Efficient Attribute-Based Searchable Encryption on Cloud Storage

WanFen GUO, XiaoLei DONG, ZhenFu CAO, JiaChen SHEN

Cryptology and Network Security, East China Normal University, Shanghai, 200062, China
wf_guo015@163.com

Abstract. Cloud service is very popular for its computing and storage capacity at lower cost. More and more data are being moved to the cloud to reduce storage cost. On the other hand, since the cloud is not fully trustable, in order to protect data privacy against third-parties and even the cloud server, they are usually encrypted by cryptology technology before uploading. However, many operations, such as searching, are hard to perform on encrypted data. To solve this problem, searchable encryption has emerged. Searchable encryption in multi-user setting is much less efficient than in single-user setting. In order to address this problem, we propose a multi-owner to multi-user searchable encryption scheme based on attribute-based encryption. Our scheme keeps data secure in the cloud even against the cloud server. It allows users with appropriate authorizations to perform search operations on encrypted data. In addition, search tokens are generated by users instead of data owners. We prove that token privacy and index privacy are well protected in our scheme. The cloud server and illegitimate users are not able to get any useful information about search tokens and ciphertexts. Ciphertexts of our scheme are constant-size, which reduce the time-complexity and bandwidth overhead of our scheme.

1. Introduction

With the development of the information technology, more and more information exchanges on the Internet. Therefore, not only the computers but also the mobile devices produce high-volume of data. As a result, cloud storage has become more and more popular with the low cost and vast capacity. While the information uploaded to the cloud may be sensitive and data owners want to keep them secret and prevent them from being exposed. What concerns data owners is that the cloud server is capable of manipulating their data in the cloud storage, so a method of encryption on the important data before uploading has been adopted. On the other hand, the goal of file storage is that we can find data when we need them. Although encryption helps in keeping data safe, it makes performing computation on the data difficult, such as search operations. One of naive methods is to download all encrypted files and decrypt them, then we can perform search operations on the plaintext files. This results in the huge bandwidth overhead and extra cost on the storage of downloaded files. The searchable encryption (SE) can solve the problem of searching on the ciphertext and take full advantage of the cloud computing.

Let's consider a scenario: In a hospital, all patients' information are uploaded to the hospital system in the form of ciphertexts, which include their names, telephone numbers, disease types, record time, the name of their doctors and so on. As a patient, he should be able to search all the information about himself and nothing about other people. As a doctor, to track the patients' recovery, he can search the names and telephone numbers of his patients. The statistical department can search the number of the patients who affected some type of diseases during a certain period of time. Therefore, in this scenario,
the different authorities should be given to different people so that they can search different information according to their roles. However, most existing schemes are not able to achieve this. In the general symmetric searchable encryption (SSE) setting, when a data user wants to search on the files, he should request a search token from the data owner. After sending the search token to the cloud, the data users will receive search results computed by the cloud server. In this case, we can see that the keyword that the data user searched is known by the data owner which is not desirable. What's more, multi-owners to multi-users scheme model is more practical than one-owners to one users. And, the computing capacity of mobile phones and wearable devices are so week that they only perform efficient algorithms. The problem of the computation complexity and space complexity of is worth noting. And the response speed of search operations should be improved.

1.1. Our Contributions

We design an efficient attribute-based searchable encryption (EABSE) to implement secure keyword search on the cloud storage scheme, which allows the cloud to execute the search operations on the ciphertext and forbids the cloud to get more information except the search results. Our contributions can be concluded as bellows:

- Our scheme implements multi-owners to multi-users searchable encryption. The data owners use a certain access policy to encrypt the keywords in index, and the data users whose attributes satisfy the access policy can achieve the corresponding search tokens.
- Our scheme protects the privacy of both the data owners and the data users. Only when data users' attributes satisfy the data's access policy, he can get the data which encrypted by the data owner. On the other hand, in this scheme, the search token is computed by the users, and the data owners don't know which keyword the users want to search. While in the general scenes, the data user must submit the keyword he want to search and apply the data owners for search tokens. Under the random oracle security model, we define the security of the EABSE basing on the DL-assumption and construct a proper scheme. Moreover, we analyze the security of the scheme and prove it secure from the aspects of correctness and privacy.
- We improve the efficiency of the scheme to meet the needs of the practical scenes. In time complexity, we improved the complex computation operations. In space complexity, we reduce the size of the ciphertext greatly.

