Accelerating Forward and Backward Private Searchable Encryption Using Trusted Execution

Viet Vo†‡, Shangqi Lai†‡, Xingliang Yuan†, Shi-Feng Sun†‡, Surya Nepal†, and Joseph K. Liu†
†Monash University, Australia; ‡Data61, CSIRO, Australia;
{viet.vo, shangqi.lai, xingliang.yuan, shifeng.sun, joseph.liu}@monash.edu; surya.nepal@data61.csiro.au

Abstract—Searchable encryption (SE) is one of the key enablers for building encrypted databases. It allows a cloud server to search over encrypted data without decryption. Dynamic SE additionally includes data addition and deletion operations to enrich the functions of encrypted databases. Recent attacks exploiting the leakage in dynamic operations drive rapid development of new SE schemes revealing less information while performing updates; they are also known as forward and backward private SE. Newly added data is no longer linkable to queries issued before, and deleted data is no longer searchable in queries issued later. However, these advanced SE schemes reduce the efficiency of SE, especially in the communication cost between the client and server. In this paper, we resort to the hardware-assisted solution, aka Intel SGX, to ease the above bottleneck. Our key idea is to leverage SGX to take over the most tasks of the client, i.e., tracking keyword states along with data addition and caching deleted data. However, handling large datasets is non-trivial due to the I/O and memory constraints of the SGX enclave. We further develop batch data processing and state compression technique to reduce the communication overhead between the SGX and untrusted server, and minimise the memory footprint in the enclave. We conduct a comprehensive set of evaluations on both synthetic and real-world datasets, which confirm that our designs outperform the prior art.

I. INTRODUCTION

Searchable encryption (SE) [37], [16] is designed to enable a user outsource its data to remote servers (i.e., cloud) securely while preserving search functionalities. It is considered as the most promising solution to build encrypted databases defending against data breaches. Generic solutions like fully homomorphic encryption, multi-party computation, and oblivious RAM (ORAM) achieve strong security but introducing considerable computational and communication overhead. Property-preserving encryption like deterministic encryption and order-preserving/revealing encryption is very efficient and legacy compatible in databases, but those solutions are not secure in practice [34], [2]. The reasonable security and performance tradeoff brought by SE drives rapid development of new SE on search functionalities [12], [42], [60], security [4], [6], [29], and efficiency [19], [20].

In [9], Cash et al. introduced the concept of active attacks against dynamic SE; the leakage in data update operations could be exploited to compromise the security of SE. After that, Zhang et al. [43] proposed the first instantiation of active attacks called file-injection attacks through the exploitation of the leakage in data addition. This work raises a question whether a dynamic SE scheme with less leakage can be designed to mitigate existing and even prevent prospective active attacks. To address this question, forward and backward private SE schemes [4], [6], [40], [24] have drawn much attention recently.

In dynamic SE, the notion of forward privacy means that the linkability between newly added data and previously issued search queries should be hidden against the server, and the notion of backward privacy means that the linkability between deleted data and search queries after deletion should be hidden. To achieve higher security for SE, efficiency of SE is compromised. Existing forward and backward private SE schemes [6], [40], [24] introduce large overhead in storage and computation at both client and server, and/or increase the client-server interaction. In order to maintain the efficiency of SE, an alternative approach is to employ the hardware-assisted solution, i.e., Intel SGX, where native code and data can be executed in a trusted and isolated execution environment. SGX provides I/O communication interface to support trusted execution from a given application. They are `ecall'-invoking a function within SGX from the application, and `ocall'-invoking a function defined in the application from SGX. Recent work in ORAM powered by SGX [33] demonstrates that SGX can be treated as a delegate of client, so as to ease the overhead of client storage and computation, and reduce the communication cost between the client and server.

Recently, Amjad et al. [1] proposed the first forward and backward private SE schemes using SGX. As generic ORAM or ORAM-like data structures can natively be adapted to achieve the strongest forward and backward privacy in SE (i.e., Type-I backward privacy [6]), one of their schemes is built from ORAM, where data addition and deletion are completely oblivious to the server [1]. It is noteworthy that such an approach could still be inefficient due to the high I/O complexity between the SGX and server. Like prior forward and backward private SE studies, Amjad et al. also proposed an efficient scheme (i.e., Type-II backward privacy [6]) that trades a security for higher efficiency named Bunker-B [1]. Timestamps of update operations will be exposed, while the rounds of interaction between the SGX and server can be reduced. In this work, we are also interested in designs with forward and Type-II backward privacy due to its efficiency.

