pi(i) \in A\} \), and \( M_i \) is the \( i \) th row of the matrix \( M \).

(ii) For any unauthorized set \( B \notin \mathcal{A} \), there are no constants \( \{w_i \in \mathbb{Z}_p\}_{i \in I} \) such that \( \sum_{i \in I} w_i M_i = (1, 0, \ldots, 0) \), where \( I = \{i : \pi(i) \notin B\} \).

The distribution and reconstruction algorithms of an LSSS are as follows:

(i) Distribution: it takes as inputs a matrix \( M_{l \times k} \) with a function \( \pi(.) \) and a secret \( s \in \mathbb{Z}_p \) to be shared. It chooses \( r_2, r_3, \ldots, r_k \in \mathbb{R} \mathbb{Z}_p \), sets \( v = (s, r_2, r_3, \ldots, r_k) \), and sends each party \( \pi(i) \in B \) a share \( v_i = \pi(i) \cdot s + r_{\pi(i)} \).


\[
\ldots, r_k) \in \mathbb{Z}_p^k, \text{ and computes share set } \{ \lambda_i : \lambda_i = M_i v_j \}.
\]

(ii) Reconstruction: it takes as inputs a matrix \( M_{i,k} \) with a function \( \pi(\cdot) \) and an authorized set \( A \in A \) with its share set \( \{ \lambda_i \}_{i \in A} \). It finds constants \( \{ w_i \in \mathbb{Z}_p \}_{i \in A} \), such that \( \sum_{i \in A} w_i M_i = (1, 0, \ldots, 0) \) and then reconstructs the secret \( s = \sum_{i \in A} w_i \lambda_i \).

**Lemma 1** (see [29]). Suppose that \( A \) is a monotone access structure with matrix \( M_{i,k} \). For any unauthorized set \( B \notin A \), there is a vector \( w = (-1, w_2, \ldots, w_k) \in \mathbb{Z}_p^k \) such that \( M_i w = 0 \) for all \( i : \pi(i) \in B \).

### 3. Cryptanalysis of Mo et al.’s EOABS Scheme

**3.1. Review of Mo et al.’s EOABS Scheme.** In this section, we review the EOABS scheme proposed by Mo et al. [17]. It comprises five algorithms and involves four entities: attribute authority (AA), S-CSP, signer, and verifier.

(i) Setup: Suppose \( U \) is the attribute universe, \( \delta \) is the default attribute, and \( m \) is the maximal length of the message.

(i) The AA chooses two prime order \( p \) cyclic groups \( G \) and \( G_T \) with a bilinear map \( e : G \times G \rightarrow G_T \).

(ii) It selects a generator \( g \) of \( G \).

(iii) It selects \( a, b \in \mathbb{Z}_p^* \) and computes \( Y = e(g, g)^{ab} \).

(iv) It samples \( u_0, u_1, \ldots, u_m \in G \).

(v) It chooses \( T_0 \in G \) and \( T_u \in G \), \( u \in U \cup \{ \delta \} \).

The system public parameters:

\[
PP = (g, p, G, G_T, Y, T_0, \{ T_u \}_{u \in U \cup \{ \delta \}}, u_0, u_1, \ldots, u_m),
\]

(1)

the master secret key:

\[
\text{MSK} = (a, b).
\]

(2)

(ii) KeyGen: it takes as inputs the master secret key \( \text{MSK} \) and an access structure \( A \) with its matrix \( M_{i,k} \).

(i) It chooses \( v_2, \ldots, v_k \in \mathbb{Z}_p^k \) and sets \( v = (a, v_2, \ldots, v_k) \), and computes \( \lambda_i = M_i v, i \in [l] \).

(ii) For each \( i \in [l] \), it chooses \( r_i \in \mathbb{Z}_p \) and computes

\[
d_i = g^{\lambda_i},
\]

\[
d_i' = g^{r_i},
\]

\[
d_i'' = T_u^m.
\]

(3)

(iii) It chooses \( r_\delta \in \mathbb{Z}_p \) and then computes

\[
d_\delta = g^{b(T_0 T_\delta)^{r_\delta}},
\]

\[
d_\delta' = g^{r_\delta}.
\]

The outsourced key:

\[
\text{OSK}_A = (d_i, d_i', d_i'').
\]

(5)

The signer’s signing key:

\[
\text{PSK}_A = (d_\delta, d_\delta').
\]

(6)

(iii) **OutSign:** it takes as inputs an attribute set \( A \) and an outsourced key \( \text{OSK}_A \).

(i) If \( A \in A \), the S-CSP finds \( \{ w_i : i \in \pi(\delta) \} \) such that \( \sum_{i \in \pi(\delta)} w_i = (1, 0, \ldots, 0) \).

(ii) It chooses \( r, s \in \mathbb{Z}_p^* \), and computes

\[
\sigma'_1 = (T_0 \prod_{u \in A} T_u)^r \left( \prod_{i \in \pi(\delta)} d_i \prod_{u \in A, \pi(u) \notin \pi(\delta)} d_i'' \right)^{w_i},
\]

\[
\sigma'_2 = g^{r \prod_{i \in \pi(\delta)} d_i''},
\]

\[
\sigma'_3 = g^{s}.
\]

(7)

The outsourced signature \( \sigma_{out} = (\sigma_1, \sigma_2, \sigma_3) \).