1.2. Related Work

Searchable Encryption. Many search schemes have been proposed after the symmetric searchable encryption was first introduced in [1] and asymmetric searchable encryption was introduced in [2]. SE technology solves the problem of searching on the encrypted files and improves the practicability of cloud storage and cloud computing. In [3], the scheme which supported searching multi-keyword at the same time was proposed. [5] introduced a searchable scheme with dynamic updating. And, the time of updating, which includes addition and deletion, was as much as searching. To improve the efficiency, utilizing the useful RAM as a solution like [6] was deployed. Since Abdalla et al. [4] constructed asymmetric searchable encryption scheme from identity-based encryption(IBE) and proved it secure, some works transformed the efficient IBE into efficient PEKS [22]. The multi-participants searchable encryption allowed data share among many people [21], where the authorised data-users can search on the files uploaded by according data-owners. Our work emphasises the research on multi-users model in searchable schemes.

Index. The index of the files is very important in search. Different indexes have both advantages and disadvantages. Curtmola et al. [1] proposed the first encrypted searchable index basing on the inverted index. Inverted index [10] is a practical data structure. The index basing on a bloom filter was introduced by Goh et al. [7]. While Chang et al. proposed a vector index in [8].

Attribute-Based Searchable Encryption. To remove the Trusted Authority (TA) in identity-based encryption schemes, Sahai and Waters [15] presented FIBE as a solution which we considered as the prototype of Attribute-Based Encryption (ABE). In practical scenes, ciphertext-policy ABE (CP-ABE)
as an effective method to solve the data share in safety between multiple data-owners and multiple data-users, was very popular and discussed by many papers [16-18]. ABE plays an important role in fine-grained access control. The searchable encryption scheme with data users’ attributes as the search secret key is more practical. Attribute-based searchable encryption (ABSE) and its application were proposed in [14, 23]. As scheme in [14], data owners encrypted their index using different access policy, then data users were able to search keywords that they were interested in if their attributes satisfied the associated access policy. Besides, [14] proposed verifiable attribute-based searchable encryption on the malicious cloud. However, the computation complexity and communication efficiency of the above schemes were not taken into account. In this paper, we use ABE as a smoothly tools to implement the search on ciphertext. Therefore, we require the ABE scheme with enough efficiency. We adopt constant-ciphertext extension ABE [19, 20] to prevent the time complexity and space complexity increase obviously with the data growing on the cloud. Besides, we reduce the communication cost between data-owners and cloud when upload the constant ciphertext.

2. Preliminary

2.1. Inverted Index

As showed in the Figure 1, the inverted index includes many inverted lists I_{w1}, I_{w2}, …, I_{wm}, where m is the size of the keyword dictionary. One inverted list I_{wi} contains all files that contain the keyword wi. The files f_{i1}, f_{i2}, …, f_{in} in I_{wi} include the keyword w1 where n1 denotes the number of the files. The reason that we use inverted index like most works [11-13] is the search efficiency can be improved comparing to other indexes [1, 9].

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{inverted_index.png}
\caption{Inverted Index}
\end{figure}

2.2. Symmetric Bilinear Group

Let G and G_1 be the two cyclic multiplicative group of prime order p, and g is the generator of G. There exists a pairing e: G \times G \rightarrow G_1, with the below three properties: 1) Bilinearity: e(g^a, g^b) = e(g, g)^{ab}, for a,b \in \mathbb{Z}_p; 2) Non-degeneracy: e(g, g) \neq 1; 3) Computability: for all a,b \in \mathbb{Z}_p, e(g^a, g^b) is efficiently computed.