Unfortunately, only the theoretical construction of Bunker-B is given in [1], and we observe that it is still far from being practical, especially when handling large datasets. First, deletion operations are realised via insertion operations, which will (a) incur large communication costs between the SGX and
server, i.e., the number of *ocalls* scales with the number of deletions, and (b) increase search latency, because all deleted data needs to be retrieved, decrypted, and filtered out from the search results. Second, re-encryption is adopted after each search for forward and backward privacy, which will also incur long search latency. The reason is that if deleted documents are only a small portion of the matched results, most of the results (non-deleted ones) need to be re-encrypted and reinserted to the database. More detailed analysis can be found in Section [VII].

To avoid the potential performance bottleneck introduced by SGX, in this paper, we devise forward and backward private SE schemes from a simple yet effective approach. Our key idea is to leverage the SGX enclave to fully act as the client. The enclave will cache both the keyword state and the deletions, so as to reduce the communication cost and roundtrips between the SGX and server in search, addition, and deletion operations, and make the client almost free in computation and storage. Furthermore, we propose several optimisations to accelerate the performance, including batch document processing, state compression via Bloom filter, and memory efficient implementation.

**Contributions**: Our contributions in this paper can be summarised as follows:

- We design and implement two forward and backward private SE schemes, named SGX-SE1 and SGX-SE2. By using SGX, the communication cost between the client and server of achieving forward and backward privacy in SE is significantly reduced.

- Both SGX-SE1 and SGX-SE2 leverage the SGX enclave to carefully track keyword states and document deletions, so as to minimise the communication overhead between SGX and untrusted memory. In particular, SGX-SE2 employs bloomfilter to compress the information of deletions, which speeds up the search operations and boosts the capacity of batch processing in addition and deletion.

- We formalise the security model of our schemes and perform security analysis accordingly.

- We conduct comprehensive evaluations on both synthetic and real-world datasets. Our experiments show that the latest art Bunker-B takes $10 \times$ more *ecall/ocalls* than our schemes SGX-SE1 and SGX-SE2 when inserting $10^6$ documents. Even more, Bunker-B needs $30 \times$ *ecall/ocalls* when deleting $25\%$ of the above documents. W.r.t. search latency, SGX-SE1 and SGX-SE2 are $30\%$ and $2 \times$ faster than Bunker-B, respectively.

**Organisation**: We discuss some relevant works in Section [II]. Section [III] present the background of SGX and dynamic SE. Section [IV] details our system architecture, threat models, design intuition, and presents our proposed schemes SGX-SE1 and SGX-SE2. Section [V] formalises our security analysis. In Section [VI], we evaluate the schemes with the prior art in SGX-supported forward and backward private schemes. Section [VII] concludes the paper.

**II. RELATED WORK**

**Searchable encryption**: Song et al. [37] presented the first searchable encryption (SE) to enable search over encrypted documents. After that, Curtmola et al. [16] and Kamara et al. [28] formalised the security definitions for static and dynamic SE, respectively, and proposed schemes with sublinear search time. Since SSE was formalised, a long line of studies have been proposed to improve query efficiency [10], [13], [19], [17], [20], and support expressive queries [42], [31], [18].

**Forward and backward privacy in SE**: In dynamic SE, forward privacy means data additions do not reveal their associations to any query made in the past, and deleted documents cannot be access to any post queries. Forward privacy has been studied widely to mitigate file-injection attacks [45], [38], [41]. Backward privacy has received less attention [6], [40], [24]. There are three types of backward privacy from Type-I to Type-III in the descending order of security. However, strong backward private (Type-I and Type-II) schemes are known to be inefficient in both computation and communication overhead, as shown in [6], [24].

**Encrypted search with trusted execution**: Another line of research [1], [14], [33], [23] enabling search over encrypted data is to leverage hardware-assisted trusted execution environment (TEEs). In general, TEE such as Intel SGX can reduce the network roundtrips between the client and server and enrich the database functions in the encrypted domain. Fuhry et al. [23] proposed HardIDX that organises database index in a $B^+$-tree structure and utilises enclave to traverse a subset of the tree nodes to do search. Later, Mishra et al. [33] designed a doubly-oblivious SE scheme that supports inserts and deletes, named Oblix. In the scheme, one oblivious data index resides in enclave to map the search index of each keyword to a location in the another oblivious structure located in untrusted memory. However, the performance of their implementation on large databases is less efficient due to the fact of using ORAM. Regarding SE, Borges et al. [3] migrates secured computation to enclave to improve the search efficiency of SE boolean query schemes. When two or more keywords are queries, their result set can be unionised or intersected within the enclave. Note that this work focuses on a different problem with ours. Very recently, Amjad et al. [1] proposed three schemes to enable single-keyword query with different search leakage (i.e., information that untrusted server can learn about the query and data). However, the practical performance of these schemes has not been investigated.

