On the security of the hierarchical attribute based encryption scheme proposed by Wang et al.

Mohammad Ali, Javad Mohajeri, Mohammad-Reza Sadeghi

Abstract

Ciphertext-policy hierarchical attribute-based encryption (CP-HABE) is a promising cryptographic primitive for enforcing the fine-grained access control with scalable key delegation and user revocation mechanisms on the outsourced encrypted data in a cloud. Wang et al. (2011) proposed the first CP-HABE scheme and showed that the scheme is semantically secure in the random oracle model [4, 5]. Due to some weakness in its key delegation mechanism, by presenting two attacks, we demonstrate the scheme does not offer any confidentiality and fine-grained access control. In this way, anyone who has just one attribute can recover any outsourced encrypted data in the cloud.

Keywords: Cloud computing, Hierarchical attribute-based encryption, Fine-grained access control

1. Introduction

Attribute-based encryption (ABE) scheme [1] is a one-to-many cryptographic primitive which provides confidentiality and fine-grained access control over the outsourced encrypted data, simultaneously. It provides access control on the shared data by specifying an access structure over the ciphertexts or data users’ secret-keys. According to the position of the access structure, this cryptographic primitive can be divided into two categories; key-Policy ABE (KP-ABE) [2] and ciphertext-policy ABE (CP-ABE) [3]. In a KP-ABE the access structure is embedded in data users’ secret-keys by the key-generator authority and each ciphertext is labeled by a set of descriptive attributes. A data user can decrypt the ciphertext if and only if the user’s access structure is satisfied by the ciphertext’s attributes. While, in a CP-ABE the access structure is embedded in the ciphertext by the data owner, and considering attributes of each data user, his/her secret-keys are issued by the key-generator authority. A data users can recover an encrypted data if and only if his/her attributes satisfy the access structure of the ciphertext.

In an ABE scheme data users have to make queries to the key generator authority for their secret-keys. However, this can make some problems in the scalability and flexibility of the system when a large number of data users want to get their secret-keys, simultaneously.

In order to address the scalability problem, Wang et al. proposed a CP-hierarchical ABE (CP-HABE) scheme [5], by combining a hierarchical identity based encryption (HIBE) scheme [6] and a CP-ABE [3] scheme. By partitioning the universal attribute set to some disjoint subsets, they considered several key generators that each of them administers one of the subsets. In this scheme for each attribute, the data user just can get the corresponding secret-key from the key generator that manage a subset which contains the mentioned attribute.
After that, this idea had been used in several ABE schemes. Wan et al. proposed a Hierarchal attribute set-based encryption (HASBE) [7], by combining the notion of HABE and the CP-ASBE scheme proposed by Bobba et al. [8]. Li et al. [9] proposed a multi-authority access control system with efficient key delegation and user revocation mechanisms. Using outsourcing technique, they significantly decrease the computational cost in the user side. Liu et al. [10] proposed a time-based proxy re-encryption scheme, by combining an HABE scheme and a proxy re-encryption scheme [11, 12], with a wide flexibility in user revocation mechanism. In this scheme, data owner can be off-line along the user revocation phase. Huang et al. [13] proposed a data collaboration scheme, by using HABE model in the key delegation mechanism. As [9], data outsourcing has been used to reduce the data user’s computational cost.

Although, it has been proved that the CP-HABE scheme proposed by Wang et al. [5] is semantically secure in the random oracle model, we showed that this scheme is fully insecure according to the given security definition in [5]. The scheme has some obvious drawbacks in its key delegation mechanism which enables a malicious user to decrypt all the shared encrypted data in the cloud with just one attribute.

The rest of this letter is organized as follows: Some necessary basic concepts will be reviewed in Section 2. We introduce CP-HABE scheme proposed by Wang et al. [5] and its security definition in Section 3. In Section 4 we give two attacks on the scheme that both of them break the security of the scheme with probability 1. The conclusion of the paper is presented in Section 5.

2. preliminaries

In this section, we introduce some required definitions and hardness assumptions.

