Cryptanalysis and Improvement on Wang et al.’s Attribute-Based Searchable Encryption Scheme

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Abstract—Searchable encryption is a powerful and useful primitive when users want to store their encrypted files on cloud storages. In this paper, we demonstrate security flaws of the searchable encryption scheme proposed by Wang et al. in 2017. Furthermore, we propose a solution to fix the flaws, and the improved scheme also largely reduces the length of the ciphertext such that it is independent of the number of the attributes.

Index Terms—Attribute-based encryption, cryptanalysis, hidden policy, searchable encryption.

I. INTRODUCTION

For the increasingly expanding implementation of cloud computing, more and more users upload their data to cloud servers. Since classified data are outsourced to cloud servers, data owners often concern about the privacy of such data. How to gain the confidentiality of cloud data while making the fullest use of secure cloud systems becomes an important issue in cloud computing. Typically, a data owner encrypts private data before outsourcing to cloud server. Thus, how to search such encrypted files in the cloud through keywords is another essential issue. A well-known solution to mitigate the aforementioned issue is to deploy searchable encryption (SE) [1] which enables cloud servers to search encrypted data without leaking any information either of the keyword or the plaintext data.

In 2017, Wang et al. [2] proposed an attribute-based encryption with keyword search (ABKS) [3]-[6] scheme based on ciphertext-policy attribute-based encryption (CP-ABE), which preserves the fine-grained access control inherited from the ABE system. However, we found that there are some problems in the scheme. The length of a ciphertext is not independent of the number of attributes. Moreover, neither the privacy of attributes nor keywords is preserved. In order to deal with these problems, we give the cryptanalysis and present an improvement on their scheme.

II. PRELIMINARIES

In this section, we briefly review some backgrounds essential to understand the proposed work.

A. Multilinear Maps

Let $\mathbb{G}_1, \ldots, \mathbb{G}_n$ and $\mathbb{G}_T$ be the prime ordered (say, $p$) cyclic groups. A cryptographic $n$-linear map [7] is defined as

$$e: \mathbb{G}_1 \times \cdots \times \mathbb{G}_n \rightarrow \mathbb{G}_T$$

for $n > 2$ that satisfies the following properties:

1. **Multilinearity:** The condition of

   $$e(g_1^{x_1}, \ldots, g_n^{x_n}) = e(g_1^{y_1}, \ldots, g_n^{y_n})^{\prod_{i=1}^n x_i}$$

   always holds for $a_i \in Z_p^*$ and $g_i \in \mathbb{G}_i$, where $i \in [1, n]$.

2. **Non-degeneracy:** For a random generator $g_i \in \mathbb{G}_i$, the condition

   $$e(g_1, \ldots, g_n) = g_T$$

   always holds where $g_T$ is the generator of $\mathbb{G}_T$.

3. **Computability:** There should be an efficient algorithm to compute the map $e$.

An $n$-linear map $e$ is called symmetric $n$-linear map if

$$\mathbb{G}_1 = \mathbb{G}_2 = \cdots = \mathbb{G}_n.$$  

Therefore, a symmetric $n$-linear map can be defined as

$$e: \mathbb{G}_1 \times \cdots \times \mathbb{G}_1 \rightarrow \mathbb{G}_T.$$  

Besides, for an $n$-linear map, there is a set of bilinear maps $e_{i,j}; \mathbb{G}_i \times \mathbb{G}_j \rightarrow \mathbb{G}_{i+j}$, $\forall i, j > 0$ and $i + j \leq n$.

B. Access Structure

In the proposed scheme, we use a series of “AND gate” on multi-value attribute as the underline access structure. Let $n$ be the total number of attributes. We consider

$$S = \{s_1, s_2, \ldots, s_n\}$$

as the universe attribute list, and for an attribute $s_i \in S$ we set

$$T_i = \{t_{i,1}, t_{i,2}, \ldots, t_{i,n_j}\}$$

where $j$ is the number of the possible values for $s_i$. Suppose,

$$A = \{x_1, x_2, \ldots, x_p\}$$

is the attribute list of any user where $x_i \in T_i$, and

$$U = \{u_1, u_2, \ldots, u_n\}$$

is an access structure in the ciphertext where $u_i \in T_i$. We mention that the user’s attribute list $A$ satisfies the access
policy $S$ if and only if $x = u_i, \forall i \in [1, \ldots, n]$.

C. Attribute-Based Encryption with Keyword Search

Attribute-based encryption with keyword search (ABKS) is an extended cryptographic primitive from attribute-based encryption. There have been lots of research on ABKS [8]-[10]. We review the definition for attribute-based encryption and authorized keyword search in the section.