2.3. Decisional Linear (DL) assumption

There exists g, f, h chosen randomly from the group G and r_1, r_2 chosen randomly from Z_p. DL assumption says the probability of a probabilistic polynomial-time algorithm A can distinguish Q = h^{r_1 + r_2} with Q is random element from the tuple (g, f, h, f^\circ, g^\circ, Q) is negligible. We define \varepsilon is a negligible parameter, then the advantage of A in solving DL problem is

$$|\Pr[A(g, f, h, f^\circ, g^\circ, h^{r_1 + r_2}) = 1] - \Pr[A(g, f, h, f^\circ, g^\circ, Q) = 1]| \leq \varepsilon$$
3. Our Scheme
The scheme implements the multi-owners to multi-users keyword search functionality with high-efficiency. In order to satisfy the requirement of real environment, we promise the correctness of the search result but also the privacy of the data in storage and transmission.

3.1. System Model
There are three main entities: data owner, data user and cloud server. Following the Figure 2, data owners encrypt their files \( F = \{f_1, f_2, \ldots, f_n\} \) into the ciphertexts \( C = \{c_1, c_2, \ldots, c_n\} \) using some symmetric encryption. Because the file encryption is common, we don't discuss it in detail in this paper. Of course, a pre-defined keyword dictionary \( WD = \{w_1, w_2, \ldots, w_m\} \) is needed. Every data owner constructs his encrypted inverted index according to the keyword dictionary. We can use the identifier of the file instead of the file itself stored in the index for convenience in actual application. Finally, data owner uploads all the above information to cloud server. When the data user wants to search some keyword, he generates search token using his attributes. The cloud server executes the search on the index after receiving the token and returns the result to the user.

![Figure 2  System Model](image)

3.2. Algorithms and Security

3.2.1. Algorithms
According to the system model, we divide our scheme into three parts: data upload, query and data download. Each part is implemented by several algorithms respectively.

- **Data upload.** This part is executed by the data owner and system. The owner generates a secure inverted index and encrypts files before uploading.
  
  \( (msk, pk) \leftarrow \text{Setup}(\lambda) \): On input a security parameter \( \lambda \) and the attribute set \( U \) (which includes the all attributes of users), this probabilistic algorithm outputs the master key \( msk \) and public key \( pk \).

  \( (cphW, cphF) \leftarrow \text{Enc}(S, WD, F, pk) \): After receiving the access policy \( S \), keyword dictionary \( WD = \{w_1, w_2, \ldots, w_m\} \) and the file set \( F = \{f_1, f_2, \ldots, f_n\} \), the probabilistic encryption algorithm generates the encrypted index and the ciphertexts of files. The file encryption is executed by some simple symmetric encryption considering of the efficiency.

- **Query.** This part is executed by the data user and the cloud server. The user generates token for the keyword he wants to query.
  
  \( sk \leftarrow \text{KeyGen}(Attr, msk, pk) \): Given the attributes \( Attr \) by the user, master key \( msk \) and public key \( pk \), the probabilistic algorithm outputs the secret key \( sk \).
• \( \text{tok} \leftarrow \text{TokenGen} (pk, sk, w) \): This algorithm is used to generate token \( \text{tok} \) with the secret key \( sk \) and the keyword \( w \) to be queried.

Data Download. This part is executed by the cloud server. After receiving the search token, the cloud server runs Search algorithm on the data in cloud storage. Then it downloads the matched ciphertexts of files and returns them to user.

• \( \text{rlt} \leftarrow \text{Search} (\text{tok}, cphW, cphF) \): This deterministic algorithm outputs the ciphertext of the files \( cphF \) if \( cphW \) can matched with the \( \text{tok} \), outputs \( \bot \) otherwise.

3.2.2. Security

In the general schemes, we suppose the data owner and the data user are trusted, but the cloud server is semi-trusted. It means that the cloud server would execute data users' instructions honestly but try to get the information about what it is curious about. In the common ABE schemes, the data is closed absolutely after encryption. While the ciphertexts in searchable encryption must leave a threshold for each keyword ciphertext. Therefore, the security of the searchable encryption is more tedious. In this paper, we guarantee the scheme secure from two aspects: correctness and privacy.