2.1. Bilinear map

Consider two cyclic groups $G_1$ and $G_2$ of a prime order $p$. Suppose that $P_0$ is a generator of $G_1$. A function $\hat{e}: G_1 \times G_1 \rightarrow G_2$ is a bilinear map if it has the following properties:

1. Non-degeneracy: $\hat{e}(P_0, P_0) \neq 1$.
2. Bilinearity: $\hat{e}(P_1, aP_2) = \hat{e}(P_1, a) \hat{e}(P_1, P_2)$, for any $a, b \in \mathbb{Z}_p$ and $P_1, P_2 \in G_1$.
3. Computability: there is a polynomial time algorithm which compute $\hat{e}(P_1, P_2)$, for any $P_1, P_2 \in G_1$.

Consider two cyclic groups $G_1, G_2$ of prime order $p$, a bilinear map $\hat{e}: G_1 \times G_1 \rightarrow G_2$, and a random generator $P_0 \in G_1$. The Bilinear Diffie–Hellman (BDH) problem is to compute $\hat{e}(P_1, P_0)^{ab}$ for three given elements $aP_0, bP_0, cP_0 \in G_1$, where $a, b, c$ are three uniform elements of $\mathbb{Z}_p$.

2.2. Access structure

Consider a universal attribute set $U = \{a_1, \ldots, a_n\}$. Each nonempty subset $A$ of $2^U$ is called an access structure on $U$. For an access structure $A$, any set in $A$ is called an authorized set of attributes and the other ones are called unauthorized sets.

Any access structure $A$ can be specified by a logical proposition $\bigvee_{i=1}^{N} CC_i$, where each $CC_i$, $i = 1, \ldots, n$, is a conjunction clause of some attributes. For example, the access structure $A = \{\{a_1, a_2\}, \{a_1, a_3\}, \{a_2, a_3, a_4\}\}$ corresponds to the logical proposition $\bigvee_{i=1}^{3} CC_i = (a_1 \land a_2) \lor (a_1 \land a_3) \lor (a_2 \land a_3 \land a_4)$. For simplicity, $A = \bigvee_{i=1}^{N} CC_i$ is used for indicating an access structure. This type of presentation is called disjunctive normal form (DNF).

3. CP-HABE proposed by Wang et al. [5].

In this section, we first introduce system model of the Wang’s scheme, then the applied algorithms of this system are introduced in detail. After that, semantic security definition for a CP-HABE scheme which is proposed by Wang et al. [5] will be presented.
3.1. Model definition and constructions

In the CP-HABE scheme proposed by Wang et al. [6] the disjunctive normal form (DNF) is used for expressing the access control policy and a hierarchical key generation and user revocation model is applied to provide scalable and flexible mechanisms. Moreover, in this scheme each domain authority manages a number of disjoint attributes.

This system consists of five entities: the root master (RM), the cloud service provider (CSP), data owners, the domain authorities, and data users. The RM is responsible for generating the global public parameters and master keys for domain authorities at the first level. The cloud service provider’s role is to let a data owner to store its data and share them with some data users. The role of data owner is determining an access structure for his/her own data, encrypting the data under it, and outsourcing the encrypted data in the cloud. The domain authorities generate attribute secret-keys for some of the entities (data users or domain authorities) which stay on the next level. Data users can decrypt the outsourced encrypted data using their attribute secret-keys.

In this scheme, the applied key generation algorithms, named CreateDM and CreateUser adopt a hierarchical approach. First, the RM generates global public parameters of the system by the Setup algorithm and then generates the master secret-key of the domain authority in the first level, using the CreateDM algorithm. After that, some domain authorities run the CreateDM algorithm and generate master secret-keys of the domain authorities in their children. Also, the domain authorities in the last level generate identity secret-keys and attribute secret-keys of the authorized data users, using the CreateUser algorithm. When a data owner wants to outsource some data to the cloud, he/she should define an access structure and encrypt his/her data under the access structure using the Encrypt algorithm and then generates the master secret-key of the domain authority in the first level, using the CreateDM algorithm. When a data user makes a query to the domain authority, the domain authorities generate attribute secret-keys for some of the entities (data users or domain authorities) which stay on the next level. Data users can decrypt the outsourced encrypted data by running the Decrypt algorithm if and only if his/her attributes satisfy the access structure corresponding to the encrypted data.