Attribute-Based Encryption

For the sake of protecting encrypted information, most applications use complex access control mechanisms. Due to the fine-grained access control policy, there has been a great deal of interest in studying attribute-based encryption, and many related schemes have been proposed [11], [12]. In 2005, introduced by Sahai and Waters [13], attribute-based encryption (ABE), which is regarded as an extension of identity-based encryption (IBE), enables users to implement fine-grained access controls on the encrypted sensitive data. However, the scheme is lack of expressiveness. In order to make ABE more efficient and more flexible, Goyal et al. [14] in 2006 presented two different types of ABKS schemes: key-policy ABE (KP-ABE) [15], [16] and ciphertext-policy ABE (CP-ABE) [17], [18]. In KP-ABE schemes, each user’s private key is related to an access policy, and a ciphertext is associated with a set of attributes. A secret key can decrypt a ciphertext if and only if the attribute set associated with the ciphertext satisfies the access policy related to the user’s private key. The situation in CP-ABE schemes is inverses.

To apply ABE schemes in terminal devices, lots of researches were proposed in literatures [19], [20]. In 2007, Cheung and Newport [21] implemented Boolean function, i.e., AND gate, in the standard model. However, the scheme cannot achieve the feature of hidden access policy. To be suitable for the data-outsourced cloud environment, Yu et al. [22] in 2010 adopted lazy re-encryption and proxy re-encryption. Several related ABE schemes can be found in references [23]-[25].

A CP-ABE scheme includes the following four algorithms:

- **Setup** ($1^k$) $\rightarrow$ ($PK, MK$)
  The private key generator (PKG) takes a security parameter $k$ as an input. It outputs a public key $PK$ and a master secret key $MK$.

- **KeyGen** $(PK, MK, U) \rightarrow SK_U$
  On inputting the public key $PK$, the master secret key $MK$ and the attribute set of user $U$, it outputs a user private key $SK_U$.

- **Encrypt** $(PK, M, S) \rightarrow CT_S$
  It takes the public key $PK$, the message $M$ and the access structure $S$ as input, and outputs a ciphertext $CT_S$.

- **Decrypt** $(CT_S, SK_U) \rightarrow M$
  The decryptor takes the ciphertext $CT_S$ and the user private key $SK_U$ as inputs, and returns a message $M$.

These algorithms must satisfy the correctness condition, i.e., for $SK_U \leftarrow (PK, MK, U)$ and $CT_S \leftarrow$ Encrypt $(PK, M, S)$, one can decrypt the ciphertext as $M \leftarrow$ Decrypt $(CT_S, SK_U)$.

Authorized Keyword Search

To avoid leaking the information of keywords while tracking over the encrypted data, Bonhe et al. [26] in 2004 proposed the concept of public key encryption with keyword search, but the scheme failed to achieve fine-grained access control on encrypted files. In 2014, Sun [27] and Zheng [28] independently presented ABKS schemes so as to resolve the problem. However, the size of the ciphertext is related to the number of attributes, so that the schemes have high computational costs. In 2015, Zheng et al. [29] proposed a certificateless keyword search scheme, but the scheme does not ensure the authority of search results.

In order to improve the computational time and above problems, Li et al. [30] in 2015 presented the authentication search scheme and made the application scene more flexible. Following Li et al.’s work, Lee et al. [31] in 2016 implemented hash table on searchable encryption. To protect the privacy information in the ciphertext, Li et al. [32] in 2017 presented a scheme which supports partially hidden access structures. More recent researches can be found in references [33]-[35].

III. RELATED WORK

In this section we review some ABKS schemes [27], [38], [39] which will compare our improved scheme with. Since we will demonstrate the comparison in secret key and ciphertext size, we show only Setup, KeyGen, Encrypt, Decrypt algorithms here. Readers are referred to [27], [38], [39] for further details. Besides, $g$ is used to denote the generator of the source pairing $G$, where $|G| = p$ is a large prime.

A. Sun et al.’s Scheme [27]

**Setup** ($1^k$): Taking the security parameter as input, the algorithm first chooses $g, t_1, t_2, \ldots, t_n \in \mathbb{Z}_p$ as the master secret key $MK$, where $n$ is the size of the attribute universe $\mathcal{U}$. The system parameter of the scheme is then generated as $PK = (g, Y = g^{(g, g)^t}, \ell \in [1, 3n])$.

