Public-key Authenticate Searchable Encryption With Probabilistic Trapdoor Generation

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Abstract. Public key encryption with keyword search (PEKS) is first introduced by Boneh et al. enabling a cloud server to search on encrypted data without leaking any information of the keyword. In almost all PEKS schemes, the privacy of trapdoor is vulnerable to inside keyword guessing attacks (KGA), i.e., the server can generate the ciphertext by its own and then run the test algorithm to guess the keyword contained in the trapdoor.
To sole this problem, Huang et al. proposed the public-key authenticated encryption with keyword search (PAEKS) achieving ciphertext indistinguishability and trapdoor indistinguishability security, in which data sender not only encrypts the keyword but also authenticates it by using his/her secret key. However, in Huang's scheme, it's very easy for any entity to check whether the ciphertext keywords in two ciphertext are identical or not. Therefore, this feature conflicts the security requirement of ciphertext indistinguishability, even the scheme is provable secure. Recent, Qin et al. revised Huang's work and proposed a PAEKS scheme without the above drawback.
Unfortunately, trapdoor generation algorithms of all above works are deterministic, which means it's easy to check whether the target keywords in two trapdoors are identical or not. This feature also conflicts with trapdoor indistinguishability security. In this paper, we solve this problem. We initially propose two public-key authenticated encryption with keyword search schemes with probabilistic trapdoor generation algorithm. We provide formal proof of our schemes in the random oracle model.

Keywords: Public key encryption · Keyword search · Keyword guessing attacks · Ciphertext indistinguishability · Trapdoor indistinguishability

1 Introduction

Cloud computing is a promising computing paradigm, in which data storage and procession is shifted from terminal devices to the cloud, enabling users to remotely maintain and manage data at lower costs. However, the data owner will lose his/her full control over data once the data is uploaded to the cloud.

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In this case, sensitive information is exposed to the cloud or other users. To protect the privacy of data, a straightforward method is encrypt the data before uploading it to the cloud server. Unfortunately, standard encryption technique doesn't provide search capability on the encrypted data.

In 2004, Boneh et al. [1] proposed the first public key encryption with keyword search (PEKS). In a PEKS scheme, data sender encrypts the data with a ciphertext keyword under the receiver's public key and uploads the ciphertext to the cloud. Searching for the ciphertext with specific keyword, the receiver generates the trapdoor with a target keyword and submits the trapdoor to the cloud. By interacting the trapdoor and each ciphertext, the cloud tests whether the target keyword of the trapdoor is identical to the ciphertext keyword of each ciphertext. If so, the cloud returns the successfully matched ciphertexts to the receiver. During the entire procedure, the cloud server learns nothing about the keywords embedded in the ciphertext and the trapdoor.

Attacks for PEKS are generally divided into two types: outside attack by malicious user and inside attacks by malicious tester (i.e., cloud server). The keyword space is ideally assumed to be super-polynomial, whereas in the real applications, keywords are often chosen from a low-entropy keyword space. Therefore, the privacy of trapdoor is compromised, since it's feasible for the adversary to guess the keywords containing in a given trapdoor by the keyword guessing attacks (KGA) [4]. Specifically, for each possible target keyword contained in the given trapdoor, the adversary encrypts it and generates a corresponding ciphertext, then checks whether it can be matched by the trapdoor. If succeed, the adversary knows that the ciphertext containing the same keyword as that of the given trapdoor. In the case of outside keyword guessing attacks (OKGA), any outside adversary obtained the given trapdoor, it can launch a KGA attack by doing the test freely. To resist OKGA, one can transmit the trapdoor by a secure channel between the receiver and the server so that only the cloud server can get the trapdoor; or restrict that only the designated server can do the test [16], i.e., any other unauthorized entity cannot check whether the trapdoor matches a ciphertext. However, neither method can prevent inside keyword guessing attacks (IGKA), since the attacks are launching by the server itself. Therefore, it's very necessary look for a method achieving trapdoor indistinguishability security to protect the privacy of trapdoor against IKGA in a PEKS scheme.

Recently, Huang and Li [10] introduced the notion of Public-key Authenticated Encryption with Keyword Search (PAEKS) to resist IKGA, in which the sender encrypts a keyword under his public key and the senders secret key and then authenticates it, such that the cloud server cannot launch IKGA successfully by encrypting a keyword itself. However, in Huang's scheme, it's very easy to check whether the ciphertext keywords in two ciphertext are identical or not. Therefore, this feature conflicts the security requirement of ciphertext indistinguishability, even the scheme is provable secure. Qin et al., [14] proposed a new security model for PAEKS, i.e., the multi-ciphertext indistinguishability, to overcome the drawback of [10].

1.1 Motivation

Trapdoor generation algorithms of [1, 9–12, 14] are all deterministic, so it's available to check whether the target keywords in two given trapdoors are identical or not. This feature obviously conflicts with trapdoor indistinguishability security mentioned in [9–12,14], even though these works are all provable secure. So, how to construct a PAEKS scheme with probabilistic trapdoor generation against inside keyword guessing attacks is still unknown.

1.2 Our contributions

Motivated by the above observations, we initially propose two public-key authenticated encryption with keyword search (PAEKS) schemes with probabilistic trapdoor generation. Briefly, we make the following contributions in this paper:

1. At first, we partially solve the open problem proposed in [14], provide a concrete PAEKS scheme with probabilistic trapdoor generation. The security of our first scheme is proved under static assumptions (i.e., modified DLIN assumption) in the random oracle model.
2. Then, to guarantee the integrity and validity of keys of sender and receiver, we provide our second PAEKS scheme with simplified key management. The security of second first scheme is proved under static assumptions (i.e., DBDH assumption) in the random oracle model.

In Table 1, we compare our schemes with some other PEKS schemes.