(iv) **Sign:** it takes as inputs \( \text{PSK}_A \), \( \sigma_{out} \), and \( M = m_1, m_2, \ldots, m_m \in \{0, 1\}^m \), and the signer selects \( s_\delta \in \mathbb{Z}_p^k \) and computes

\[
\sigma_1 = d_\delta (T_\delta T_\delta)^{s_\delta} \sigma'_1 \left( u_0 \prod_{i \in \pi(\delta)} T_i^{m_i} \right)^{s_\delta}, \quad \sigma_2 = \sigma'_2 d_\delta g^{s_\delta}, \quad \sigma_3 = \sigma'_3.
\]

(8)

The final signature \( \sigma = (\sigma_1, \sigma_2, \sigma_3) \).

(v) **Verify:** it takes as inputs \((PP, \sigma, M)\), and the verifier checks whether
\[ e(g, \sigma_i) = Ye\left( \sigma_2, T_0 \prod_{u \in A \setminus \{\delta\}} T_u \right) e\left( \sigma_3, u_0 \prod_{i=1}^{m} u_i^{m_i} \right). \]

outputs 1 if it holds; otherwise it outputs 0.

3.2. Attacks on Mo et al.’s EOABS Scheme. Mo et al.’s EOABS scheme [17] does not achieve any of the three security properties, although it was proven to be secure under their security models.

3.2.1. On Correctness. Mo et al.’s EOABS scheme is incorrect.

In Mo et al.’s scheme

\[
\begin{align*}
\sigma_1' &= \left( T_0 \prod_{u \in A} T_u \right)^r \left( \prod_{i \in I} \left( d_i \prod_{u \in A \setminus \{\pi(i)\}} r_i \right)^{w_i} \right), \\
&= \left( T_0 \prod_{u \in A} T_u \right)^r \left( \prod_{i \in I} \left( g^{h_i}(T_0 T_{\pi(i)})^{r_i} \prod_{u \in A \setminus \{\pi(i)\}} r_i \right)^{w_i} \right), \\
&= g^{\sum_{i \in I} r_i w_i} \left( T_0 \prod_{u \in A} T_u \right)^{r \sum_{i \in I} r_i w_i}, \\
\sigma_2' &= g^r \prod_{i \in I} d_i^{w_i}, \\
&= g^{r \sum_{i \in I} w_i}, \\
\sigma_1 &= d_{\delta}(T_0 T_{\delta})^{r_{\delta}} \sigma_1' \left( u_0 \prod_{i=1}^{m} u_i^{m_i} \right)^z, \\
&= g^{h}(T_0 T_{\delta})^{r_{\delta}} (T_0 T_{\delta})^{l_{\delta}} g^r \left( T_0 \prod_{u \in A} T_u \right)^{r \sum_{i \in I} r_i w_i} \left( u_0 \prod_{i=1}^{m} u_i^{m_i} \right)^z, \\
&= g^{a_{\delta}} (T_0 T_{\delta})^{r_{\delta}+s_{\delta}} \left( T_0 \prod_{u \in A} T_u \right)^{r \sum_{i \in I} r_i w_i} \left( u_0 \prod_{i=1}^{m} u_i^{m_i} \right)^z, \\
\sigma_2 &= \sigma_2' d_{\delta} g^{s_{\delta}}, \\
&= g^{r \sum_{i \in I} w_i} g^{s_{\delta} s_{\delta}}, \\
&= g^{r s_{\delta}} g^{r \sum_{i \in I} w_i}, \\
\sigma_3 &= g^r.
\end{align*}
\]

So we have
Thus, the verification equation does not hold.

3.2.2. Forgery Attack. Mo et al.’s EOABS scheme is forgeable. Adversaries can collude with the malicious S-CSP to forge signatures.

Suppose that $A$ is an attribute set, $\mathcal{A}$ is adversary $\mathcal{B}$’s access structure, and $A \notin \mathcal{A}$. Adversary $\mathcal{B}$ can collude with the malicious S-CSP to forge signatures for $(M, A)$ as follows:

(i) The malicious S-CSP finds an outsourced key $OSK_{\mathcal{A}}$ with access structure $\mathcal{A}$ satisfied by $A$. It runs the OutSign algorithm with $OSK_{\mathcal{A}}$ and generates and sends the outsourced signature $\sigma_{\text{out}} = (\sigma_1, \sigma_2, \sigma_3)$ for $A$ to adversary $\mathcal{B}$.

(ii) With the outsourced signature $\sigma_{\text{out}}$ and message $M$, adversary $\mathcal{B}$ runs the Sign algorithm with his signing key $PSK_{\mathcal{A}}$ and then outputs a signature $\sigma = (\sigma_1, \sigma_2, \sigma_3)$ on $M$ and $A$.

The attack above is executable for the following reasons:

(i) The signing key $PSK_{\mathcal{A}}$ is only related to the master secret key $b$ and the default attribute $\delta$, but not to the access structure $\mathcal{A}$.

(ii) $A \in \mathcal{A}$, so the outsourced signature $\sigma_{\text{out}}$ for $A$ can be generated correctly using $OSK_{\mathcal{A}}$.

Obviously, the output of adversary $\mathcal{B}$ above is a valid signature on the message $M$ and the attribute set $A$. But the attribute set $A$ does not satisfy $\mathcal{B}$’s access structure $\mathcal{A}$.

3.2.3. On Anonymity. Mo et al.'s EOABS scheme does not achieve anonymity. The S-CSP can identify the corresponding access structures of the signatures as follows:

(i) The S-CSP stores all outsourced signature $\sigma_{\text{out}}$ with its corresponding access structure $\mathcal{A}$ into a list $L$ in the form of $(\sigma_1, \sigma_2, \sigma_3, \mathcal{A})$.