Correctness. The search algorithm outputs the right result if only if the inputs of the Search(token, cphW, cphF) algorithm are from the Setup, KeyGen, Enc and TokenGen. We say the scheme is correct when the above statement holds.

Privacy. For the files, the ciphertexts cphF are semantic security by adopting a symmetric encryption, such as AES, then the adversary can not get information from what the file ciphertext revealed with non-negligible probability. For the keyword, we have:

Index Privacy: A probabilistic polynomial-time adversary can not get any useful information from the encrypted keyword cphW without associate search tokens. That is, the adversary can not determine which of the ciphertext of the keyword \( w_1 \) and the ciphertext of the keyword \( w_2 \) is about the keyword \( w \) he submitted.

Token Privacy: Given the keyword token, a probabilistic polynomial-time adversary can not learn the keyword plaintext. In other words, the cloud server can not learn which keyword the data user queried.

Our scheme implements a secure searchable encryption if it satisfies all above requirements.

3.2.3. Threat Model.

Under the random oracle model, we prove the index privacy of the EABSE scheme with selectively chosen-keyword attack game and prove the token privacy with token privacy game [14].

· Selectively Chosen-Keyword Attack(SCKA) Game:

  Setup: At first, the adversary gives a access policy \( S \) to the challenger. The challenger plays as the system and runs Setup(U, 1\(^{λ} \)), then it keeps the master key.

  Query Phase1: For the efficiency, the challenger applies for a query list \( ql \) and sets it empty before the Phase1 running. The adversary adaptively queries the below for polynomial times:

  With the KeyGen(Attr, msk, pk) algorithm, the adversary inputs the attributes Attr to challenger and gets associated secret key sk from the challenger if the attributes can not satisfy access policy S, otherwise the procedure aborts; according to the TokenGen(pk, sk, w) algorithm, the adversary can get a search token after inputting sk and keyword w. The challenger puts w into the querylist \( ql \) if the token is legitimate for the keyword.

  Challenge phase: The adversary selects two keywords \( w_0 \) and \( w_1 \) randomly which are excluded from the list \( ql \). The challenger flips a coin to select \( \mu \leftarrow \{0, 1\} \) and then runs the Enc algorithm. The challenger returns the ciphertext \( cph^* \) of the \( w_\mu \) to the adversary.

  Query Phase 2: The adversary can execute the queries as Phase1 did but the keyword \( w_0 \) and \( w_1 \) can not be queried any more.

  Guess: Finally, adversary gives a guess \( \mu' \) of \( \mu \) and wins the game if \( \mu' = \mu \).
We can define the advantage of adversary winning the game is $|\Pr[\mu' = \mu] - \frac{1}{2}|$. If the advantage is negligible, our scheme is secure with index privacy.

- Token Privacy Game:
  
  **Setup:** The challenger plays as the system and runs $\text{Setup}(U, 1^\lambda)$, then it keeps the master key $\text{msk}$.

  **Query Phase 1:** As in SCKA game, the challenger selects a list $\text{kl}$ which is empty initially. The adversary can execute below process for polynomial times. The adversary chooses a attribute set $\text{Attr}$ as the input of $\text{KeyGen}$ algorithm. The challenger returns $\text{KeyGen}$'s output $\text{sk}$ to adversary and add $\text{Attr}$ into $\text{kl}$. Then, challenger runs $\text{TokenGen}$ algorithm and returns $\text{tok}$ to adversary after receiving the $\text{sk}$ and keyword $w$.

  **Challenge phase:** The adversary submits a access policy $\text{S}$ with the restriction that each $\text{Attr}$ in $\text{kl}$ can not satisfy $\text{S}$. The challenger randomly chooses a keyword $w^*$ from the keyword dictionary and encrypt it with the $\text{S}$ into $\text{cphW}^*$. The challenger selects a attribute set $\text{Attr}^*$ which satisfies $\text{S}$. The adversary gets $\text{tok}^*$ from challenger.