Table 1. Comparison among various PEKS schemes

	Ciphertext indistinguishability	Trapdoor indistinguishability	Probabilistic trapdoor
[1]	√		
[10]	√	√	
[12]	√	√	
[14]	√	√	
[11]	√	√	
Ours 1	√	√	√
Ours 2	√	√	√

1.3 Related works

In 2000 [1], Song et al. [19] introduced the first searchable symmetric encryption (SSE), which allows keyword search over encrypted data in the outsourcing scenarios. In 2004, Boneh et al. [2] initialized proposed the first public key encryption with keyword search scheme (PEKS). In 2005, Abdalla et al. [1] revised Boneh's work and provided a transform from an anonymous identity-based encryption scheme to a secure PEKS scheme. In addition, they also extended the

basic notions of anonymous hierarchical identity-based encryption, public-key encryption with temporary keyword search, and identity-based encryption with keyword search. Since then, various PEKS schemes have been proposed. Golle et al. [8] defined the security model for conjunctive keyword search over encrypted data and presented the first schemes for conducting such searches securely. Park et al. [13] proposed the public key encryption with conjunctive field keyword search enabling an email gateway to search keywords conjunctively. Boneh et al. [3] provided several public key system that support comparison queries, subset queries and arbitrary conjunctive queries on encrypted data. Shi et al. [18] designed an encryption scheme called multi-dimensional range query over encrypted data to deal with the privacy issues related to the sharing of network audit logs. Moreover, proxy re-encryption with keyword search [17], decryptable searchable encryption [7], keyword updatable PEKS [15] and attribute-based encryption with keyword search [6, 20] enjoyed some other interesting features compared with standard PEKS.

However, in actual practice, keywords are chosen from much smaller space than the space of passwords, thus all the above schemes are susceptible to the keyword guessing attacks (KGA). Byun et al. [4] analysed the security vulnerabilities on [1, 8] by performing off-line keyword guessing attacks. Rhee et al. [16] introduced the concept of trapdoor indistinguishability and show that trapdoor indistinguishability is sufficient for thwarting keyword-guessing attacks and proposed a provably secure PEKS scheme in the designated tester model (dPEKS). Unfortunately, dPEKS suffers from an inherent insecurity called inside keyword guessing attack (IKGA) launched by the malicious tester (i.e., cloud server). Chen et al. [5] proposed a new PEKS framework named dual-server PEKS scheme (DS-PEKS) using two uncolluded semi-trusted servers. Huang et al. [10] proposed a public-key authenticated encryption with keyword search scheme (PAEKS), which is secure against IKGA. It was then extended to certificateless PAEKS [9], identity-based setting with designed tester [11]. Recently, Noroozi et al. [12] found that Huang's work is insecure in the multi-receiver model and Qin et al. [14] extended the security model of PAEKS and proposed a PAEKS scheme secure against both inside keyword attacks and chosen multi-keyword attacks.

1.4 Organization

This paper is organized as follows. Section 2 describes the necessary preliminaries. Section 3 presents the system and security model. We give a concrete construction and explicit analysis of our PAEKS in section 4 and section 5 respectively. In the end, section 6 summarizes the paper and prospects for the future research.

2 Preliminaries

In this section, we briefly introduce some background knowledge.

2.1 Bilinear map

We briefly recall the definitions of the bilinear map. Let $\mathbb{G}_0$ and $\mathbb{G}_T$ be two multiplicative cyclic groups of prime order p. Let g be a generator of $\mathbb{G}_0$ and e be a efficient computable bilinear map, $e : \mathbb{G}_0 \times \mathbb{G}_0 \to \mathbb{G}_T$. The bilinear map e has a few properties: (1) Bilinearity: for all $u, v \in \mathbb{G}_0$ and $a, b \in \mathbb{Z}_p$, we have $e(u^a, v^b) = e(u, v)^{ab}$. (2) Non-degeneracy: for any generator $g \in \mathbb{G}_0$, $e(g, g) \in \mathbb{G}_T$ is the generator of $\mathbb{G}_T$. (3) Computability: For any $g, h \in \mathbb{G}_0$, there is an efficient algorithm to compute $e(g, h)$.

2.2 DBDH assumption

The decisional bilinear Diffie-Hellman (DBDH) assumption is defined as: given the bilinear map parameter $(\mathbb{G}_0, \mathbb{G}_T, p, e, g)$ and three random elements $x, y, z \in_R \mathbb{Z}_p^*$. We say that the DBDH assumption holds, if there is no probabilistic polynomial time (PPT) adversary $\mathcal{B}$ can distinguish between the tuple $(g, g^x, g^y, g^z, e(g, g)^{xyz})$ and the tuple $(g, g^x, g^y, g^z, \vartheta)$, where ϑ is randomly selected from $\mathbb{G}_T$. More specifically, the advantage ϵ of $\mathcal{B}$ in solving the DBDH problem is defined as

$$\Big|\Pr[\mathcal{A}(g,g^x,g^y,g^z,e(g,g)^{xyz})=1]-\Pr[\mathcal{A}(g,g^x,g^y,g^z,\vartheta)=1]\Big|. \tag{1}$$

Definition 1 (DBDH). *We say that the DBDH assumption holds if no PPT algorithm has a non-negligible advantage ϵ in solving DBDH problem.*

2.3 mDLIN assumption

The Decisional Linear (DLIN) assumption is defined as: given $g, g^a, g^b, g^{ac}, g^{bd} \in \mathbb{G}_0$ and $a, b, c, d \in_R \mathbb{Z}_p^*$, if there is no probabilistic polynomial time (PPT) adversary $\mathcal{B}$ can distinguish between the tuple $(g, g^a, g^b, g^{ac}, g^{bd}, g^{c+d})$ and the tuple $(g, g^a, g^b, g^{ac}, g^{bd}, \vartheta)$, where $\vartheta \in_R \mathbb{G}_0$, then the DLIN assumption holds.

In this paper, we make use of the variant of DLIN assumption called the modified DLIN assumption (mDLIN) [10]: given $g, g^a, g^b, g^{ac}, g^{d/b} \in \mathbb{G}_0$, the mDLIN assumption holds, if there is no probabilistic polynomial time (PPT) adversary $\mathcal{B}$ can distinguish between the tuple $(g, g^a, g^b, g^{ac}, g^{d/b}, g^{c+d})$ and the tuple $(g, g^a, g^b, g^{ac}, g^{d/b}, \vartheta)$, where $\vartheta \in_R \mathbb{G}_0$. Specifically, the advantage ϵ of $\mathcal{B}$ in solving the DLIN problem is defined as

$$\Big|\Pr[\mathcal{A}(g,g^a,g^b,g^{ac},g^{d/b},g^{c+d})=1]-\Pr[\mathcal{A}(g,g^a,g^b,g^{ac},g^{d/b},\vartheta)=1]\Big|. \tag{2}$$

Definition 2 (mDLIN). *We say that the mDLIN assumption holds if no PPT algorithm has a non-negligible advantage ϵ in solving mDLIN problem.*

3 Definition and Security Model of PAEKS

Public-key authenticated encryption with keyword search (PAEKS) was first introduced by Huang et al. [10], in which the privacy of trapdoor is secure against inside keyword guessing attacks. In this section, we recall the definition and security model of PAEKS.