In this scheme, it is assumed that each domain authority $DM_i$, data user $u$, and attribute $a$ in the universal attribute set has a unique public-key $PK_i$, $PK_u$ and $PK_a$, respectively. The scheme can be described by the following five algorithms:

1. **Setup**: This algorithm is run by the RM. It takes the security parameter $n$ as input and picks a large prime number $q$, two cyclic groups $G_1$ and $G_2$ of order $q$, a bilinear map $\hat{\delta} : G_1 \times G_1 \to G_2$, a uniform element $mk_0 \in Z_q$, three random oracle $H_1 : \{0, 1\}^* \to G_1$, $H_2 : G_2 \to \{0, 1\}^n$ and $H_3 : \{0, 1\}^* \to Z_q$, and a random generator $P_0 \in G_1$. The algorithm outputs the master secret-key $MK_0 = mk_0$ and system public parameters $\text{params} = (q, G_1, G_2, P_0, Q_0, H_1, H_2, H_3)$, where $Q_0 = mk_0 P_0$.

2. **CreateDM**: This algorithm is run by the root master or a domain authority as the parent. The inputs are the domain public parameters $\text{params}$, master secret-key $MK_i$ of the parent and the public-key of the domain authority $DM_{i+1}$, $PK_{i+1}$. The output of the algorithm is the $DM_{i+1}$’s master secret-key $MK_{i+1} = \left( mk_{i+1}, H_{mk_{i+1}}, SK_{i+1}, Q - \text{tuple}_{i+1} \right)$, where $mk_{i+1} \in Z_q$ is the index of the random oracle $H_{mk_{i+1}} : \{0, 1\}^* \to Z_q$, $\text{tuple}_{i+1} = H_3(PK_{i+1})$, $SK_{i+1} = SK_i + mk_i P_{i+1}$, $Q - \text{tuple}_{i+1} = (Q - \text{tuple}_i, Q_{i+1} = \text{mk}_{i+1} P_0)$, for $i \geq 0$.

3. **CreateUser**: When a data user $u$ makes a query to the domain authority $DM_i$ for a secret-key corresponding to an attribute $a$, $DM_i$ checks whether the user is authorized for $a$ or not. If so, it runs this algorithm to generate the identity secret-key $SK_{i,a} = (Q - \text{tuple}_{i-1}, mk_i mk_u P_0)$ and attribute secret-key $SK_{i,a,a} = SK_i + mk_i mk_u P_a$, where $mk_u = H_3(PK_u)$ and $P_a = H_{mk_i}(PK_a) P_0$.

4. **Encrypt**: This algorithm is run by a data owner. It takes public parameter $\text{params}$, a message $M$, an access structure $A = \bigvee_{i=1}^N CC_i = \bigvee_{i=1}^N \bigwedge_{j=1}^{m_i} a_{ij}$, and a set of the corresponding public-key of the attributes, $\{PK_{a_{ij}} : 1 \leq i \leq m_i, 1 \leq j \leq n\}$. Suppose that all of the attributes in $CC_i$ are covered by a specified domain authority $DM_{i_j}$. For each $1 \leq i \leq N$, consider the unique path $(ID_1, \ldots, ID_{i_j})$ for $DM_j$ to the domain $DM_{i_j}$. The algorithm outputs a ciphertext $CT = (A, V, U_0, U_{12}, \ldots, U_{11,}, U_1, \ldots, U_{23}, \ldots, U_{N12}, \ldots, U_{N10},$
$V = M \oplus H_2(\hat{e}(Q_0, r_nA))$ and $n_A$ is the lowest common multiple (LCM) of $n_1, \ldots, n_N$, $r \in \mathbb{Z}_q$ is a uniform element, $U_0 = rP_0$, $U_i = r \sum_{j=1}^{n_i} Pa_{ij}$, and $U_{ik} = rP_{ik}$, for $i = 1, \ldots, N$ and $k = 1, \ldots, t_i$.