**KeyGen** $(PK, MK, S)$: Sun et al. consider the access structure supporting don’t care condition in their scheme. The attribute set $S$ in the input denotes for the positive attributes. The algorithm first chooses $n$ randomness $r_1, \ldots, r_n \in \mathbb{Z}_p$ and compute $r = \sum_i [1, n]r_i$. Then it computes $R = g^{r/t}$ and $K_i = \left( g^{t_i/t}, i \in S \right)$, where $g^{t_i/t}$ is $i \in \mathcal{U}$ \| $S$. Next, for $i \in [1, n]$, it computes $F_i = g^{r_i/t_{n+1}}$. Finally, the secret key for $S$ is $\left( R, \{K_i, F_i\}_{i \in [1, n]} \right)$.

**Encrypt** $(PK, \omega, W)$: In Sun et al.’s scheme, they only considered how to generate the encrypted index for a file, and the encryption of the file can be done using standard data encryption method. The algorithm first chooses a randomness $s \in \mathbb{Z}_p$ and computes $\tilde{Y} = g^s, \tilde{Y} = Y^s$. Then it computes $D_i = \left( T_i^s, i \in \mathcal{U} \setminus W \right)$. To simplify the case, here we assume that there is no don’t care condition in $W$. Besides we omit the computation for the keyword indices since the ciphertext size is already proportional to the size of $W$.

**Decrypt**: They did not provide this algorithm in their paper since the file encryption is not in their consideration.

B. Li et al.’s Scheme [38]

In Li et al.’s scheme, a part of the secret key will be
outsourced to a semi-trusted party in order to reduce the decryption cost on the user ends. Therefore, there are two algorithms for generating secret keys, $\text{KeyGen}_{\text{out}}$ and $\text{KeyGen}_{\text{in}}$. The former generates the outsourced secret keys and the latter generates the secret key for user ends. Besides, some necessary steps for generating secret keys will be performed in another algorithm called $\text{KeyGen}_{\text{init}}$. In this paper, we use the algorithm $\text{Decrypt}_{\text{out}}$ to denote the process of outsourcing decryption.

The access structure supported in [38] is a $(d, t)$-threshold-gate, where $d$ is the threshold value which can be decided later in the $\text{KeyGen}_{\text{out}}$ algorithm. By setting $d = t$, a threshold-gate is equivalent to an AND-gate.

**Setup$(1^d)$**: Let $n$ be the size of the attribute universe. Taking the security parameter as input, the algorithm first chooses $x$ and computes $g_1 = g^x$. Then it randomly chooses $g_2, h, h_1, h_2, ..., h_n \in \mathbb{G}$. Also, two cryptographic hash functions $H_1, H_2$ are chosen such that $H_1: \{0,1\}^t \rightarrow \mathbb{G}$ and $H_2: \mathbb{G} \rightarrow \{0,1\}^{|\log p|}$. The system parameter $PK = \{(g_1, g_2, h, h_1, h_2, ..., h_n, H_1, H_2)\}$ and the master secret key $MK = x$.

**KeyGen$_{\text{init}}(MK)$**: Taking as input the master secret key, the algorithm chooses $x_1 \in \mathbb{Z}_p$ and computes $x_2 = x - x_1 \pmod{p}$. The algorithm outputs $\text{OK}_{\text{KGGSP}}, \text{OK}_{\text{TA}} = (x_1, x_2)$.

**KeyGen$_{\text{out}}(A, \text{OK}_{\text{KGGSP}})$**: Taking as input the access policy $A$ and $\text{OK}_{\text{KGGSP}} = x_1$, the algorithm first chooses an $(d - 1)$ degree polynomial $q(x)$ with $q(0) = x_1$. For $i \in A$, then chooses $r_i \in \mathbb{Z}_p$ randomly, and computes $(d_{i0}, d_{i1}) = (g_2^{q(i)}(g, h_i)^{r_i}, g_i^{r_i})$. Finally, the outsourcing secret key $\text{SK}_{\text{KGGSP}} = ((d_{i0}, d_{i1}))_{i \in A}$.

**KeyGen$_{\text{in}}(\text{OK}_{\text{TA}}, \text{SK}_{\text{KGGSP}})$**: The attribute authority $\text{TA}$ first chooses $r_0 \in \mathbb{Z}_p$ and computes $\text{SK}_{\text{TA}} = (d_{00}, d_{01}) = (g_2^{g_1}(g_2 h)^{r_0}, g_1^{r_0})$. The full secret key $SK$ is set to be $(\text{SK}_{\text{KGGSP}}, \text{SK}_{\text{TA}})$.