3.1 Definition of PAEKS

The PAEKS includes the following six algorithms:

- **Setup**$(1^\lambda) \rightarrow PP$: Given security parameter λ, the algorithm generates the global public parameter PP.
- **KeyGen**$_R(PP) \rightarrow (PK_R, SK_R)$: On input the public parameter PP, the algorithm generates the public/secret key pair (PK_R, SK_R) for the receiver.
- **KeyGen**$_S(PP) \rightarrow (PK_S, SK_S)$: On input the public parameter PP, the algorithm generates the public/secret key pair (PK_S, SK_S) for the data sender.
- **PAEKS**$(PP, PK_R, PK_S, SK_S, KW) \rightarrow CT$: On input public parameter PP, public key of receiver PK_R, the key pair of sender (PK_S, SK_S) and a ciphertext keyword KW, the algorithm generates the ciphertext CT related to the keyword KW.
- **TrapGen**$(PP, PK_R, PK_S, SK_R, KW') \rightarrow Tr$: On input public parameter PP, public key of receiver PK_S, the key pair of receiver (PK_R, SK_R) and a target keyword KW, this algorithm generates the trapdoor Tr of KW'.
- **Test**$(PP, Ct, Tr) \rightarrow 0/1$: On input public parameter PP, ciphertext CT and trapdoor Tr, this algorithm checks whether the ciphertext keyword KW is identical to the target keyword KW'. If so, it outputs 1; otherwise it outputs 0.

Correctness: for any honestly generated key pairs (PK_R,SK_R) and (PK_S,SK_S), any two keywords KW, KW', let PAEKS$(PP, PK_R,PK_S,SK_S,KW) \rightarrow CT$ and TrapGen$(PP,PK_R,PK_S,SK_R,KW') \rightarrow Tr$. If $KW = KW'$, then the text algorithm outputs 1 with probability 1 i.e., $\Pr[\text{Test}(PP, Ct, Tr) = 1] = 1$; otherwise $\Pr[\text{Test}(PP, Ct, Tr) = 0] = 1 - negl(\lambda)$.

3.2 Security Model

In this section, we describe two security model introduced by Huang et al. [10]: ciphertext and trapdoor indistinguishability security. The notion of ciphertext indistinguishability (CI) security is defined as follows:

- **Setup**: Given a security parameter λ, the challenger $\mathcal{C}$ runs the algorithms Setup, KeyGen$_R$, KeyGen$_S$, and responds the adversary $\mathcal{A}$ with PP, PK_R, PK_S.
- **Phase** 1: The adversary $\mathcal{A}$ is allowed to issue polynomial queries the following oracles:

  Ciphertext Oracle $\mathcal{O}_C$: Given a ciphertext query (PK_R, PK_S, KW), $\mathcal{C}$ responds $\mathcal{A}$ with the ciphertext CT of keyword KW.

  Trapdoor Oracle $\mathcal{O}_T$: Given a trapdoor query (PK_R, PK_S, KW'), $\mathcal{C}$ responds $\mathcal{A}$ with the trapdoor Tr of keyword KW'.

- **Challenge**: $\mathcal{A}$ chooses two keywords KW_0^* and KW_1^* with the restriction that no element of $\{PK_R, PK_S, KW_j^*\}_{j\in 0,1}$ has been queried on $\mathcal{O}_C$ or $\mathcal{O}_T$. $\mathcal{C}$ randomly chooses a bit $\theta \in 0, 1$ and responds $\mathcal{A}$ with CT_θ^*, where $CT_\theta^* \leftarrow \text{PAEKS}(PP, PK_R, PK_S, SK_S)$.
- **Phase** 2: This phase is the same as Phase 1 with the restriction that no element of $\{PK_R, PK_S, KW_j^*\}_{j\in 0,1}$ can be queried on $\mathcal{O}_C$ or $\mathcal{O}_T$.
- **Guess**: $\mathcal{A}$ outputs a guess bit θ' of θ and it wins the game if $\theta' = \theta$. The advantage of $\mathcal{A}$ to win the ciphertext indistinguishability (CI) security game is defined as $Adv_{\mathcal{A}}^{CI}(\lambda) = \left| \Pr[\theta' = \theta] - \frac{1}{2} \right|$.

Definition 3. *The PAEKS achieves ciphertext indistinguishability security, if there exist no PPT adversary winning the above security game with a non-negligible advantage ϵ.*

The notion of trapdoor indistinguishability (TI) security is defined as follows:

- **Setup**: Given a security parameter λ, the challenger $\mathcal{C}$ runs the algorithms $\text{Setup}, \text{KeyGen}_R, \text{KeyGen}_S$, and responds the adversary $\mathcal{A}$ with PP, PK_R, PK_S.
- **Phase** 1: The adversary $\mathcal{A}$ is allowed to issues polynomial queries the following oracles:
  Ciphertext Oracle $\mathcal{O}_C$: Given a ciphertext query (PK_R, PK_S, KW), $\mathcal{C}$ responds $\mathcal{A}$ with the ciphertext CT of keyword KW.
  Trapdoor Oracle $\mathcal{O}_T$: Given a trapdoor query (PK_R, PK_S, KW'), $\mathcal{C}$ responds $\mathcal{A}$ with the trapdoor Tr of keyword KW'.
- **Challenge**: $\mathcal{A}$ chooses two keywords KW_0^* and KW_1^* with the restriction that no element of $\{PK_R, PK_S, KW_j^*\}_{j\in 0,1}$ has been queried on $\mathcal{O}_C$ or $\mathcal{O}_T$. $\mathcal{C}$ randomly chooses a bit $\theta \in 0, 1$ and responds $\mathcal{A}$ with Tr_θ^*, where $Tr_\theta^{i*} \leftarrow \text{TrapGen}(PP, PK_R, PK_S, SK_R)$.
- **Phase** 2: This phase is the same as Phase 1 with the restriction that no element of $\{PK_R, PK_S, KW_j^*\}_{j\in 0,1}$ can be queried on $\mathcal{O}_C$ or $\mathcal{O}_T$.
- **Guess**: $\mathcal{A}$ outputs a guess bit θ' of θ and it wins the game if $\theta' = \theta$. The advantage of $\mathcal{A}$ to win the trapdoor indistinguishability security game is defined as $Adv_{\mathcal{A}}^{TI}(\lambda) = \left| \Pr[\theta' = \theta] - \frac{1}{2} \right|$.