5. **Decrypt**: A data user whose attributes satisfy the access structure $A = \bigvee_{i=1}^{N} CC_i = \bigwedge_{i=1}^{N} n_i \land a_{ij}$ of a ciphertext $CT$, can run this algorithm and recover the corresponding message. Suppose that for an $i \in \{1, \ldots, n_i\}$, a data user has all the determined attributes in $CC_i$, then the corresponding message can be obtained as follows:

$$V \oplus H_2(\hat{e}(mk_i, mk_{ij}, P_0, \sum_{j=1}^{n_i} SK_{i, ij, a_{ij}}) \prod_{j=2}^{t_i} \hat{e}(U_{ij}, n_A Q_i(j - 1))).$$

We refer the reader to [5] for more detail about this scheme.

### 3.2. Security definition:

Consider the following game:

1. **Setup**: The challenger runs Setup algorithm and gives the system public parameters to the adversary.

2. **Phase 1**: First of all, challenger runs CreateDM algorithm, then the adversary $A$ makes an arbitrary number of queries for users’ attribute secret-keys. For each data user $u$, once the adversary makes a query for the user’s secret-key corresponding to an attribute $a$, the challenger runs CreateUser algorithm, and gives the requested secret-key to the adversary $A$.

3. **Challenge**: When the adversary decides to terminate Phase 1, he/she gives two equal length messages $m_0, m_1$ and an access structure $A$ to the challenger, where the set of specified attributes for any data users in Phase 1, dose not satisfied the access structure $A$. Then, the challenger randomly chooses $b \in \{0, 1\}$, encrypts $m_b$ under the access structure, and returns the encrypted message to the adversary $A$.

4. **Phase 2**: The adversary is allowed to make more attribute secret-key queries, with the same constraints in the previous phases.

5. **Guess**: The adversary outputs a bit $b' \in \{0, 1\}$. It wins this game if $b = b'$.

Let notation $\text{Succeed}(A)$ denotes the event that the adversary $A$ succeeds in the above game. A CP-HABE scheme is semantically secure if $|P(\text{Succeed}(A) - \frac{1}{2})|$ is a negligible function in term of the security parameter, for each polynomial time adversary $A$.

In Appendix A of [5], the semantic security of the CP-HABE scheme has been proved based on the hardness assumption of BDH problem, in the random oracle model. In the next section we will show that this scheme is vulnerable against our two proposed attacks.

### 4. Security analysis of the CP-HABE scheme proposed by Wang et al.

We show that there are two drawbacks in the key delegation mechanism of the CP-HABE proposed by Wang et al. [4, 5]. Considering these drawbacks, a malicious data user with just one or two attributes can decrypt any outsourced encrypted data in the cloud.

In the following, we propose two non-adaptive attacks on the CP-HABE scheme. Each of them breaks the semantic security of the scheme with probability 1.
Remark. For an arbitrary domain $DM_{it}$, let $(ID_1, \ldots, ID_{it})$ be the unique path from $DM_1$ to $DM_{it}$. Then, we have:

$$SK_{it} = SK_{i(t_i-1)} + mk_{i(t_i-1)}P_{it}$$

$$= SK_{1} + \sum_{j=1}^{t_i-1} mk_{ij}P_{(j+1)}.$$  \hspace{1cm} (1)

**Theorem 1.** For an arbitrary domain $DM_{it}$ with $(ID_1, \ldots, ID_{it})$, any user $u$ who has received his/her identity secret-key $SK_{it,u}$ and obtained the secret-key of $DM_{it}$, $SK_{it}$, can recover any outsourced encrypted data to the cloud.