(ii) Receiving a final signature $\sigma = (\sigma_1, \sigma_2, \sigma_3)$, the S-CSP outputs the corresponding access structure $\mathcal{A}$ if there is $\sigma_3 = \sigma_3$ in $L$.

The attack above is practicable for the following reasons:

(i) The S-CSP needs to know the access structure $\mathcal{A}$ when using $OSK_{\mathcal{A}}$ to generate outsourced signatures. So it can maintain the list $L$ correctly.

(ii) Since $\sigma_3 = \sigma_3'$, the S-CSP can correctly establish the link between the final signature $\sigma$ and the outsourced signature $\sigma_{\text{out}}$.

4. Outsourced Attribute-Based Signature

The attacks above suggest that the security models in [17] are not conforming to the actual. Their models are similar to the nonoutsourced models [2, 30]. We present more accurate security models in this section.

4.1. Definition. An outsourced attribute-based signature (OABS) scheme is composed of the following algorithms.

(i) Setup $(1^k) \rightarrow (pp, msk)$. It takes the security parameter $\lambda$ as input and returns the public parameters $pp$ and master key $msk$.

(ii) KeyGen $(pp, msk, \mathcal{A}, f_u) \rightarrow (OSK_{\mathcal{A}, f_u}, PSK_{\mathcal{A}, f_u})$. It takes the public parameters $pp$, master key $msk$, and an access structure $\mathcal{A}$ with a flag $f_u$ as inputs and returns the outsourced key $OSK_{\mathcal{A}, f_u}$ and private signing key $PSK_{\mathcal{A}, f_u}$.

(iii) Sign$_{\text{out}}$ $(pp, OSK_{\mathcal{A}, f_u}, A) \rightarrow \sigma_{\text{out}}$. The outsourced signing algorithm takes the public parameters $pp$, an outsourced key $OSK_{\mathcal{A}, f_u}$, and an attribute set $A \in \mathcal{A}$ as inputs and returns an outsourced signature $\sigma_{\text{out}}$.

(iv) Sign $(pp, PSK_{\mathcal{A}, f_u}, M, A, \sigma_{\text{out}}) \rightarrow \sigma$. The signing algorithm takes the public parameters $pp$, a private signing key $PSK_{\mathcal{A}, f_u}$, a message $M$, and an outsourced signature $\sigma_{\text{out}}$ as inputs and returns a signature $\sigma$ for $(M, A)$.

(v) Verify $(pp, \sigma, M, A) \rightarrow 0/1$. It takes the public parameters $pp$, a signature $\sigma$, a message $M$, and an attribute set $A$ as inputs. If $\sigma$ is valid, it returns 1; otherwise, it returns 0.
Note: The flag $f_u$ we introduced above is just an identifier used to match the outsourced key and private signing key correctly. It does not take part in any operation and does not affect efficiency and security.

4.2.1. Unforgeability. A trivial requirement for the unforgeability is that the adversary cannot possess the key required for signing because anyone who has the signing key can run the signing algorithm to generate a valid signature. In the scenario of outsourced signatures, all outsourced keys are sent to the S-CSP, and the S-CSP is not necessarily trusted. Therefore, it should be assumed that the adversary may have all the outsourced keys and only restrict him from possessing the required private signing key. To this end, we need to provide different oracles for the outsourced key and the private signing key. In addition, since the adversary is permitted to obtain all outsourced keys and can generate outsourced signatures by himself, he need not make any authorized signing oracle query.

The unforgeability model of Mo et al. [17] does not reflect the above requirements and is therefore inaccurate. We present a more accurate unforgeability model in the following. There are two main differences between our model and Mo et al.’s model: First, our model provides the adversary with two oracles, OSK-Oracle and SK-Oracle, while their model only provides one oracle, KeyGen-Oracle. Second, our model restricts the adversary from possessing any private signing key of the access structure satisfied by the challenge attribute. In contrast, their model does not provide the above requirements and is therefore inaccurate.

where are two main differences between our model and Mo et al.’s model: First, our model provides the adversary instead and then sent to the challenger. (ii) Verify: Adversary $\mathcal{A}$ chooses and sends a message $M$ to $\mathcal{C}$. $\mathcal{C}$ returns a signature $\sigma$ to $\mathcal{A}$.

Adversary $\mathcal{A}$ wins the game, if
(i) $(M^*, A^*)$ was not queried to Sign-Oracle;
(ii) any access structure $\mathcal{A}$ queried to SK-Oracle is not satisfied by $A^*$;
(iii) Verify $(pp, \sigma^*, M^*, A^*) = 1$.

Adversary $\mathcal{A}$’s advantage is defined as its probability of winning the above game, denoted as $\text{Adv}_{\text{OABS,df}}^{\text{EUF-sA-CMA}}(1^\lambda)$.

Definition 2 (unforgeability). An OABS scheme is existentially unforgeable under selective attribute set but adaptive chosen message attack, if $\text{Adv}_{\text{OABS,df}}^{\text{EUF-sA-CMA}}(1^\lambda)$ is negligible in the security parameter $\lambda$ for any PPT adversary $\mathcal{A}$.