Definition 4. *The PAEKS achieves trapdoor indistinguishability security, if there exist no PPT adversary winning the above security game with a non-negligible advantage ϵ.*

4 PAEKS with probabilistic trapdoor generation

In this section, we propose the concrete construction of our first PAEKS scheme with probabilistic trapdoor generation.

4.1 Construction

The construction detail of our first scheme is shown as follows.

- **Setup**$(1^\lambda, \mathcal{L}) \rightarrow (PP)$: Given a security parameter λ, the algorithm chooses a bilinear map $e : \mathbb{G}_0 \times \mathbb{G}_0 \rightarrow \mathbb{G}_T$, where $\mathbb{G}_0$ and $\mathbb{G}_T$ are groups with prime order p and g is the generator of $\mathbb{G}_0$, and a hash function $H : \{0,1\}^* \longrightarrow \mathbb{G}_0$. It outputs the public parameter $PP = (e, \mathbb{G}_0, \mathbb{G}_T, p, g, H)$.
- **KeyGen**$_\mathbf{R}(PP) \rightarrow (PK_R, SK_R)$: The receiver picks a random $x \in_R \mathbb{Z}_p^*$ and sets $PK_R = g^x, SK_R = x$.
- **KeyGen**$_\mathbf{S}(PP) \rightarrow (PK_S, SK_S)$: The sender picks a random $y \in_R \mathbb{Z}_p^*$ and sets $PK_S = g^y, SK_S = y$.
- **PAEKS**$(PP, PK_R, PK_S, SK_S, KW) \rightarrow CT$: It randomly chooses $s, r \in_R \mathbb{Z}_p^*$, then computes

$$C_1 = H(PK_R, PK_S, KW)^{ys} g^r, C_2 = g^{xr}, C_3 = g^{ys}, C_4 = g^s. \tag{3}$$

  Finally, it outputs $CT = (C_1, C_2, C_3, C_4)$.
- **TrapGen**$(PP, PK_R, PK_S, SK_R, KW') \rightarrow Tr$: It randomly chooses $s', r' \in_R \mathbb{Z}_p^*$, then computes

$$T_1 = H(PK_R, PK_S, KW')^{xs'} g^{r'}, T_2 = g^{xs'}, T_3 = g^{yr'}, T_4 = g^{s'}. \tag{4}$$

  Finally, it outputs $Tr = (T_1, T_2, T_3, T_4)$.
- **Test**(PP, Ct, Tr): The algorithm checks whether the following equation holds or not:

$$e(T_1, C_3) \cdot e(C_2, T_4) = e(C_1, T_2) \cdot e(T_3, C_4). \tag{5}$$

  If so, it outputs 1; otherwise it outputs 0.

4.2 Correctness

The receiver's key pair is $(PK_R = g^x, SK_R = x)$ and the sender's key pair is $(PK_S = g^y, SK_S = y)$, while H is a collusion resistant hash function. If the ciphertext keyword KW is identical to the target keyword KW', we have the following equation:

$$\begin{aligned} e(T_1, C_3) \cdot e(C_2, T_4) =& e(H(PK_R, PK_S, KW')^{xs'} g^{r'}, g^{ys}) \cdot e(g^{xr}, g^{s'}) \\ =& e(H(PK_R, PK_S, KW), g)^{xyss'} \cdot e(g, g)^{r'ys} \cdot e(g, g)^{xrs'} \\ =& e(H(PK_R, PK_S, KW')^{ys} g^r, g^{xs'}) \cdot e(g^{yr'}, g^s) \\ =& e(C_1, T_2) \cdot e(T_3, C_4). \end{aligned} \tag{6}$$

The above equation holds with probability 1, if $KW = KW'$; it doesn't hold with overwhelming probability when $KW \neq KW'$.

4.3 Security proof

In this section, we provide a security analysis of our scheme.

Theorem 1. *Our scheme is semantically ciphertext indistinguishability secure against outside chosen keyword attacks in the random oracle model under the mDLIN assumption.*

Proof. Supposed that a PPT adversary $\mathcal{A}$ can break the CI security of our scheme with a non-negligible advantage $\epsilon > 0$, then there exists a PPT simulator $\mathcal{B}$ that can distinguish a mDLIN tuple from a random one with a non-negligible probability. The mDLIN challenger $\mathcal{C}$ selects $a, b, c, d \in_R \mathbb{Z}_p^*$, $\theta \in \{0, 1\}$, $\mathcal{R} \in_R \mathbb{G}_0$ at random. Let $\mathcal{Z} = g^{c+d}$, if $\theta = 0$, $\mathcal{R}$ else. Next, $\mathcal{C}$ sends $\mathcal{B}$ the mDLIN tuple $\langle g, g^a, g^b, g^{ac}, g^{d/b}, \mathcal{Z}\rangle$. Then, $\mathcal{B}$ plays the role of simulator in the following security game.

- **Setup**: $\mathcal{B}$ selects a collusion resistant hash function H and sets $PK_R = g^a, PK_S = g^b$ which implies $SK_R = a, SK_S = b$. Then, it sends $PP = (e, \mathbb{G}_0, \mathbb{G}_T, p, g, H)$ and PK_R, PK_S to $\mathcal{A}$.
- **Phase1**: The adversary $\mathcal{A}$ may issue at most q_H, q_C, q_T queries to the hash oracle $\mathcal{O}_H$, the ciphertext oracle $\mathcal{O}_C$ and the trapdoor oracle $\mathcal{O}_T$. We make some necessary restriction: q_H, q_C, q_T are polynomial; $\mathcal{A}$ isn't allowed to repeat a query to the hash oracle $\mathcal{O}_H$ and may repeat r_C queries to $\mathcal{O}_C$ and r_T queries to $\mathcal{O}_T$; $\mathcal{A}$ couldn't issue a ciphertext query (PK_R, PK_S, KW) to $\mathcal{O}_C$ or a trapdoor query to $\mathcal{O}_T$ before issuing the hash query (PK_R, PK_S, KW) to $\mathcal{O}_H$.