  **Query Phase 2:** As did in Phase 1 except that keyword $w^*$ can not be queried.

  **Guess:** The adversary outputs guess keyword $w'$, and can win the game if $w' = w^*$.

### 3.3. Constructions

In our scheme, we use inverted index structure as introduced above and implement searchable encryption with AND gate as access control. The scheme consists of 6 main algorithms. We introduce them in detail as below:

**Init.** We suppose all the attributes are included in set $U = \{\text{attr}_1, \text{attr}_2, \cdots, \text{attr}_n\}$, where $n$ is the size of $U$. For each attribute $\text{attr}_i (1 \leq i \leq n)$, there has 2 values $\text{vi}$ and $\neg \text{vi}$. If the attributes set $\text{Attr}$ of one data user include attribute $\text{attr}_i (1 \leq i \leq n)$, the value of $\text{attr}_i$ is $\text{vi}$ and the value of $\text{attr}_i$ is $\neg \text{vi}$ if $\text{attr}_i$ is not in $\text{Attr}$.

To formalize the description of attributes, we adopt the value of attribute to represent whether user's set contains this attribute.

**Setup.** Given a bilinear group $e: G \times G \rightarrow G_T$, $p$ as prime order of $G$ and $G_T$, and $\{\cdot\}^*_{0,1} : \mathbb{Z}_p \rightarrow \mathbb{Z}$ as an one-way hash function, randomly select three numbers $\{\alpha, \beta, \gamma\} \leftarrow \mathbb{Z}_p$ and a set $\{r_1, r_2, \cdots, r_{2n}\} \leftarrow \mathbb{Z}_p$ and a set $\{x_1, x_2, \cdots, x_{2n}\} \leftarrow G$. Set and, where $(1 \leq i \leq 2n)$. Then, output the public key $\text{pk} = (g, g^\alpha, g^\beta, g^\gamma, (u_i, y_i) | (1 \leq i \leq 2n))$ and the master key $\text{msk} = (a, b, c, (r_i, x_i) | (1 \leq i \leq 2n))$.

**Enc.** Choose random $\{t_1, t_2\} \leftarrow \mathbb{Z}_p$. Suppose the access policy structure $\text{ivU} \in \left(\bigwedge_{0 \leq i \leq n} \text{ivV}_i\right)$, where $\text{ivV}_i \in \{\text{vi}, \neg \text{vi}\}$. Compute $\text{ugate} = \prod_{0 \leq i \leq 2n} u_i$. For each keyword $w \in \text{WD}$, then set $W = g^\text{ugate}, W' = g^\text{ugate}\cdot g^{\text{bht}(w)}$, and encrypt files $F$ which associate with the keyword $w$ with some symmetric encryption algorithm into $\text{cphF}$. Obviously, $\text{cphW} = (W, W', \text{ugate})$. Then, the whole $\text{cph} = (\text{cphW}, \text{cphF})$ as the result of encryption.

**KeyGen.** At First, we set $\text{V} = g^\text{ugate}$. For each attribute $\text{v}_i$ in data user's attribute collection, set $\text{v}_i = \text{vi}$ if $\text{v}_i = \text{vi}$, $\text{v}_i' = \text{uy}_i$ otherwise. Compute $\text{ugate} = g^\text{ugate}\cdot \prod_{0 \leq i \leq 2n} u_i'$. For each keyword $w \in \text{WD}$, then set $\text{ugate} = g^\text{ugate}\cdot g^{\text{bht}(w)}$, and encrypt files $F$ which associate with the keyword $w$ with some symmetric encryption algorithm into $\text{cphF}$. Obviously, $\text{cphW} = (W, W', \text{ugate})$. Then, the whole $\text{cph} = (\text{cphW}, \text{cphF})$ as the result of encryption.

**TokenGen.** Select $s \leftarrow \mathbb{Z}_p$. To generate the search token for keyword $w$, compute $\text{tok1} = (g^\text{ugate}\cdot g^{\text{bht}(w)})^s, \text{tok2} = g^{\text{ugate}}$. Therefore, the search token $\text{tok} = (\text{tok1, tok2})$.

**Search.** At first, compute $E = e(g, g^\text{ugate}^w, g^{\text{ugate}})$. If user's attributes satisfy the access policy according to the ciphertext, $E = e(g, g^\text{ugate}^w) \cdot e(W, \text{tok1}) = e(W, \text{tok2})$ hold.