4.2.2. Perfect Anonymity. In the outsourced attribute-based signature, the untrusted S-CSP generates the outsourced signature, and then the signer generates the final signature. This is the essential difference from the general attribute-based signature, which must be reflected in the security model. In the model of Mo et al., the outsourced signature is generated by the challenger, and the adversary has no way of knowing it. This makes it impossible for the adversary to determine the access structure corresponding to the signatures through the outsourced signatures. But in the outsourced attribute-based signature scheme, the outsourced signatures are calculated by the S-CSP, so that the S-CSP may track the access structures corresponding to the signatures through the outsourced signatures. This is why Mo et al.’s scheme is anonymous under their model, but the above attack exists. In our model, the outsourced signatures are generated by the adversary instead and then sent to the challenger. Under such a model, Mo et al.’s scheme does not achieve anonymity. Our model reflects the difference between outsourced attribute-based signatures and general attribute-based signatures.

We formalize our definition by a game between challenger $\mathcal{C}$ and adversary $\mathcal{A}$ as follows.

(1) GAME 2 (Perfect Anonymity).

(1) Initialization. Adversary $\mathcal{A}$ selects and sends a challenge attribute set $A^*$ to challenger $\mathcal{C}$.

(ii) Setup. $\mathcal{C}$ generates and sends the public parameters $pp$ to $\mathcal{A}$.

(iii) OSK-Oracle. $\mathcal{A}$ chooses and sends an access structure $\mathcal{A}$ with a flag $f_u$ to $\mathcal{C}$. $\mathcal{C}$ returns an outsourced key $\text{OSK}_{A_{f_u}}$ to $\mathcal{A}$.

(iv) SK-Oracle. $\mathcal{A}$ chooses and sends an access structure $\mathcal{A}$ with a flag $f_u$ to $\mathcal{C}$. $\mathcal{C}$ returns a private signing key $\text{PSK}_{A_{f_u}}$ to $\mathcal{A}$.
In this section, we propose a simple but significant improvement to Mo et al.’s scheme. The outsourced key and private signing key are combined to generate a signature, then the verification equation is not equal to the public key. The signature will not be accepted as a valid signature.

In Mo et al.’s scheme, $\sigma'_4$ is not blinded but directly used as a component of the final signature. This allows the adversary to track the access structure used to generate the signature. To ensure anonymity, the outsourced signature must be blinded. But the computation cost of blinding $\sigma'_4$ is the same as that of computing $\sigma'_3$. Therefore, in our improved scheme, the user computes $\sigma'_4$ by himself, and the server no longer computes $\sigma'_3$. In our improvement is equivalent to $\sigma'_3$ in Mo et al.’s scheme.

We split $\sigma'_1$ into $\sigma'_{11}$ and $\sigma'_{12}$, and $\sigma'_3$ into $\sigma_3$ and $\sigma'_3$, all for the signature to satisfy the verification equation.

5.1. Improved Scheme

(i) Setup: it is the same as Mo et al.’s EOABS scheme, except that $Y = e(g, g)^{a+b}$ and MSK = $a \in \mathbb{Z}_p$

(ii) KeyGen: it is the same as Mo et al.’s EOABS scheme but chooses $a \in \mathbb{Z}_p$ and sets $b = a - a$.

(iii) OutSign: it takes as inputs an attribute set $A$, an outsourced key $OSK_{A,f_{w_u}}$ with matrix $M_A$, and a flag $f_{w_u}$.

(i) If $A \subseteq A_i$, the S-CSP finds $\{w_i; i \in I_{A_i} = \{i \in [I_i]; \pi(i) \in A\}$ such that $\sum_{i \in I_i} w_i M_{A_i} = (1, 0, \ldots, 0)

(ii) computes

$$\sigma_{11}' = T_0 \prod_{i \in A} T_{w_i}$$

$$\sigma_{12}' = \prod_{i \in I_{A_i}} \left( d_i \prod_{u \in A_i \cup \pi(i)} d_{iu}^{w_i} \right),$$ (14)

$$\sigma_{12}' = \prod_{i \in I_{A_i}} d_i^{w_i}.$$ (15)

The outsourced signature $\sigma_{out} = (\sigma'_{11}, \sigma'_{12}, r')$.

(iv) Sign: with a private signing key $PSK_{A,f_{w_u}}$, a message $M = m_1 m_2 \ldots m_m$, and an outsourced signature $\sigma_{out}$, the signer selects $r, s, s_3 \in \mathbb{Z}_p$ and computes

$$\sigma_1 = d_b \left( T_0 T_{A_i} \right)^{s_3} \sigma_{11}' \sigma_{12}' \left( u_0 \prod_{i=1}^m u_i^{m_i} \right)^{s},$$

$$\sigma_2 = g^{s'},$$

$$\sigma_3 = d_s g^{s'},$$

$$\sigma_4 = g^\delta.$$

The final signature on $(M, A)$ is $\sigma = (\sigma_1, \sigma_2, \sigma_3, \sigma_4)$.

(v) Verify: with $(PP, \sigma, M, A)$, the verifier checks whether
Theorem 1 (correctness). The improved scheme is correct.

\[ e(g, \sigma_1) = \text{Ye} \left( \text{Ye} \left( g, \sigma_2, T_0 \prod_{u \in A} T_u \right) \right) e \left( \sigma_3, T_0 \prod_{u \in A} T_u \right) \text{Ye} \left( \sigma_4, \prod_{i=1}^{m} u_i^{m_i} \right). \tag{16} \]

If the equation holds, the verifier outputs 1. Otherwise, it outputs 0.