  $\mathcal{B}$ simulates these oracles as follows:

  Hash Oracle $\mathcal{O}_H$: To response the hash query, $\mathcal{B}$ maintains a list of tuple $\{(PK_R, PK_S, KW_j), h_j, a_j, c_j\}$ called the "H-list". This list is initially empty. Given a hash query tuple (PK_R, PK_S, KW_i), $\mathcal{B}$ responds as follows:
  1. If (PK_R, PK_S, KW_i) has already existed in the H-list, $\mathcal{B}$ responds $\mathcal{A}$ with $H(PK_R, PK_S, KW_i) = h_i \in \mathbb{G}_0$.
  2. Otherwise, $\mathcal{B}$ flips a random coin $c_i \in \{0, 1\}$ with the probability $\Pr[c_i = 0] = \delta$.
  3. $\mathcal{B}$ picks a random $a_i \in_R \mathbb{Z}_p^*$. If $c_i = 0$, it sets

  $$H(PK_R, PK_S, KW_i) = h_i = g^{d/b} \cdot g^{a_i} \in \mathbb{G}_0;$$

  If $c_i = 1$, it sets

  $$H(PK_R, PK_S, KW_i) = h_i = g^{a_i} \in \mathbb{G}_0$$

  .
  4. $\mathcal{B}$ adds the tuple $\{(PK_R, PK_S, KW_j), h_j, a_j, c_j\}$ into the H-list and responds $\mathcal{A}$ with $H(PK_R, PK_S, KW_i) = h_i$.

  Ciphertext Oracle $\mathcal{O}_C$: Given a ciphertext query (PK_R, PK_S, KW_i), $\mathcal{B}$ retrieves the tuple $\{(PK_R, PK_S, KW_j), h_j, a_j, c_j\}$ from H-list. If $c_i = 0$, it aborts the game and outputs a random bit θ' as the guess of θ. Otherwise, it picks $s, r \in_R \mathbb{Z}_p^*$, and responds $\mathcal{A}$ with the ciphertext $Ct = (C_1, C_2, C_3, C_4)$, where

  $$C_1 = h_i^{bs} \cdot g^r = (g^b)^{a_i s} \cdot g^r, C_2 = (g^a)^r, C_3 = (g^b)^s, C_4 = g^s.$$

Trapdoor Oracle $\mathcal{O}_T$: Given a trapdoor query (PK_R, PK_S, KW_i), $\mathcal{B}$ retrieves the tuple $\{(PK_R, PK_S, KW_j), h_j, a_j, c_j\}$ from H-list. If $c_i = 0$, it aborts the game and outputs a random bit θ' as the guess of θ. Otherwise, it picks $s', r' \in_R \mathbb{Z}_p^*$, and responds $\mathcal{A}$ with the trapdoor $Tr = (T_1, T_2, T_3)$, where

$$T_1 = h_i^{as'} g^{r'} = (g^a)^{a_i s'} g^{r'}, T_2 = (g^a)^{s'}, T_3 = (g^b)^{r'}, T_4 = g^{s'}.$$

- **Challenge**: $\mathcal{A}$ chooses two keywords KW_0^* and KW_1^* with the restriction that no element of $\{PK_R, PK_S, KW_j^*\}_{j\in[0,1]}$ has been queried on $\mathcal{O}_C$ or $\mathcal{O}_T$. $\mathcal{B}$ retrieves $\{(PK_R, PK_S, KW_j^*), h_j^*, a_j^*, c_j^*\}_{j\in[0,1]}$ from H-list and generates the challenge ciphertexts as follows:
  1. If, $c_0^* = c_1^* = 1$, $\mathcal{B}$ aborts the game and outputs a random bit θ' as the guess of θ.
  2. Otherwise, $c_0^* = 0$ or $c_1^* = 0$. Then, $\mathcal{B}$ generates the challenge ciphertext CT^* as Phase 1; $\mathcal{B}$ picks a bit $\hat{\theta} \in \{0, 1\}$ such that $c_{\hat{\theta}}^* = 0$. Then, it picks $s \in_R \mathbb{Z}_p^*$, sets $r^* = c \cdot s$ and generates the challenge ciphertext $CT^* = (C_1^*, C_2^*, C_3^*, C_4^*)$ for $\mathcal{A}$ as:

$$C_1^* = (h_{\hat{\theta}}^*)^{bs} \cdot g^{r^*} = (g^{d/b} \cdot g^{a_{\hat{\theta}}^*})^{bs} \cdot (g^c)^s = (g^{c+d})^s \cdot (g^b)^{a_{\hat{\theta}}^* s} = \mathcal{Z}^s \cdot (g^b)^{a_{\hat{\theta}}^* s}$$
$$C_2^* = (g^a)^{r^*} = (g^{ac})^s, C_3^* = (g^b)^s, C_4^* = g^s.$$

  If if $\mathcal{Z} = g^{c+d}$, CT^* is a valid ciphertext; otherwise, $\mathcal{Z} = \mathcal{R} \in_R \mathbb{G}_0$ so that C_1^* is a random element in $\mathbb{G}_0$ and CT^* is random in the view of $\mathcal{A}$.
- **Phase2**: This phase is the same as Phase 1.
- **Guess**: $\mathcal{A}$ outputs a guess bit θ'' of $\hat{\theta}$. If $\theta'' = \hat{\theta}$, $\mathcal{B}$ guesses $\theta = 0$ which indicates that $\mathcal{Z} = g^{c+d}$ in the above game. Otherwise, $\mathcal{B}$ guesses $\theta = 1$ i.e., $\mathcal{Z} = \mathcal{R}$.