**Encrypt$(PK, W, M)$**: The algorithms first chooses $s \in \mathbb{Z}_p$ and computes $C_0 = M \cdot (g_1, g_2)^s, C_1 = g^s, C_0 = (g_2 h)^s, C_1 = (g_2 h_i)^s$, for $i \in W$. The ciphertext $CT$ is $\text{CT} = (C_0, C_1, C_{i \in W})$.

**Decrypt$_{\text{out}}(PK, SK_{\text{KGGSP}}, CT)$**: The condition for successful decryption is that $|A \cap W| \geq d$. Assume that the condition holds, then there must be an authorized attribute set $S$ where $|S| \geq d$. The algorithm first computes the Lagrange coefficients $\Delta_{iS}(0)$ for $i \in S$. Then it computes

$$Q_{CT} = \prod_{i \in S} e(C_i, d_{i0})^{\Delta_{iS}(0)} / \prod_{i \in S} e(C_i, d_{i1})^{\Delta_{iS}(0)} = e(g_2, g_2)^{xS_1}.$$

Finally, $Q_{CT}$ is outputted as the outsourcing decryption result.

**Decrypt$(PK, CT, Q_{CT}, SK_{\text{TA}})$**: An end user is able to recover the message $M$ by computing

$$M = \frac{C_0 \cdot e(C_0, d_{00})}{Q_{CT} \cdot e(C_0, d_{01})}.$$ 

C. **Wang et al.’s Scheme** [39]

In Wang et al.’s scheme, there is an entity called CS to perform the outsourcing decryption. After the attribute authority AA generating the secret key $SK$, the secret key will be divided into two parts ($SK_t, SK_h$). $SK_h$ will be sent to CS for outsourcing decryption, and $SK_t$ will be kept by the user. For decrypting a ciphertext, CS will first perform the algorithm $\text{PreDecryt}$ to generate the partial result.

**Setup$(1^d)$**: Taking as input the security parameter, the algorithm first chooses three cryptographic hash functions $H: \{0, 1\}^t \rightarrow G, H_2: G \rightarrow \{0, 1\}^{|\log p|}$. Then it randomly chooses $a, a, \alpha \in \mathbb{Z}_p$ and $v_i \in \mathbb{Z}_p$ for $i \in U$, where $U$ is the attribute universe. Finally, the algorithm outputs the system parameter

$$PK = (g^a, e(g, g)^a, g^\alpha, (PK_1 = g^{v_i})_{i \in U}, H, H_2, H_2).$$

and the master secret key $MK = (a, \alpha, (v_i)_{i \in U})$.

**KeyGen$(MK, S_{uid})$**: The attribute authority AA generates the secret key for $S_{uid}$ as follows, where $uid$ is the identity of the user. It first chooses $a_1, a_2 \in \mathbb{Z}_p$ such that $a_1 + a_2 = \alpha \mod p$. Also it randomly chooses $t, \delta_{uid} \in \mathbb{Z}_p$. Then it computes the secret key $SK = (SK_t, SK_h)$ where

$$SK_1 = \left(\hat{\alpha} = \frac{\alpha}{\delta_{uid}}, K = g^{a_1}g^{\alpha t}\right),$$

$$SK_2 = \left(\delta_{uid}, E = g^{a_2}, L = g^{t}, \{K_i = H(i)^\frac{1}{r_i}\}_{i \in S_{uid}}\right).$$

Finally, $SK_1$ is sent to the user $uid$ and $(uid, S_{uid}, SK_2)$ is sent to CS.

**Encrypt$(PK, (M, \rho), M)$**: Wang et al.’s adopts linear secret sharing scheme in their scheme. For a monotonic access structure, there is an efficient algorithm to transform it into a matrix $M \in \mathbb{Z}_p^{\ell \times n}$ and a labelling function $\rho$, where $\ell$ and $n$ are the parameter regarding to the access structure. We refer readers to [39] for further details. To encrypt a message $M$, the encryptor first chooses $s, y_2, ..., y_n \in \mathbb{Z}_p$ and set a vector $v = (s, y_2, ..., y_n)$. Next, for $i = 1$ to $t$, it computes $\lambda_i = M \cdot v_i$, where $M_i$ is the $i$-th row of $M$. Then, the encryptor chooses $r_1, ..., r_{t-1} \in \mathbb{Z}_p$ and computes

$$CT = \left\{C_i = g^{a_1}H(\rho(i)^{r_i}), D_i = (PK_1(i)^{r_i})_{i \in [1, \ell]}\right\}.$$ 