5.2. Proofs of Security

Theorem 2 (unforgeability). The improved scheme is existentially unforgeable. If an adversary \( \mathcal{A} \) can win GAME 1 with advantage \( \epsilon \), then there exists an algorithm \( \mathcal{B} \) that solves the CDHE problem with probability \( \epsilon' \geq (\epsilon/8q_s)(m+1) \), where \( q_s \) is the maximum number of Sign-Oracle queries and \( m \) is the length of the message.

Proof. In the following, \( \mathcal{A} \) is an adversary with advantage \( \epsilon \), and \( \mathcal{C} \) is the challenger to the CDHE problem. We build \( \mathcal{B} \) as follows, which uses \( \mathcal{A} \) to solve the CDHE problem.

Proof. When \( A \in \mathcal{A} \), we can find \( \{w_i : i \in I_A\} \) such that

\[ \sum_{i \in I_A} w_i \mathcal{M}_{A_i} = (1, 0, \ldots, 0), \tag{17} \]

and then

\[ \sum_{i \in I_A} w_i \lambda_i = \sum_{i \in I_A} w_i \mathcal{M}_{A_i} v = a. \tag{18} \]

So

Without loss of generality, we assume the attribute universe \( U = \{1, 2, \ldots, n\} \). \( \mathcal{B} \) maintains an initially empty list \( L_{\text{key}} \).

(i) CDHE Problem Gen.

(i) \( \mathcal{C} \) chooses two prime order \( p \) multiplicative cyclic groups \( G, G_T \) and a bilinear map \( e : G \times G \rightarrow G_T \).

(ii) \( \mathcal{C} \) chooses a generator \( g \in G \) and \( a \in \mathbb{Z}_p \) and computes \( \{g, g^a, g^{a^2}, \ldots, g^{a^{2^n}}\} \).

(iii) \( \mathcal{C} \) sends \( \{p, G, G_T, g, \{g_i = g_i^{a_i} \}_{i=1, \ldots, m}\} \) to \( \mathcal{B} \).

(ii) Init Phase. \( \mathcal{A} \) chooses and sends \( A^* \) to \( \mathcal{B} \).

(iii) Setup.
\( \mathcal{A} \) chooses \( a', t_0 \in \mathbb{R}\mathbb{Z}_p \) and \( t_u \in \mathbb{R}\mathbb{Z}_p \) for all \( u \in U \), and computes
\[
\begin{align*}
T_u &= g^{n_u} \cdot_{u \in U} g^{n_u} u \in U, \\
T_0 &= g^6 \cdot_{u \in A} T_u^{-1}, \\
T_\delta &= g^{6 \cdot T_0^{-1}}.
\end{align*}
\]
(ii) computes \( Y = e(g, g)^{a'} e(g_1, g_p) \) (i.e., it sets the master secret key \( \alpha = a' + a'' \) implicitly).
(iii) Let \( I_M = 4q_u \), choosing \( k_M \in \mathbb{R}[m] \), picking \( x_0 \in \mathbb{R}\mathbb{Z}_p, y_1 \in \mathbb{R}\mathbb{Z}_p \), \( \{x_i \in \mathbb{R}\mathbb{Z}_p: i \in [m]\}, \{y_j \in \mathbb{R}\mathbb{Z}_p: i \in [m]\} \), and computing
\[
\begin{align*}
u_0 &= g_n^{-l_M u+x_0} g^{y_j}, \\
v_i &= g_n{x_i} g^{y_j}: i \in [m].
\end{align*}
\]
(iv) sends the public parameters \( pp = (p, g, G, G_T, Y, e, T_0, \{T_u: u \in U \cup \delta\}, u_0, u_t, \ldots, u_m) \) to \( \mathcal{A} \).
(iv) OSK-Oracle. Assume \( \mathcal{A} \) queries an outsourced key on access structure \( \mathcal{A} \) with the matrix \( M_0 \) of size \( l_x \times k_n \) and flag \( f_u \). If \( (\mathcal{A}, f_u) \) in \( L_{key} \), it returns the corresponding outsourced key \( OSK_{\mathcal{A}, f_u} \) to \( \mathcal{A} \).
Otherwise, we compute the keys as follows:
\[
\begin{align*}
d_i &= g^{M_{0,i}(-v_i - w_i)}(T_0 T_{\pi(i)})^{v_i}

\left(g_{\pi(i)}^{-1}\cdot_{u \in A^*} g_{\pi(i)+1 - u + \pi(i)}\cdot_{u \in A^*} \right)^{-M_{0,w}}, \\
d_i' &= g^{M_{0,i} w}, \\
d_i'' &= T_u^{(M_{0,i}(-v_i - w_i))} g_{\pi(i) + 1 - u + \pi(i)}\cdot_{u \in A^*}.
\end{align*}
\]
(iv) selects \( r_i \in \mathbb{R}\mathbb{Z}_p \) and computes
\[
\begin{align*}
T_{\delta} &= g^{\delta_i} \cdot_{u \in U} T_u^{r_i}.
\end{align*}
\]
(v) returns \( OSK_{\mathcal{A}, f_u} = (d_i, d_i', d_i'') \in \{l_x\} \cup \{u \in \delta\} \) to \( \mathcal{A} \).
(vi) adds \( (OSK_{\mathcal{A}, f_u}, PSK_{\mathcal{A}, f_u} = (d_i, d_i', d_i'')) \) into the key list \( L_{key} \).

(iii) SK-Oracle. It is the same as the OSK-Oracle above, except that it returns a private signing key \( PSK_{\mathcal{A}, f_u} \) to \( \mathcal{A} \).