If $\mathcal{Z} = \mathcal{R}$, then CT^* is random from the view of $\mathcal{A}$. Hence, $\mathcal{B}$'s probability to guess θ correctly is

$$\Pr\left[\mathcal{B}\left(g, g^a, g^b, g^{ac}, g^{d/b}, \mathcal{Z} = \mathcal{R}\right) = 1\right] = \frac{1}{2}. \tag{7}$$

Else $\mathcal{Z} = g^{c+d}$, then CT^* is an available ciphertext and $\mathcal{A}'s$ advantage of guessing θ' is ϵ. Therefore, $\mathcal{B}$'s probability to guess θ correctly is

$$\Pr\left[\mathcal{B}\left(g, g^a, g^b, g^{ac}, g^{d/b}, \mathcal{Z} = g^{c+d}\right) = 0\right] = \frac{1}{2} + \epsilon. \tag{8}$$

Now, we donate the event $\mathcal{B}$ aborts in the above game by $\mathbf{E}_0$ and compute the probability of $\overline{\mathbf{E}_0}$. Note that, $\mathcal{B}$ aborts in the following two cases:

1. $c_i = 0$ in the simulation of $\mathcal{O}_C$ or $\mathcal{O}_T$ in phase 1 and phase 2. We denote this event by $\mathbf{E}_1$ and the probability $\mathbf{E}_1$ doesn't occur is that

$$\Pr\left[\overline{\mathbf{E}_1}\right] = (1-\delta)^{q_C + q_T - r_C - r_T}.$$

2. We denote the event $c_0^* = c_1^* = 1$ in the challenge phase by $\mathbf{E}_2$ and the probability $\mathbf{E}_2$ doesn't occur is that

$$\Pr\left[\overline{\mathbf{E}_2}\right] = 1 - (1-\delta)^2.$$

We sets $\delta = 1 - \sqrt[2l]{\frac{q_C+q_T-r_C-r_T}{q_C+q_T-r_C-r_T+1}}$, then $\mathcal{B}$ doesn't abort in the above game is that

$$\begin{aligned}\Pr\left[\overline{\mathbf{E}_0}\right] &= \Pr\left[\overline{\mathbf{E}_1}\right] \cdot \Pr\left[\overline{\mathbf{E}_2}\right] \\ &= \left(\frac{q_C+q_T-r_C-r_T}{q_C+q_T-r_C-r_T+1}\right)^{\frac{q_C+q_T-r_C-r_T}{2l}} \cdot \frac{1}{q_C+q_T-r_C-r_T+1} \\ &\approx \frac{1}{(q_C+q_T-r_C-r_T+1)\cdot e^{\frac{1}{2}}}.\end{aligned} \tag{9}$$

Hence, $\mathcal{B}$ doesn't abort with a non-negligible probability.

In conclusion, $\mathcal{B}$'s probability to win the above security game is

$$\begin{aligned}\Pr\left[\theta' = \theta\right] &= \Pr\left[\theta' = \theta \wedge \mathbf{E}_0\right] + \Pr\left[\theta' = \theta \wedge \overline{\mathbf{E}_0}\right] \\ &= \Pr\left[\theta' = \theta \| \mathbf{E}_0\right] \cdot \Pr\left[\mathbf{E}_0\right] + \Pr\left[\theta' = \theta \| \overline{\mathbf{E}_0}\right] \cdot \Pr\left[\overline{\mathbf{E}_0}\right] \\ &= \frac{1}{2} \cdot \Pr\left[\mathbf{E}_0\right] + (\frac{1}{2} + \epsilon) \cdot \Pr\left[\overline{\mathbf{E}_0}\right] \\ &= \frac{1}{2} + \epsilon \cdot \Pr\left[\overline{\mathbf{E}_0}\right].\end{aligned} \tag{10}$$

Theorem 2. *Our scheme is semantically trapdoor indistinguishability security against inside keyword guessing attacks in the random oracle model under the mDLIN assumption.*

Proof. The proof of Theorem 2 is almost the same as Theorem 1, so we omit it here.

5 PAEKS with simplified key management

In our first scheme, both sender and receiver generate their public and secret keys by their own. To guarantee the integrity and validity of these keys, we apply a key generation (KGC) center to authorize a sender associated with an unique identity ID_S or a receiver with ID_R.

5.1 Construction

- **Setup**$(1^\lambda, \mathcal{L}) \to (PP)$: Given a security parameter λ, the algorithm chooses a bilinear map $e : \mathbb{G}_0 \times \mathbb{G}_0 \to \mathbb{G}_T$, where $\mathbb{G}_0$ and $\mathbb{G}_T$ are groups with prime order p and g is the generator of $\mathbb{G}_0$, and two hash functions $H_1 : \{0,1\}^* \longrightarrow \mathbb{G}_0$ and $H_2 : \mathcal{ID} \longrightarrow \mathbb{G}_0$. It picks a random $\alpha \in_R \mathbb{Z}_p^*$, then outputs the public parameter $PP = (e, \mathbb{G}_0, \mathbb{G}_T, p, g, H_1, H_2)$ and the master secret key $MSK = \alpha$.

- $\mathbf{KeyGen_R}(PP, MSK) \rightarrow (PK_R, SK_R)$: The KGC generates a secret key $H_2(ID_R)^\alpha$ for the receiver. The receiver picks a random $x \in_R \mathbb{Z}_p^*$, then sets $PK_R = (g^x, ID_R)$ and $SK_R = (x, H_2(ID_R)^\alpha)$.
- $\mathbf{KeyGen_S}(PP) \rightarrow (PK_S, SK_S)$: The KGC generates $H_2(ID_S)^\alpha$ for the sender. The sender picks a random $y \in_R \mathbb{Z}_p^*$, then sets $PK_S = (g^y, ID_S)$ and $SK_S = (y, H_2(ID_S)^\alpha)$.
- $\mathbf{PAEKS}(PP, PK_R, PK_S, SK_S, KW) \rightarrow CT$: It randomly chooses $s, r \in_R \mathbb{Z}_p^*$, then computes $K = e(H_2(ID_S)^\alpha, H_2(ID_R))$ and

$$C_1 = H_1(ID_R, ID_S, KW, K)^{ys} g^r, C_2 = g^{xr}, C_3 = g^{ys}. \tag{11}$$

  Finally, it outputs $CT = (C_1, C_2, C_3)$.
- $\mathbf{TrapGen}(PK_R, PK_S, SK_R, KW') \rightarrow Tr$: It randomly chooses $r' \in_R \mathbb{Z}_p^*$, then computes $K' = e(H_2(ID_S), H_2(ID_R)^\alpha)$ and

$$T_1 = H_1(ID_R, ID_S, KW', K')^{xr'}, T_2 = g^{xr'}, T_3 = g^{r'}. \tag{12}$$

  Finally, it outputs $Tr = (T_1, T_2, T_3)$.
- $\mathbf{Test}(PP, Ct, Tr)$: The algorithm checks whether the following equation holds or not:

$$e(C_1, T_2) = e(T_1, C_3) \cdot e(T_3, C_2). \tag{13}$$

  If so, it outputs 1; otherwise it outputs 0.