**PreDecryt$(CT, SK_2)$**: Let $I \subseteq \{1, 2, ..., \ell\}$ be defined as $I = \{i : \rho(i) \in S_{uid}\}$. If $S_{uid}$ satisfies the access structure of $CT$, then there is an efficient algorithm to compute a set of constants $\{\alpha_i \in \mathbb{Z}_p\}_{i \in I}$ such that $\sum_{i \in I} \alpha_i \delta_i = s$ . After obtaining $\{\alpha_i \in \mathbb{Z}_p\}_{i \in I}$, CS is able to compute the partial result

$$A = \prod_{i \in I} e(C_i, L)^{\alpha_i} / e(C_i, E) \prod_{i \in I} e(D_i, K_1(i))^{\alpha_i},$$

Finally, CS outputs $CT' = \{C_i, C_i', A\}$ to the user $uid$.

**Decrypt$(CT', SK)$**: The user $uid$ is able to recover the message $M$ by computing

$$M = \frac{C \cdot A}{e(C', K)}.$$
IV. REVIEW ON WANG ET AL.’S SCHEME

In this section, we review the scheme which Wang et al. [2] proposed as follows:

Wang et al. exploit a series of AND gates on multi-value attributes as the access structure. Assume that the total number of attributes is $n$, and they are indexed as

$$U = \{\text{att}_1, \text{att}_2, \ldots, \text{att}_n\}.$$ 

For each attribute

$$\text{att}_i \in U, (i = 1, 2, \ldots, n),$$

let

$$V_i = \{v_{i,1}, v_{i,2}, \ldots, v_{i,n}\}$$

be a set of possible values of $\text{att}_i$. Then the attribute list $S$ for a user is

$$S = (x_1, x_2, \ldots, x_n),$$

where $x_i \in V_i$. The access policy in a ciphertext is

$$W = (W_1, W_2, \ldots, W_n),$$

where $W_i \in V_i$. Let $\text{PairGen}$ be an algorithm that, on inputting a security parameter $1^\lambda$, outputting a tuple

$$Y = (p, G_0, G_1, G_2, e_1, e_0),$$

where $G_0, G_1$ and $G_2$ have the same prime order $p$, and $e_i: G_0 \times G_1 \rightarrow G_{i+1}, i \in \{0, 1\}$

are efficient non-degenerate multilinear maps such that

$$\forall \alpha, \beta \in \mathbb{Z}_p,$$

$$e_i(g_0^\alpha, g_0^\beta) = e_0(g_0, g_0)^{\alpha \beta}.$$ 

Wang et al.’s scheme consists of six algorithms, including $\text{Setup}, \text{KeyGen}, \text{Encrypt}, \text{Trapdoor}, \text{Test},$ and $\text{Decrypt}$. We give the details for these algorithms in the follows.

- **Setup** ($1^\lambda$) $\rightarrow$ ($PK, MSK$)

  The algorithm runs the generator algorithm $\text{PairGen}(1^\lambda)$ and gets the group and the multilinear mapping description

  $$Y = (p, G_0, G_1, G_2, e_1, e_0),$$

  where $G_0$ is generated by $g_0$. The algorithm randomly chooses $\alpha, \beta \in \mathbb{Z}_p$ and a hash function $H:\{0, 1\}^* \rightarrow G_0$. Let

  $$A = e_0(g_0, g_0)^{\alpha},$$

  $$B = g_0^\beta.$$ 

  The system public key is

  $$PK = (Y, g_0, A, B, H)$$

  and the master secret key is $MSK = (\alpha, \beta)$.

- **KeyGen** ($MSK, S$) $\rightarrow$ $SK$

  The key generation algorithm will take as input a set of attributes

  $$S = (x_1, x_2, \ldots, x_n)$$

  and output the secret key $SK$. The key generation algorithm selects random

  $$r_i \in \mathbb{Z}_p (i = 1, 2, \ldots, n)$$

  and sets

  $$r = \sum_{i=1}^n r_i$$

  and computes

  $$\bar{D} = g_0^{(\alpha + r)/\beta}.$$ 

  Randomly select $r' \in \mathbb{Z}_p^n$, for each attribute $x_i \in S$, compute

  $$D_i = g_0^{x'_i} \cdot H(x_i)^{r'_i},$$

  and set

  $$\bar{D} = g_0^{r'_i}.$$ 

  The secret key is defined as

  $$SK = (\bar{D}, D_i, \{D_i\}_{i \in S}).$$

- **Encrypt** ($1^\lambda$) $M \in G_1, PK, \omega, W$ $\rightarrow$ ($CT, I_\omega$)