Claim 1. The keys simulated above are correct.

Proof. If \( A^* \in \mathcal{A} \), and \( OSK_{\mathcal{A}, f_u} \) is generated by KeyGen, it is correct certainly.

If \( A^* \notin \mathcal{A} \), according to Lemma 1, we can find a vector \( w = (-1, w_2, \ldots, w_{k_n}) \in \mathbb{Z}_p^{k_n} \) such that \( M_{0,i} w = 0 \) for each \( i: \pi(i) \in A^* \). We prove \( OSK_{\mathcal{A}, f_u} \) is a correct outsourced key with \( v = -(v_1 + a'' w) + v' \) as follows:

(i) When \( \pi(i) \in A^* \), \( M_{0,i} w = 0 \), and \( \lambda_i = M_{0,i} v = -(v_1 + a'' w)M_{0,i} + M_{0,i} w = M_{0,i} v' \), we have
\[
\begin{align*}
d_i &= g^{M_{0,i} v'(T_0 T_{\pi(i)})^{v_i}} = g^{v_i (T_0 T_{\pi(i)})^{v_i}}, \\
d_i' &= g^{v_i}, \\
d_i'' &= T_u^{(M_{0,i} v')} = u \in U/\pi(i)\}].
\end{align*}
\]
(ii) When \( \pi(i) \notin A^* \), we have \( \lambda_i = M_{0,i} v = M_{0,i} v' \) and \( (v' - v_1 w) - a'' \cdot M_{0,i} w \), and

\[d''_{\delta} = T_u^{(M_{0,i} v')} = u \in U/\pi(i)\}].
\[ d_i = g^{M_u(v - v_i)}(T_0^{T_{\pi(i)}})^{\gamma_i} \left( g^{\prod_{u \in A^*} (g_{\pi(i)j} g_{n+1-u \pi(i)})} \right)^{-M_u w}, \]

\[ = g^{M_u(v - v_i)}(T_0^{T_{\pi(i)}})^{\gamma_i} g^{\alpha(x_i \alpha M_u w)} g^{\alpha v_i M_u w}, \]

\[ \prod_{u \in A^*} \left( g^{\alpha M_u w} g^{\alpha v M_u w} \right) g^{\alpha M_u w}, \]

\[ = g^{M_u(v - v_i)} a^{\alpha M_u w}(T_0^{T_{\pi(i)}})^{\gamma_i} \left( g^{\prod_{u \in A^*} (g_{\pi(i)j} g_{n+1-u \pi(i)})} \right)^{-a^{\alpha M_u w}}, \]

\[ = g^{\gamma_i} \left( T_0^{T_{\pi(i)}} \right)^{\gamma_i} g^{a^{\gamma M_u w}}, \]

\[ = g^{\gamma_i} \left( T_0^{T_{\pi(i)}} \right)^{\gamma_i}, \]

\[ = g^{\gamma_i} \left( T_0^{T_{\pi(i)}} \right)^{\gamma_i}, \]

\[ \alpha(v_i + a^{\alpha}) = (a + a^{\alpha}) - (v_i + a^{\alpha}) = a - v_i. \]

Thus PSK_{A_{fu}} = (d_{\delta} = g^{d_i - v_i} (T_0^{T_{\delta}}), d_{\delta} = g^{d_i}) is a correct private signing key.

(vi) **Sign-Oracle.** It takes \((M, A, \sigma_{out}, f_u)\) as inputs.

Define functions

\[ F(M) = p - l_M K_M + x' + \sum_{i=1}^{m} \tilde{x}_i m_i, \]

\[ J(M) = y' + \sum_{i=1}^{m} \tilde{y}_i m_i, \]

\[ K(M) = \begin{cases} 0, & \text{if } x' + \sum_{i=1}^{m} \tilde{x}_i \equiv 0 \pmod{l_M}, \\ 1, & \text{otherwise}. \end{cases} \]

If \( K(M) = 0 \), it aborts. Otherwise, \( B \) chooses \( \mu_0, \delta', \gamma' \in \mathbb{Z}_p^* \) and computes and returns

\[ \sigma_1 = (T_0^{T_{\delta'}})^{\gamma_0} g^{\gamma_0}, \]

\[ \sigma_2 = g^{\gamma'}, \]

\[ \sigma_3 = g^{a^{\gamma \gamma_0}}, \]

\[ \sigma_4 = g^{\gamma' g_1^{1/F(M')}}. \]

Claim 2. The simulated signatures are correct.