5.2 Correctness

The receiver's key pair is $PK_R = (g^x, ID_R); SK_R = (x, H_2(ID_R)^\alpha)$ and the sender's key pair is $PK_S = (g^y, ID_S); SK_S = (y, H_2(ID_S)^\alpha)$, while H is a collusion resistant hash function. If the ciphertext keyword KW is identical to the target keyword KW', we have the following equations:

$$K = e(H_2(ID_S)^\alpha, H_2(ID_R)) = e(H_2(ID_S), H_2(ID_R)^\alpha) = K' \tag{14}$$

$$\begin{aligned} e(C_1, T_2) =& e(H(ID_R, ID_S, KW, K)^{ys} g^r, g^{xr'}) \\ =& e(H(ID_R, ID_S, KW, K), g)^{xysr'} \cdot e(g, g)^{xrr'} \\ =& e(H(ID_R, ID_S, KW', K')^{xr'}, g^{ys}) \cdot e(g^{r'}, g^{xr}) \\ =& e(T_1, C_3) \cdot e(T_3, C_2). \end{aligned} \tag{15}$$

The above equation holds with probability 1, if $KW = KW'$ and $K = K'$; it doesn't hold with overwhelming probability when $KW \neq KW'$ or $K \neq K'$.

5.3 Security proof

Theorem 3. *Our second scheme is ciphertext indistinguishability secure against outside chosen keyword attacks in the random oracle model under the DBDH assumption.*

Proof. Supposed that a PPT adversary $\mathcal{A}$ can break the CI security of our second scheme with a non-negligible advantage $\epsilon > 0$, then there exists a PPT simulator $\mathcal{B}$ that can distinguish a DBDH tuple from a random one with a non-negligible probability. The DBDH challenger $\mathcal{C}$ selects $a, b, c \in_R \mathbb{Z}_p^*$, $\theta \in \{0, 1\}$, $\mathcal{R} \in_R \mathbb{G}_0$ at random. Let $\mathcal{Z} = e(g, g)^{abc}$, if $\theta = 0$, $\mathcal{R}$ else. Next, $\mathcal{C}$ sends $\mathcal{B}$ the DBDH tuple $\langle g, g^a, g^b, g^c, \mathcal{Z}\rangle$. Then, $\mathcal{B}$ plays the role of simulator in the following security game.

- **Setup**: $\mathcal{B}$ selects two hash function H_1, H_2. H_1 is a collusion resistant and H_2 serves as a random oracle.
- **Phase1**: The adversary $\mathcal{A}$ may issue at most q_{H_2} queries to the hash oracle $\mathcal{O}_{H_2}$, secret key oracle $\mathcal{O}_{SK}$, the ciphertext oracle $\mathcal{O}_C$ and the trapdoor oracle $\mathcal{O}_T$. We make some necessary restriction: q_{H_2} are polynomial; $\mathcal{A}$ isn't allowed to repeat a query to the hash oracle $\mathcal{O}_{H_2}$ or secret key oracle $\mathcal{O}_{SK}$, but may repeat queries to $\mathcal{O}_C$ and $\mathcal{O}_T$; $\mathcal{A}$ cannot issue any query $\mathcal{O}_{SK}$, $\mathcal{O}_C$ or $\mathcal{O}_T$ before issuing the associated ID to $\mathcal{O}_{H_2}$.

  $\mathcal{B}$ simulates these oracles as follows:

  Hash Oracle $\mathcal{O}_{H_2}$: $\mathcal{B}$ maintains a list of tuple $\{ID_j, H_2(ID_j), v_j, g^{z_j}, z_j\}$ as the "H_2-list", which is initially empty. Given a hash query ID_i, $\mathcal{B}$ responds as follows:

  1. If ID_i has already existed in the H_2-list, $\mathcal{B}$ responds $\mathcal{A}$ with $H_2(ID_i)$ and the public key PK_{ID_i} associated with ID_i.
  2. Otherwise, if $i = i^*$, i.e., $ID_i = ID_R^*$, $\mathcal{B}$ picks $x \in_R \mathbb{Z}_p^*$, sets $H_2(ID_R^*) = g^a$, adds $\{ID_R^*, g^a, v_R = \perp, g^x, x\}$ to H_2-list, and then responds $\mathcal{A}$ with $H_2(ID_R^*)$ and $PK_{ID_R^*} = (g^x, ID_R^*)$; if $i = j^*$, i.e., $ID_i = ID_S^*$, $\mathcal{B}$ picks $y \in_R \mathbb{Z}_p^*$, sets $H_2(ID_S^*) = g^b$, adds $\{ID_S^*, g^b, v_R = \perp, g^y, y\}$ to H_2-list, and then responds $\mathcal{A}$ with $H_2(ID_S^*)$ and $PK_{ID_S^*} = (g^y, ID_S^*)$; else, $\mathcal{B}$ picks a random $z_i, v_i \in_R \mathbb{Z}_p^*$, sets $H_2(ID_i) = g^{v_i}$, adds $\{ID_i, g^{v_i}, v_i, g^{z_i}, z_i\}$ to H_2-list, and then responds $\mathcal{A}$ with $H_2(ID_i)$ and $PK_{ID_i} = (g^{z_i}, ID_i)$.

  Secret Key Oracle $\mathcal{O}_{SK}$: Given a secret key query ID_i, if $ID_i = ID_S^*$ or $ID_i = ID_R^*$, $\mathcal{B}$ aborts the game and outputs a random bit θ' as the guess of θ. Otherwise, it retrieves the tuple $\{ID_i, g^{v_i}, v_i, g^{z_i}, z_i\}$ from H_2-list and returns $SK_{ID_i} = \{z_i, (g^c)^{v_i}\}$.