**III. BACKGROUND**

**A. Intel SGX**

Intel SGX [32] is a set of new x86 instructions that designed for improving the security of application code and data. On SGX-enabled platforms, ones need to partition the application into both trusted part and untrusted part. The trusted part, dubbed enclave, is located in a dedicated memory portion of physical RAM with strong protection enforced by SGX. The untrusted part is executed as an ordinary process and can
invoke the enclave only through the well-defined interface, named \textit{ecall}, while the enclave can encrypt clear data and send to untrusted code via the interface named \textit{ocall}. Furthermore, decryption and integrity checks are performed when the data is loaded inside the enclave. All other software, including OS, privileged software, hypervisor, and firmware cannot access the enclave’s memory. In that way, outside applications (e.g., malicious software) cannot learn the plaintext.

SGX’s enclave is constructed with very limited 128 MB cache memory size. That memory is used for both SGX metadata and the enclave itself. The actual memory for storing data in the enclave is only up to 96 MB. SGX will automatically apply page swapping with proper integrity and confidentiality guarantees when allocating more than 96 MB.

SGX has a remote attestation feature that allows to verify the creation of enclaves on a remote server. During the creation, initial code and data are loaded into the enclave for measurement. Then, the enclave attests itself to the remote provider via authentication checking. After that, an encrypted communication channel can be established between the two parties. Secrets such as credentials or sensitive data can be provisioned directly to the enclave.

There has been a lot of existing SGX side-channel attacks such as hardware side-channels \cite{44, 27}, cache timing \cite{8, 25, 27}, and page-fault attacks \cite{36, 43}. However, we are also aware that the security in future SGX versions will be improved by both hardware and software based countermeasures \cite{22}. For instance, Dr. SGX \cite{7} provided new data randomisation strategies to defend against side-channel attacks that target data access patterns. Cloak \cite{26} implements new hardware transaction memory techniques to detect and prevent adversarial observation of cache misses on the sensitive code and data. Sanctum \cite{15} and Varys \cite{35} provide new verifiable hardware/software extensions to mitigate page-fault attacks.

### B. Dynamic Searchable Symmetric Encryption

In this section, we briefly overview dynamic SE. More details of forward and backward privacy are in \cite{4, 6}.

Following the verbatim in \cite{4, 6}, let DB represent a database of documents, and each document \texttt{doc} with a unique identifier \texttt{id} is a variable-length set of unique keywords. We use DB(w) to present the set of documents where \texttt{w} occurs. The total number of keyword-document pairs is denoted by \(N\), \(W\) is the total number of distinct keywords in DB. All \(N\) keyword-document pairs are stored in an index \(M_L\), which is a dictionary structure mapping each unique keyword \texttt{w} to a list of matching documents in DB(w). The encrypted database, named EDB is a collection of encrypted documents. A dynamic SE scheme \(\Sigma = (\text{Setup}, \text{Search}, \text{Update})\) consists of three protocols between a client and a server as follows:

- **Setup**: The protocol inputs a security parameter \(\lambda\) and outputs a secret key \(K\), a state \(ST\) for the client, and an encrypted database EDB that will be sent to the server.

- **Search**: The protocol allows to perform a query on \texttt{w} based on the state \(ST\), the secret key \(K\) and the state \(ST\) from the client, and the encrypted database EDB from the server. After that, it outputs the search result \texttt{Res}\(\) matching \texttt{w}.

- **Update**: The protocol takes the secret key \(K\), the state \(ST\), an input \texttt{in} associated with an operation \texttt{op} from the client, and the database EDB, where \(\texttt{op} \in \{\text{add, del}\}\) and \(\texttt{in}\) consists of a document identifier \texttt{id} and a set of keywords in that document. Then, the protocol inserts \texttt{in} to or removes \texttt{in} from EDB upon \texttt{op}.

Giving a list of queries \(Q\) sent by the client, the server records the timestamps \(\tau\) for every query with \(Q = \{q : q = (u, w)\text{ or } (u, \text{op}, \text{in})\}\). Following the verbatim from \cite{4, 6}, we let TimeDB(\(w\)) be the access pattern which consists of the non-deleted documents currently matching \texttt{w} and the timestamps of inserting them to the database. Formally,

\[
\text{TimeDB}(w) = \{ (u, \text{id}) : (u, \text{add}, (w, \text{id})) \in Q \quad \text{and} \quad \forall u' , (u', \text{del}, (w, \text{id})) \notin Q \}
\]

and let Updates(\(w\)) be the list of timestamps of updates:

\[
\text{Updates}(w) = \{ u : (u, \text{op}, (w, \text{id})) \in Q \}
\]

Based on the leakage function of dynamic SE \cite{6}, there are two security properties. The \textit{forward privacy} ensures that each update leaks no information about the keyword that was queried in the past and currently is in the document to be updated. The \textit{backward privacy} guarantees that when a keyword-document pair \((w, \text{id})\) is added to and then deleted from the database, subsequent searches on \texttt{w} do not reveal \texttt{id}. There are three types of backward privacy with varying levels of leakages from Type-I to Type-III introduced in \cite{6}.