Proof. By simple calculating, we have \( u_0 \prod_{i=1}^{m} u_i^{m_i} = g^{F(M)} g^{J(M)} \). If \( K(M) \neq 0 \), then \( F(M) \neq 0 \pmod{p} \), because we can assume \( l_M (m+1) < p \) for any reasonable values of \( p, m, \) and \( l_M \). Then, we have
\[ \sigma_1 = (T_0 T_\delta)^{r_1} g^{\Delta_1} \left( T_0 \prod_{u \in A} T_u \right)^{r'} \left( g_n^{F(M)} g_1^J(M) \right)^{i} g_1^{-F(M)} g_1^{-J(M)}, \]
\[ = (T_0 T_\delta)^{r_1} g^{\Delta_1} g^{a_{\Delta_1}} \left( T_0 \prod_{u \in A} T_u \right)^{r'} \left( g_n^{F(M)} g_1^J(M) \right)^{i} g_n^{a_{\Delta_1} F(M)} g_1^{-a_{\Delta_1} F(M)}, \]
\[ = (T_0 T_\delta)^{r_1} g^{\Delta_1} \left( T_0 \prod_{u \in A} T_u \right)^{r'} \left( g_n^{F(M)} g_1^J(M) \right)^{i} \left( g_n^{F(M)} g_1^J(M) \right)^{-a_{\Delta_1} F(M)}, \]
\[ = g^{\Delta_1} \left( T_0 \prod_{u \in A} T_u \right)^{r'} \left( T_0 T_\delta \right)^{r_1} \left( u_0 \prod_{i=1}^m u_i^{m_i} \right)^{-a_{\Delta_1} F(M)}, \]
\[ \sigma_2 = g^{r'}, \]
\[ \sigma_3 = g^{\Delta_1 + r'}, \]
\[ \sigma_4 = g^{r'} g_1^{-J(M)/F(M)} = g^{r' - a_{\Delta_1} F(M)}. \]

Then have

\[ e(g, \sigma_1) = e(g, g^{\Delta_1} \left( T_0 \prod_{u \in A} T_u \right)^{r'} \left( T_0 T_\delta \right)^{r_1} \left( u_0 \prod_{i=1}^m u_i^{m_i} \right)^{-a_{\Delta_1} F(M)}, \]
\[ = Ye(\sigma_2, T_0 \prod_{u \in A} T_u) e(\sigma_3, T_0 T_\delta) e(\sigma_4, u_0 \prod_{i=1}^m u_i^{m_i}). \]

The verification equation holds. Thus the simulated signature is correct.

(vii) Forging. \( A \) outputs a signature \( \sigma^* = (\sigma_1^*, \sigma_2^*, \sigma_3^*, \sigma_4^*) \) on \( (M^*, A^*) \).

(viii) Output. If \( F(M^*) \neq 0 \) (mod \( p \)), it aborts. Otherwise, \( A \) computes and outputs

\[ \frac{\sigma_1^*}{g^{\Delta_1 + J(M^*)} (\sigma_2^* \sigma_3^*)_0} \]

Claim 3. The output of \( A \) is \( g^{\Delta_1 + r'}. \)

Proof. Because \( F(M^*) = 0 \) mod \( p \), so \( u_0 \prod_{i=0}^m m_i = g_n^{F(M^*)} g_1^{J(M^*)} = g^{J(M^*)}, \)

\( \sigma^* \) is a valid signature on message \( M^* \) for \( A^* \), so we have

\[ e(g, \sigma_1^*) = Ye(\sigma_2^*, T_0 \prod_{u \in A^*} T_u) e(\sigma_3^*, T_0 T_\delta) e(\sigma_4^*, u_0 \prod_{i=1}^m u_i^{m_i}), \]
\[ = e(g, g^{\Delta_1}) e(\sigma_2^*, g^{r'}) e(\sigma_3^*, g^{i}) e(\sigma_4^*, g^{J(M^*)}), \]
\[ = e\left(g, g^{\Delta_1 + r'} (\sigma_2^* \sigma_3^*)^i \sigma_4^* g^{J(M^*)}\right), \]

and then
Claim 4. The probability that the simulation is not aborted is 1/8q_b(m + 1).

Proof. The same as Claim 2 of Waters [31].

Claims 1 and 2 show that the simulation above is correct. Thus, by Claim 3 and Claim 4, $B$ can compute $g^{\sigma_1^{\text{out}}}$ with probability $\epsilon' \geq \epsilon/8q_b(m + 1).

Theorem 3 (perfect anonymity). The improved scheme is perfect anonymous.

Proof. Challenger $C$ executes the Setup algorithm to set up the system and responds to the oracle requests by running the corresponding algorithm.

Receiving $(M, A, \beta_0, \alpha_1, \sigma_0^{\text{out}}, \sigma_1^{\text{out}}, f_{u_0}, f_{u_1})$, $C$ flips a fair coin $b \in \{0, 1\}$, chooses $r_b, s_b, s_{b0} \in \mathbb{Z}_p$, and computes and returns a signature $\sigma_b = (\sigma_{b1}, \sigma_{b2}, \sigma_{b3}, \sigma_{b4})$ from $\sigma_{\text{out}}$ using $\text{OSK}_{\beta_0, f_{u_0}}$.

Challenger $C$ continues to respond to the oracle requests by running the corresponding algorithm. Since $\sigma_{\text{out}}^b = (\sigma_{b1}^{11}, \sigma_{b2}^{11}, \sigma_{b2}^{12})$ is an outsourced signature on $A$ using $\text{OSK}_{\beta_0, f_{u_0}}$, we have

\[
\sigma_{11}^b = T_0 \prod_{u \in A} T_u, \\
\sigma_{12}^b = \prod_{i \in I_{A, b}} \left( d_{b0} \prod_{u \in A^{\pi(i)}} d_{i}^{n_{u}} \right)^{w_u}, \\
\sigma_{2}^b = \prod_{i \in I_{A}} d_{i}^{u_{i}}.
\]