  Give a message $M \in G_1$, and an AND gate

  $$W = (W_1, W_2, \ldots, W_n),$$

  and the corresponding keyword $\omega$, the encryption algorithm selects random numbers $s, s' \in \mathbb{Z}_p^n$ and sets

  $$C = M \cdot A^s,$$

  $$\bar{C} = B^s,$$

  $$\tilde{C} = g_0^{s'}. $$

  For each attribute $W_i$ in the AND gate $W$, compute

  $$C_i = H(W_i)^s$$ for $i = 1$ to $n$, 

  and set

  $$\tilde{C}_1 = e_0(B, g_0^{as'}).$$

  $$\tilde{C}_2 = g_0^{s'}. $$

  The ciphertext is

  $$CT = (C, \bar{C}, \tilde{C}, \{C_i\}_{i \in S}^n),$$

  and index

  $$I_\omega = (\tilde{C}_1, \tilde{C}_2).$$

- ** Trapdoor** ($SK, \omega$) $\rightarrow$ $t_\omega$

  User $U_i$ generates the trapdoor of his chosen keyword $\omega$ as:

  $$t_\omega = e_0(\bar{D}, g_0^{\omega i}).$$

- ** Test** ($I_\omega, t_\omega$) $\rightarrow$ 0 or 1

  Given the trapdoor $t_\omega$ and index $I_\omega$, the cloud server checks the following formula

  $$e_1(t_\omega, \tilde{C}_2) = e_1(\prod_{i=1}^n C_i, \tilde{C}_1).$$

  If the formula holds, return 1 and 0 otherwise.

- **Decrypt** ($I_\omega, t_\omega$) $\rightarrow$ $M$

  If the attribute list $S$ satisfies the access policy $W$ i.e. $x_i$ =
\(W_i\), \(i = 1, 2, \ldots, n\). On inputting ciphertext \(CT\) and secret key \(SK\), output a message \(M\) as:

\[
E = \prod_{i=1}^{n} e_0(D_i, \hat{C})
\]

\[
= e_0(g_0^s g_0^{rS})
\]

\[
M = C / (e_0(D, \hat{C}) / E).
\]

V. COMMENTS ON WANG ET AL.'S SEARCHABLE ENCRYPTION

First, the length of a ciphertext is obviously not independent of the number of attributes. In their scheme,

\[
C_i = H(W_i)^s \quad (i = 1, 2, \ldots, n)
\]

need to be published in a ciphertext

\[
CT = (C, \hat{C}, \tilde{C}, C_i)
\]

and an index

\[
I_\omega = (C_i, \hat{C}_1, \hat{C}_2).
\]

When it comes to “constant-size ciphertext” [36], [37], we usually mean “the length of a ciphertext is independent of the number of attributes in the access structure”.

Another problem is that they did not achieve the hidden policy. To guess if a keyword \(w^\ast\) has been used in the Encrypt algorithm, an attacker verifies whether the following formula holds:

\[
e_1(\hat{C}, \hat{C}_1) = e_1(\hat{C}_2, e_0(B, g_0^{rS}))
\]

The correctness analysis is given as follows.

\[
e_1(\hat{C}, \hat{C}_1) = e_1(g_0^s, e_0(B, g_0^{rS}))
\]

\[
= e_1(g_0^s, e_0(B, g_0^{rS}))
\]

\[
= e_1(\hat{C}_2, e_0(B, g_0^{rS}))
\]

The formula holds due to the linearity of multi-linear maps.

Furthermore, to test if an attribute value \(W_i^\ast\) has been used in the Encrypt algorithm, an attacker checks whether the following formula holds:

\[
e_0(C_i, g_0^s) = e_0(H(W_i^\ast), \hat{C})
\]

It is because that

\[
e_0(C_i, g_0^s) = e_0(H(W_i)^s, g_0^s)
\]

\[
= e_0(H(W_i), g_0)
\]

\[
= e_0(H(W_i), \hat{C})
\]

The attacker only needs to perform \(O(n \times \max\{v_{i,n}\})\) pairings to guess the \(n\) attribute values in a ciphertext.

VI. AN IMPROVEMENT ON WANG ET AL.'S SCHEME

One solution is to add a new ciphertext component:

\[
\tilde{C} = \prod_{i=1}^{n} C_i
\]

instead of directly publishing all \(C_i\)’s such that the ciphertext

\[
CT = (C, \hat{C}, \tilde{C}, C_i)
\]

and the index

\[
I_\omega = (C, \hat{C}_1, \hat{C}_2).
\]

In this setting an attacker needs to guess the \(n\) values corresponding to the \(n\) attributes, respectively, at one time, and thus the number of all possible combinations becomes exponentially large, i.e.

\[
(v_1 \times v_2 \times \ldots \times v_n) \geq 2^n.
\]

Furthermore, the length of the ciphertext now is indeed independent of the number of the attributes in the access structure.