  Ciphertext Oracle $\mathcal{O}_C$: Given a ciphertext query $(PK_{ID_i}, PK_{ID_j}, KW)$, $\mathcal{B}$ picks $s, r \in_R \mathbb{Z}_p^*$, and responds $\mathcal{A}$ with the ciphertext $Ct = (C_1, C_2, C_3)$ according to the following two cases:

  1. $(ID_i, ID_j) = (ID_R^*, ID_S^*)$ or $(ID_i, ID_j) = (PK_{ID_S^*}, PK_{ID_R^*})$. Without loss of generality, we assume $ID_i = ID_R^*$. $\mathcal{B}$ sets $K = \mathcal{Z}$ and sets

$$C_1 = H_1(ID_R^*, ID_S^*, KW, \mathcal{Z})^{ys} g^r, C_2 = g^{xr}, C_3 = g^{ys}.$$

2. $ID_i \notin \{ID_R^*, ID_S^*\}$ or $ID_j \notin \{ID_R^*, ID_S^*\}$. Without loss of generality, we assume $ID_i \notin \{ID_R^*, ID_S^*\}$. $\mathcal{B}$ computes

$$K = e(H_2(ID_i), H_2(ID_j)^c) = e(g^c, H_2(ID_j))^{z_i}$$

and sets

$$C_1 = H_1(ID_i, ID_j, KW, K)^{ys} g^r, C_2 = g^{xr}, C_3 = g^{ys}.$$

Trapdoor Oracle $\mathcal{O}_T$: Given a trapdoor query $(PK_{ID_i}, PK_{ID_j}, KW')$, $\mathcal{B}$ picks $r' \in_R \mathbb{Z}_p^*$, and responds $\mathcal{A}$ with the trapdoor $Tr = (T_1, T_2, T_3)$ according to the following two cases:

1. $(ID_i, ID_j) = (ID_R^*, ID_S^*)$ or $(ID_i, ID_j) = (PK_{ID_S^*}, PK_{ID_R^*})$. Without loss of generality, we assume $ID_i = ID_R^*$. $\mathcal{B}$ sets $K' = \mathcal{Z}$ and sets

$$T_1 = H_1(ID_R^*, ID_S^*, KW', \mathcal{Z})^{xr'}, T_2 = g^{xr'}, T_3 = g^{r'}.$$

2. $ID_i \notin \{ID_R^*, ID_S^*\}$ or $ID_j \notin \{ID_R^*, ID_S^*\}$. Without loss of generality, we assume $ID_i \notin \{ID_R^*, ID_S^*\}$. $\mathcal{B}$ computes

$$K' = e(H_2(ID_i), H_2(ID_j)^c) = e(g^c, H_2(ID_j))^{z_i}$$

and sets

$$T_1 = H_1(ID_i, ID_j, KW', K')^{xr'}, T_2 = g^{xr'}, T_3 = g^{r'}.$$

- **Challenge**: $\mathcal{A}$ chooses two keywords KW_0^* and KW_1^* that no element of $\{PK_{ID_R^*}, PK_{ID_S^*}, KW_j^*\}_{j\in[0,1]}$ has been queried on $\mathcal{O}_C$ or $\mathcal{O}_T$. $\mathcal{B}$ picks a random bit $\hat{\theta} \in_R \{0,1\}$ and $s^*, r^* \in_R \mathbb{Z}_p^*$, and generates each challenge ciphertext $CT^* = (C_1^*, C_2^*, C_3^*)$ as:

$$C_1^* = H_1(ID_R^*, ID_S^*, KW_{\hat{\theta}}^*, \mathcal{Z})^{ys^*} g^{r^*}, C_2^* = g^{xr^*}, C_3^* = g^{ys^*}.$$

- **Phase2**: This phase is the same as Phase 1.
- **Guess**: $\mathcal{A}$ outputs a guess bit θ'' of $\hat{\theta}$. If $\theta'' = \hat{\theta}$, $\mathcal{B}$ guesses $\theta = 0$ which indicates that $\mathcal{Z} = e(g,g)^{abc}$ in the above game. Otherwise, $\mathcal{B}$ guesses $\theta = 1$ i.e., $\mathcal{Z} = \mathcal{R}$.

If $\mathcal{Z} = \mathcal{R}$, then CT^* is random from the view of $\mathcal{A}$. Hence, $\mathcal{B}$'s probability to guess θ correctly is

$$\Pr\left[\mathcal{B}\left(g, g^a, g^b, g^{ac}, g^{d/b}, \mathcal{Z} = \mathcal{R}\right) = 1\right] = \frac{1}{2}. \tag{16}$$

Else $\mathcal{Z} = e(g,g)^{abc}$, then CT^{i^*} is a set of available ciphertexts and $\mathcal{A}'s$ advantage of guessing θ' is ϵ. Therefore, $\mathcal{B}$'s probability to guess θ correctly is

$$\Pr\left[\mathcal{B}\left(g, g^a, g^b, g^{ac}, g^{d/b}, \mathcal{Z} = g^{c+d}\right) = 0\right] = \frac{1}{2} + \epsilon. \tag{17}$$

Since, $\mathcal{B}$ doesn't abort in the security game with the probability $\frac{1}{q_{H_2}(q_{H_2}-1)}$, its advantage to win the above security game is $\frac{\epsilon}{2q_{H_2}(q_{H_2}-1)}$.

Theorem 4. *Our second scheme is trapdoor indistinguishability security against inside keyword guessing attacks in the random oracle model under the DBDH assumption.*

Proof. The proof is similar with that of Theorem 3 except that $\mathcal{B}$ picks generates the challenge trapdoor $Tr^* = (T_1^*, T_2^*, T_3^*)$, as:

$$T_1^* = H_1(ID_R^*, ID_S^*, KW_{\hat{\theta}}^*, \mathcal{Z})^{x\hat{r}^*}, T_2^* = g^{x\hat{r}^*}, T_3^* = g^{\hat{r}^*},$$

where $\hat{r}^* \in_R \mathbb{Z}_p^*$ chosen by $\mathcal{B}$. For simplicity, we omit the detailed proof here.

6 Conclusion

In this paper, we initially propose two public-key authenticated encryption with keyword search schemes with probabilistic trapdoor generation against inside keyword guessing attacks. In the area of PAEKS, combining our schemes and [11], it would be able to design a secure designated PAEKS scheme with probabilistic trapdoor generation. For the compact of this paper, we omit it here.

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