According to the above, the search token $\text{tok}^s$ can match with the $\text{cphW}$ in the ciphertext $\text{cph}$, if the
attributes of data user can satisfy the access policy used for encrypting the keyword. The right answer should be returned to the data user.

4. Security Analysis
From the scheme construction, the correctness is easy to prove. Because of space limitation, we will introduce the security of the EABSE scheme in our full edition which was posted in the Cryptology ePrint Archive as report 2017/782. The full edition will show that our scheme meets the previous security definition.

5. Conclusion
In the practical scenes, the users prefer the scheme with quicker response and less bandwidth cost. Therefore, we considered the efficiency of the scheme when we designed the scheme. In our scheme, we achieved the constant-size ciphertext. Basing on the computation on the group of prime order \( p \), we mainly evaluate the exponentiation operation, multiplication operation and pairing operation in time complexity and the size of group \( G \) and \( G_T \) in space complexity. It is worth mentioning that multiplication operation is much more efficient than the exponentiation.

| Table 1 Time Complexity Analysis |
|------------------------------------|
| **Our Scheme** | [14] |
| Enc | \( 4E+(N+2)M \) | \( (2N+4)E+M \) |
| KeyGen | \( (S+1)E+2SM +SM_T \) | \( (2S+2)E+SM \) |
| TokenGen | \( 6E+M \) | \( (2S+4)E+M \) |
| Search | \( 4Pair+E_T+3 \) \( M_T \) | \( (2N+3)Pair+NE_T+(N+2)M_T \) |

| Table 2 Space Complexity Analysis |
|------------------------------------|
| **Our Scheme** | [14] |
| Enc | \( 3|G| \) | \( (2N+3)|G| \) |
| KeyGen | \( 2|G|+|G_T| \) | \( (2S+1)|G| \) |
| TokenGen | \( 4|G|+|G_T| \) | \( (2S+3)|G| \) |

Compared to the CP-ABKS in [14], we analyse the efficiency of the scheme from the two aspects of time complexity and space complexity. The results are showed in Table 1 and Table 2. \( E \) denotes the exponentiation operation on the element in group \( G \), \( E_T \) denotes the exponentiation operation on the element in group \( G_T \). Similarly, \( M \) denotes the multiplication operation on the element in group \( G \), \( M_T \) denotes the multiplication operation on the element in group \( G_T \). And \( \text{Pair} \) is the symbol of the pairing operation. We use \( |G| \) and \( |G_T| \) as the remarks of the size of \( G \) and \( G_T \) respectively. At last, we use \( N \) to represent the number of attributes which satisfy the access policy and \( S \) to represent the number of attributes which owned by the data-user. (In our scheme, \( S=N \).)

6. Conclusion
We introduced an efficient searchable scheme basing on the ciphertext-policy attribute-based encryption. The EABSE scheme allows secure data share in multi-owners and multi-users system model. The data owners upload the data wrapped with a certain access policy, and others can not get any information about the data whose attributes can not satisfy the access policy. While the authenticated data users are able to search a keyword on the ciphertexts and get the encrypted files including w. Besides, the search token is generated by data users. This action prevents the keyword that users queried from being known by owners and improves the users' privacy. It is mentioned that, our scheme raised the efficiency of
computation and reduced the cost of communication because of the constant-size ciphertext. Our performance and efficiency analysis illustrated this effectively. The new requirements also rise with the times, and the efficient search on the dynamic dataset is still for future work.