And $\sigma_b = (\sigma_{11}, \sigma_{12}, \sigma_{b3}, \sigma_{b4})$ is a signature calculated from $\sigma_{\text{out}}^b$, so we have

\[
\sigma_{b1} = d_{b0}^{g^{(T_0 T_1)^{\gamma_0} \prod_{u \in A} T_u}} \left( T_0 \prod_{u \in A} T_u \right)^{\gamma_T + \sum_{i \in I_{A, b}} r_i w_i + \sum_{i \in I_{A}} r_i w_i} \left( u_0 \prod_{i = 1}^{m} u_i^{m_i} \right)^{\gamma_0}, \\
\sigma_{b2} = g^{r_T \sum_{i \in I_{A, b}} r_i w_i + \sum_{i \in I_{A}} r_i w_i} \left( u_0 \prod_{i = 1}^{m} u_i^{m_i} \right)^{\gamma_T}, \\
\sigma_{b3} = d_{b0}^{g^{r_T \sum_{i \in I_{A, b}} r_i w_i + \sum_{i \in I_{A}} r_i w_i}} = g^{r_T \sum_{i \in I_{A, b}} r_i w_i}, \\
\sigma_{b4} = g^{\gamma_T}.
\]

We can rewrite $\sigma_b$ as

\[
\sigma_{b1} = g^{(T_0 T_1)^{\gamma_0} \prod_{u \in A} T_u} \left( T_0 \prod_{u \in A} T_u \right)^{\gamma_T + \sum_{i \in I_{A, b}} r_i w_i + \sum_{i \in I_{A}} r_i w_i} \left( u_0 \prod_{i = 1}^{m} u_i^{m_i} \right)^{\gamma_0}, \\
\sigma_{b2} = g^{r_T \sum_{i \in I_{A, b}} r_i w_i + \sum_{i \in I_{A}} r_i w_i} \left( u_0 \prod_{i = 1}^{m} u_i^{m_i} \right)^{\gamma_T}, \\
\sigma_{b3} = d_{b0}^{g^{r_T \sum_{i \in I_{A, b}} r_i w_i + \sum_{i \in I_{A}} r_i w_i}} = d_{b0}^{g^{r_T \sum_{i \in I_{A, b}} r_i w_i}}, \\
\sigma_{b4} = g^{\gamma_T}.
\]
where \( r_p = r_b + \sum_{i \in 1_{\lambda_2}} r_{bi} w_{bi} - \sum_{i \in 1_{\lambda_2}} r_{bi} w_{bi} \in \mathbb{Z}_p \), \( s_b = s_b \),
\( s_{sb} = r_{sb} - r_{sb} + s_{sb} \), \( b = b \oplus 1 \).

This concludes that \( \sigma_b \) is also a signature calculated from \( \sigma_{out} \) out using \( (r_p, s_p, s_{sb}) \) and \( PSK_{\text{ref}} \). Because \( r, s, s_b \) are randomly selected from \( \mathbb{Z}_p \), the probability of selecting \( (r_p, s_p, s_{sb}) \) is the same as that of \( (r_p, s_p, s_{sb}) \), and both are \( p^{-3} \). Therefore, even if the adversary has an unlimited capability, it is impossible to distinguish which access structure was used to generate the signature.

On the other hand, the adversary may generate signatures by him/herself. Assuming that the random integer selected by the adversary is \( (r, s, s_b) \), then the probabilities of \( (r, s, s_b) = (r_p, s_p, s_{sb}) \) and \( (r, s, s_b) = (r_p, s_p, s_{sb}) \) are the same \( p^{-3} \). So, even if the adversary possesses all the private signing keys and outsourced keys, it is impossible to determine which access structure was used to generate the signature.

In summary, adversary \( \mathcal{A} \)'s advantage \( \text{Adv}_{\text{OABS}, \mathcal{A}}^{\text{PerAnon}} (1^1) \) is 0, and the improved scheme achieves perfect anonymity.

5.3. Performance Analysis. Denote by \( \mathbb{G} \) an element of \( \mathbb{G}_1 \), by \( \mathbb{Z}_p \) an element of \( \mathbb{Z}_p \), by \( E \) an exponentiation in \( \mathbb{G}_1 \) by \( \mathbf{M} \) a multiplication in \( \mathbb{G}_1 \), by \( P \) a computation of the pairing, and by \( I \) an inner product operation. Let \( n \) be the size of the attribute universe \( U \), \( m \) be the length of the message, \( l \) be the number of rows of \( \mathbf{M}_A \), \( l_b \) be the number of rows whose attribute belongs to the attribute set, i.e., \( l_b = |1_{ \lambda_2} | \), and \( l_a \) be the size of the attribute set, i.e., \( l_a = |A| \). We compare our scheme to Mo et al.’s scheme in Table 2.

In terms of data size, our scheme has one less integer in the master private key and one more group element in the final signature. The other items are the same size. There is not much difference between the two schemes.

In terms of computational overhead, our scheme has an extra \( 2E + 1M \) in signature generation. Estimated with the message length \( m = 160 \), this is an increase of about 0.7%.

Although our scheme is slightly inferior to Mo et al.’s schemes in terms of data length and computational overhead, our scheme has an overwhelming advantage in terms of security. Our scheme achieves correctness, unforgeability, and perfect anonymity, while their scheme does not achieve any of these three properties. It shows that our improvement is meaningful.

6. Conclusion

OABS was introduced to solve the problem that ABS is not suitable for scenarios with limited computing power. Recently, Mo et al. proposed an expressive outsourced attribute-based signature scheme. In this paper, we analyze the security of Mo et al.’s EOABS scheme. We show that it does not achieve the correctness, unforgeability, and anonymity that they claimed. We present more accurate security models for OABS and propose an improved OABS scheme to fix our attacks. Our scheme is provably secure in the standard model.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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