**Proof.** Since the user has received $SK_{it,u} = (Q_{0}, \ldots, Q_{i(t_i-1)}, mk_{u}Q_{it})$ and can obtain $mk_{u} = H_{A}(PK_{u})$, he/she can calculate $Q_{it}$ by multiplying $mk_{u}^{-1} = (H_{A}(PK_{u}))^{-1} \in \mathbb{Z}_{q}$ to the last component of $SK_{it,u,u}$. So, the user knows $Q_{ij}$ for each $1 \leq j \leq t_i$. Let $CT = (A, V, U_0, U_{12}, \ldots, U_{1t_r}, U_1, \ldots, U_{N2}, \ldots, U_{Nt_r}, U_N)$ be an arbitrary outsourced encrypted data. Then, since $V = M \oplus H_{2}(e(Q_0, n_ARP_1))$ we have:

$$M = V \oplus H_{2}(e(Q_0, n_ARP_1))$$

$$= V \oplus H_{2}(e(mkP_0, n_ARP_1))$$

$$= V \oplus H_{2}(e(n_ARP_0, mkP_{1}))$$

$$= V \oplus H_{2}(e(n_ARP_0, SK_{1}))$$

$$= V \oplus H_{2}(e(n_ARP_0, SK_{1}) + \sum_{j=1}^{t_i-1} mk_{ij}P_{(j+1)} - \sum_{j=1}^{t_i-1} mk_{ij}P_{(j+1)}))$$ \hspace{1cm} (2)

From Equation 1, we conclude that:

$$M = V \oplus H_{2}(e(n_ARP_0, SK_{it} - \sum_{j=1}^{t_i-1} mk_{ij}P_{(j+1)}))$$

$$= V \oplus H_{2}(e(n_ARP_0, SK_{it}) \cdot e(-n_ARP_0 \sum_{j=1}^{t_i-1} mk_{ij}P_{(j+1)}))$$

$$= V \oplus H_{2}(e(n_ARP_0, SK_{it}) \cdot \prod_{j=1}^{t_i-1} e(-n_ARP_0, mk_{ij}P_{(j+1)}))$$

$$= V \oplus H_{2}(e(n_ARP_0, SK_{it}) \cdot \prod_{j=1}^{t_i-1} e(-n_ARP_0, mk_{ij}P_{(j+1)}))$$

$$= V \oplus H_{2}(e(n_ARP_0, SK_{it}) \cdot \prod_{j=1}^{t_i-1} e(-n_ARP_0, Q_{ij}, U_{(i(j+1))}),$$ \hspace{1cm} (3)

According to the assumption that the data user $u$ has obtained $SK_{it,u}$, since he/she know $Q_{ij}$ for $j = 1, \ldots, t_i$, and the other involved parameter in (3), the ciphertext can be decrypted by the user. \hfill \Box

4.1. **Attack 1**

This attack shows that any user who has just one attribute administrated by a domain $DM_{it}$ can obtain $SK_{it}$. Therefore, from Theorem 1, we get the user can recover any outsourced encrypted data to the cloud.

According to the Security definition presented in the last section. Let a challenger has run the **Setup** and **CreateDM** algorithms and $A$ be a polynomial time adversary which is taken the system public parameters $params$ generated by **Setup** algorithm.
• Then $\mathcal{A}$ picks just an arbitrary attribute $a_0$ and authorized data user $u_0$ to the attribute and makes a query for the corresponding secret-key. The challenger runs the $\text{CreateUser}$ algorithm and gives the requested secret-keys, $SK_{i_1,u_0}$ and $SK_{i_1,u_0}=SK_{i_1}+mk_{i_1}mk_{a_0}P_{a_0}$, to the adversary $\mathcal{A}$.

• At $\text{Challenge}$ step, $\mathcal{A}$ gives two random equal length plaintexts $m_0$ and $m_1$, and a DNF access structure $A=\bigwedge_{i=1}^N CC_i$ to the challenger, where $CC_1$ includes $a_0$ and also $|CC_1|>1$, therefore $a_0$ does not satisfy $CC_1$. The challenger chooses a random bit $b \in \{0,1\}$ and encrypts $m_b$ under an access structure $A=\bigwedge_{i=1}^N CC_i$. The generated ciphertext $CT$ is given to $\mathcal{A}$.