Besides, we can add a new component

\[
\tilde{D} = \prod_{i=1}^{n} D_i
\]

\[
= g_0^r \left( \prod_{i=1}^{n} H(x_i) \right)^r
\]

instead of using all \(D_i\)’s such that the secret key is \((\tilde{D}, \tilde{D}, \tilde{D}, \tilde{D})\). Thus, the size of the secret key can also be independent of the number of the attributes.

Since we have changed the forms of ciphertexts and secret keys, the Test and the Decrypt algorithms need to be changed accordingly. The Test algorithm is changed to

\[
e_1(t_\omega, \hat{C}_1) = e_1(\hat{C}, \hat{C}_1).
\]

To compute \(e_0(g_0^s g_0^{rS})\) in the Decrypt algorithm, one now computes

\[
E = e_0(\tilde{D}, \hat{C}) = e_0(\tilde{D}, \hat{C})
\]

\[
= e_0(g_0^s g_0^{rS}).
\]

Note that the number of pairings is now independent of the number of the attributes in the access structure.

VII. COMPARISON

In this section, we compare our improved scheme with the schemes of [27], [38], [39] in terms of ciphertext size, secret key size, and the decryption cost.

A. Sun et al.'s Scheme [27]

In Sun et al.'s scheme [27], a secret key is \((\tilde{R}, \{K_i, F_i\}_{i \in \{1, n\}})\), where

\[
\tilde{R} = g^{\nu_{i,t}} K_i = \left\{ \begin{array}{ll}
g^{r_{i,t} i}, & i \in S \\
g^{r_{i,t} i + n}, & i \in U \setminus S' \end{array} \right.
\]

and \(n\) is the size of the attribute universe. Therefore, the secret key size is \(2n + 1\) elements in \(G\).

A ciphertext in their scheme is

\[
(C, \hat{C}, \tilde{C}, C_i) = \left\{ \begin{array}{l}
T_i \setminus, i \in W \\
T_i \setminus, i \in U \setminus W
\end{array} \right.
\]
Thus the ciphertext size is \( n + 1 \) elements in \( \mathbb{G} \) plus one element in \( \mathbb{G}_T \). Since Sun et al. only consider how to generate the encrypted indices, there is no Decrypt algorithm in their paper.

B. Li et al.’s Scheme [38]

Li et al.’s scheme supports threshold-gate in the access structure. Let \( d \) be the threshold value for the access policy. The secret key of a user is with the form

\[
SK = (SK_{KGCSP}, SK_{TA}),
\]

where

\[
SK_{KGCSP} = \{(d_{iO}, d_{i1}) \}_{i \in A} = \left\{ \left( g_2^{g(i)}(g_1 h_i)^{r_i}, g^{r_i} \right) \right\}_{i \in A}
\]

and

\[
SK_{TA} = (d_{g0}, d_{g1}) = \left( g_2^{g_2}(g_1 h)^{r_0}, g^{r_0} \right).
\]

Though the size of \( SK_{TA} \) is independent of the number of attributes in \( A \), the size of \( SK_{KGCSP} \) is \( 2|A| \).

Thus the size of a full secret key is \( 2|A| + 2 \) elements in \( \mathbb{G} \), where \( |A| \) denotes the size of \( A \). A ciphertext in [38] is with the form

\[
C_0 = M \cdot e(g_1, g_2)^{\Delta S(0)}, C_1 = g^s,
\]

\[
C_0 = (g_1 h)^{\Delta S(0)}, C_1 = (g_1 h)^s \in \mathbb{G}.
\]

Thus the size of a ciphertext is \( |W| + 2 \) elements in \( \mathbb{G} \) plus one element in \( \mathbb{G}_T \), where \( |W| \) is the size of the attribute set \( W \).

The decryption process in [38] is twofold. One is the cost of Decrypt, which is performed by a semi-trusted server, another is the cost of Decrypt, which is performed by the user. In algorithm Decrypt, the server needs to compute

\[
Q_{CT} = \prod_{i \in S} e(C_i, d_{i0})^{\Delta S(0)}
\]

where \( |S| = |A \cap W| \geq d \), and thus at least \( 2d \) bilinear maps are necessary. In the user side, a user needs to compute

\[
C_0 \cdot e(C_0, d_{g0})
\]

to recover the message \( M \). Therefore, two pairings are necessary for a user to recover \( M \). Totally, to decrypt a ciphertext needs at least \( 2d \) + 2 pairings.