References
[1] Curtmola R, Garay J, Kamara S, et al. Searchable symmetric encryption: improved definitions and efficient constructions[J]. Journal of Computer Security, 2011, 19(5): 895-934.
[2] Boneh D, Di Crescenzo G, Ostrovsky R, et al. Public key encryption with keyword search[C]. Eurocrypt. 2004, 3027: 506-522.
[3] Golle P, Staddon J, Waters B. Secure conjunctive keyword search over encrypted data[C]. ACNS. 2004: 4: 31-45.
[4] Abdalla M, Bellare M, Catalano D, et al. Searchable encryption revisited: Consistency properties, relation to anonymous IBE, and extensions[C]. Crypto. 2005, 3621: 205-222.
[5] Gajek S. Dynamic symmetric searchable encryption from constrained functional encryption[C]. Cryptographers’ Track at the RSA Conference. Springer, Cham, 2016: 75-89.
[6] Garg S, Mohassel P, Papamanthou C. TWORAM: efficient oblivious RAM in two rounds with applications to searchable encryption[C]. Annual Cryptology Conference. Springer Berlin Heidelberg, 2016: 563-592.
[7] Goh E J. Secure indexes[J]. IACR Cryptology ePrint Archive, 2003, 2003: 216.
[8] Chang Y C, Mitzenmacher M. Privacy preserving keyword searches on remote encrypted data[C]. ACNS. 2005, 5: 442-455.
[9] Chen R, Mu Y, Yang G, et al. Server-aided public key encryption with keyword search[J]. IEEE Transactions on Information Forensics and Security, 2016, 11(12): 2833-2842.
[10] Knuth D E. Fundamental algorithms: the art of computer programming[M]. 1973.
[11] Ji S. On the Correctness of Inverted Index Based Public-Key Searchable Encryption Scheme for Multi-time Search[J]. arXiv preprint arXiv:1608.06753, 2016.
[12] Zhang R, Xue R, Yu T, et al. Dynamic and Efficient Private Keyword Search over Inverted Index-Based Encrypted Data[J]. ACM Transactions on Internet Technology (TOIT), 2016, 16(3): 21.
[13] Wang B, Song W, Lou W, et al. Inverted index based multi-keyword public-key searchable encryption with strong privacy guarantee[C]. Computer Communications (INFOCOM), 2015 IEEE Conference on. IEEE, 2015: 2092-2100.
[14] Zheng Q, Xu S, Atieniese G. VABKS: verifiable attribute-based keyword search over outsourced encrypted data[C]. Infocom, 2014 proceedings IEEE. IEEE, 2014: 522-530.
[15] Sahai A, Waters B. Fuzzy identity-based encryption[C]. Eurocrypt. 2005, 3494: 457-473.
[16] Ibraimi L, Tang Q, Hartel P H, et al. Efficient and Provably Secure Ciphertext-Policy Attribute-Based Encryption Schemes[C]. ISPEC. 2009: 1-12.
[17] Waters B. Ciphertext-policy attribute-based encryption: An expressive, efficient, and provably secure realization[C]. Public Key Cryptography. 2011, 6571: 53-70.
[18] Yu G, Cao Z, Zeng G, et al. Accountable Ciphertext-Policy Attribute-Based Encryption Scheme Supporting Public Verifiability and Nonrepudiation[C]. International Conference on Provable Security. Springer International Publishing, 2016: 3-18.
[19] Zhang K, Gong J, Tang S, et al. Practical and efficient attribute-based encryption with constant-size ciphertexts in outsourced verifiable computation[C]. Proceedings of the 11th ACM on Asia Conference on Computer and Communications Security. ACM, 2016: 269-279.
[20] Chen C, Zhang Z, Feng D. Efficient Ciphertext Policy Attribute-Based Encryption with Constant-Size Ciphertext and Constant Computation-Cost[J]. ProvSec, 2011, 11: 84-101.
[21] Zhao F, Nishide T, Sakurai K. Multi-user keyword search scheme for secure data sharing with fine-grained access control[C]. International Conference on Information Security and Cryptology. Springer, Berlin, Heidelberg, 2011: 406-418.
[22] Wang X A, Xhafa F, Cai W, et al. Efficient privacy preserving predicate encryption with fine-
grained searchable capability for Cloud storage[J]. Computers & Electrical Engineering, 2016, 56: 871-883.

[23] Sun W, Yu S, Lou W, et al. Protecting your right: Attribute-based keyword search with fine-grained owner-enforced search authorization in the cloud[C]. INFOCOM, 2014 Proceedings IEEE. IEEE, 2014: 226-234.