• With no need to run Phase 2, in $\text{Guess}$ step, first, $\mathcal{A}$ calculates $H_{mk_{a_1}}(PK_a)$, then using the last component of $SK_{i_1,u_0}, mk_{i_1}mk_{a_0}P_0$, it calculates $A_{a_0,u_0}=H_{mk_{a_1}}(PK_{a_1})mk_{i_1}mk_{a_0}P_0=mk_{i_1}mk_{a_0}P_{a_0}$. Therefore, $\mathcal{A}$ can obtain $SK_{i_1}=SK_{i_1,a_0,u_0}-A_{a_0,u_0}$.

Now, from Theorem 1, since the adversary has $SK_{i_0,i_1}$ and $SK_{i_1}$, he/she can decrypt $CT$ and get $m_0$. So the adversary can win the game with probability 1

**Theorem 2.** By using the described techniques in Attack 1, a polynomial time adversary $\mathcal{A}$ in a non-adaptive manner can break the semantic security of the CP-HABE scheme proposed by Wang et al. [5] with probability 1.

Note that using Attack 1, an adversary with just one attribute secret-key, can decrypt any given ciphertext.

4.2 Attack 2

The attack shows that any user who has two attributes administrated by same domain can obtain master secret key of the domain and therefore from Theorem 1 he/she can decrypt any outsourced ciphertext to the cloud.

As before, considering the security definition presented in Section 3, Let the $\text{Setup}$ and $\text{CreateDM}$ algorithms have been run by a challenger and system pubic-parameters are given to the adversary $\mathcal{A}'$.

• The adversary picks two attributes $a_1$ and $a_2$, and a data user $u_0$. Then it makes two queries for the corresponding secret-keys. The challenger runs $\text{CreateUser}$ algorithm and gives the secret-keys $SK_{i,u_0}=(Q-tupe_{i-1}, mk_{i}mk_{u_0}P_0)$, $SK_{i,a_1,u_0}=SK_{i}+mk_{i}mk_{a_0}P_{a_1}$ and $SK_{i,a_2,u_0}=SK_{i}+mk_{i}mk_{a_0}P_{a_2}$ to the adversary.

• In $\text{Challenge}$ step, the adversary $\mathcal{A}'$ gives two equal length messages $m_0$ and $m_1$, and an access structure $A=\bigwedge_{i=1}^N CC_i$ to the challenger, where $|CC_1|>2$. The challenger uniformly chooses $b \in \{0,1\}$ and sends the generated ciphertext $CT$ corresponding to $m_b$ and $A$ to the adversary.

• Without running Phase 2, in $\text{Guess}$ step, the adversary sets:

\[
B_{a,u_0} = (SK_{i,a_1,u_0} - SK_{i,a_2,u_0}) \\
= mk_{i}mk_{a_0}(P_{a_1} - P_{a_2}) \\
= (H_{mk_{a_1}}(PK_{a_1}) - H_{mk_{a_2}}(PK_{a_2}))(mk_{i}mk_{a_0}P_0).
\]

So, $C_{i,a_1,u_0} = H_{mk_{a_1}}(PK_{a_1})(H_{mk_{a_1}}(PK_{a_1}) - H_{mk_{a_2}}(PK_{a_2}))^{-1}B_{a,u_0} = H_{mk_{a_1}}(PK_{a_1})mk_{a_1}mk_{a_0}P_0 = mk_{a_0}mk_{a_1}$ can be obtained by the adversary. Now, if $\mathcal{A}'$ sets $SK_i = SK_{i,a_1,u_0} - C_{i,a_1,u_0}$, for Lemma 1 it can decrypt any outsourced ciphertext. Therefore the adversary can win the game with probability 1.

**Theorem 3.** Attack 2 enables a non-adaptive adversary to break the semantic security of the CP-HABE proposed by Wang et al. with probability 1.
5. Conclusion

In this manuscript, we showed that the CP-HABE proposed by Wang et al. [5] is fully insecure. We provided two attacks which break the scheme’s security with probability 1, that is contrary to the authors’ claim. Moreover, it was shown that any malicious user who has just one attribute can recover any outsourced encrypted data in the cloud.

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