C. Wang et al.’s Scheme [39]

In Wang et al.’s scheme, a secret key \( SK \) consists of the following two parts,

\[
SK_1 = \left( \tilde{a} = \frac{\tilde{a}}{\delta_{uid}}, K = g^{a_1}g^{a_2} \right),
\]

\[
SK_2 = \left( \delta_{uid}, E = g^{a_2}, L = g^{t_1}, \{K_i = H(i)^{t_1}\} \right)_{i \in S_{uid}}.
\]

As the same case as that in [38], the size of \( SK_1 \) is independent of the number of the user’s attributes, which is an element in \( \mathbb{Z}_p \) plus an element in \( \mathbb{G} \), while the size of \( SK_2 \) is proportional to the number of the user’s attributes, which is an element in \( \mathbb{Z}_p \) plus \( |S_{uid}| \) + 2 elements in \( \mathbb{G} \).

A ciphertext in [39] consists of the following components

\[
CT = \left( C = M \cdot e(g, g)^{\Delta S}, C' = g^s, \right)
\]

\[
\{C_i = g^{a_2}H(\rho(i)^t_1), D_i = (PK_{\rho(i)^t_1})^{t_1}\}_{i \in [1, \ell]}
\]

where \( \ell \) is the number of rows in \( M \), which is equal to or greater than the number of attributes in the access structure. Therefore, the size of a ciphertext is at least \( 2|W| + 1 \) elements in \( \mathbb{G} \) plus an element in \( \mathbb{G}_T \), where \( |W| \) denotes the number of attributes in the access structure.

The decryption cost is also twofold. Recall that in the algorithm PreDecrypt, CS needs to compute

\[
A = \prod_{i \in S} e(C_i, l)^{\Delta i}
\]

to recover the message \( M \), thus a bilinear map is necessary. Totally, to decrypt a ciphertext needs approximately

\[
D. Our Improved Scheme
\]

In our improved scheme, a ciphertext and a secret key are with the form \( CT = (C, C, C, C) \) and \( SK = (D, D, D, D) \), respectively. Both the sizes are independent of the number of attributes.

To decrypt a ciphertext, a user first computes

\[
E = \frac{e_0(D, C)}{e_0(D, C)}
\]

then recover the message by computing

\[
M = \frac{C \cdot A}{e(C', K)}
\]

Thus, three \( e_0 \) operations is needed.

The notations used in the comparison is shown in Table I. To simplify the case for comparison, we have to make some assumptions. Here we consider only AND-gate access structure. For [38], we assume that \( |S| = |A \cap W| = d \). For [39], we assume that \( |I| = |S_{uid}| = |A| \). The comparison is summarized in Table II.

<table>
<thead>
<tr>
<th>TABLE I: NOTATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_e )</td>
</tr>
<tr>
<td>( T_{e_0} )</td>
</tr>
<tr>
<td>(</td>
</tr>
<tr>
<td>(</td>
</tr>
<tr>
<td>(</td>
</tr>
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<tr>
<td>( n )</td>
</tr>
<tr>
<td>( A )</td>
</tr>
<tr>
<td>( d )</td>
</tr>
</tbody>
</table>

VIII. Conclusion

To protect the privacy, users usually encrypt their files.
before uploading to clouds. Searchable encryption has then been proposed for efficient searches over encrypted files on clouds. In this paper, we first give a review on Wang et al.’s ABKS scheme, and then give a cryptanalysis to their work. Our analysis shows that Wang et al.’s scheme did not achieve hidden policy, and the ciphertext lengths of their scheme are not independent of the number of attributes. We further proposed an improvement to solve the aforementioned problems. By applying our method, the improved scheme achieves constant-size ciphertext. In the future, we will focus on proving the security of our improved scheme under standard security models.

<table>
<thead>
<tr>
<th>TABLE II: COMPARISON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secret Key Size</td>
</tr>
<tr>
<td>[27]</td>
</tr>
<tr>
<td>(2n + 1)G + (n + 1)G_r</td>
</tr>
<tr>
<td>[38]</td>
</tr>
<tr>
<td>(2(A + 2)G)</td>
</tr>
<tr>
<td>[39]</td>
</tr>
<tr>
<td>Ours</td>
</tr>
<tr>
<td>G_r</td>
</tr>
</tbody>
</table>

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REFERENCES


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