- **Type-I**  backward privacy is the most secure. It only reveals what time the current (non-deleted) documents matching to \texttt{w} added (i.e., TimeDB(\(w\))). Type-II additionally leaks what time updates on \texttt{w} made, presented as \{TimeDB(\(w\)), Updates(\(w\))\}. In a less secure manner, Type-III inherits the leakage of Type-II and additionally reveals which addition updates cancel which deletion updates.

Current Type-II schemes Fides \cite{6} and Mitra \cite{24} require multiple roundtrips and high communication cost, while Horus \cite{24} relies on Path-ORAM \cite{39}. Until recently, Amjad et al. \cite{1} proposed three SGX-supported schemes, including the Type-I scheme Fort, Type-II scheme Bunker-B, and Type-III scheme Bunker-A. However, Fort requires an oblivious map (OMAP) similar to the one in Orion \cite{24} to do the update, causing high computation overhead. Bunker-A \cite{1} improves the update computation, but it downgrades the security guarantees. In contrast, Bunker-B is designed with good tradeoff in computation/communication cost and security guarantees. We will later compare the performance of Bunker-B with our schemes in Section \textbf{VII}.

### IV. Our Proposed Schemes

In this section, we present the high level SGX-supported system of our proposed schemes, as shown in Fig.1. After that, we detail our scheme design intuition by analysing previous SGX-supported schemes \cite{1} in terms of communication/computation overhead and then highlight our technical
solution. Finally, we present SGX-SE1 and SGX-SE2 with corresponding protocols to resolve the recognised limitations.

A. System Overview

The design involves three entities: the client (who is the data owner and therefore trusted), the untrusted server, and the trusted SGX enclave within the server. The system flow involves 9 steps.

At step 1, the client uses the SGX attestation feature for authenticating the enclave and establishing a secure channel between the client and the enclave. The client then provisions a secret key $K$ to the enclave through this channel. This completes the Setup protocol of our proposed system. Note that this operation does not deploy any EDB to the server as in dynamic SE schemes \[6, 5\]. Instead, we consider that the client should outsource documents to the server via Update operations later.

At step 2, giving a document with a unique document identifier $id$, the Client Manager encrypts the document with the key $K$ and sends the encrypted version of the document to the Server Manager (see step 3). The encrypted version with its $id$ is then inserted to EDB. After that, the Client Manager sends the original document to the State Manager located in the enclave via the secure channel (see step 4). At this step, the State Manager performs trusted cryptographic operations to generate update tokens that will be sent to Server Manager (see step 5). The tokens are used to update the encrypted index of dynamic SE located in the Server Manager. Note that traditional dynamic SE schemes \[11, 6, 40\] often consider EDB as the underlying encrypted index of dynamic SE, and omit the data structure storing encrypted documents. Here, we locate them separately to avoid that ambiguity, i.e., the index of dynamic SE $M_I$ is located in Server Manager, and encrypted documents reside in EDB as an encrypted document repository, respectively. To delete a document with a given $id$ (step 6), the Client Manager directly sends the document to the State Manager (see step 7).

At step 8, the client wants to search documents matching a given query keyword $w$. The Client Manager will send the keyword $w$ to the State Manager (see step 9). Then, the State Manager computes query tokens and excludes the tokens for deleted documents according to the deletion information from step 6. Later, the State Manager sends them to the Server Manager (in step 10). The Server Manager will search over the received tokens and return the list of encrypted matching documents back to the Client Manager. At that stage, the encrypted documents are decrypted with $K$.

B. Assumptions and Threat Models

Our Assumptions with Intel SGX: We assume that SGX behaves correctly, (i.e., there are no hardware bugs or backdoors), and the preset code and data inside the enclave are protected. Also, the communication between the client and the enclave relies on the secure channel created during SGX attestation. Like many other SGX applications \[21, 33\], we consider side-channel attacks \[44, 8, 25, 27, 36, 43\] against SGX are out of our scope. Denial-of-service (DoS) attacks are also out of our focus, i.e., the enclave is always available whenever the client invokes or queries. Finally, we assume that all the used cryptographic primitives and libraries of SGX are trusted.

Threat Models: Like existing work \[22, 1\], we consider a semi-honest but powerful attacker at the server-side. Although the attacker will not deviate from the protocol, he/she can gain full access over software stack outside of the enclave, OS and hypervisor, as well as hardware components in the server except for the processor package and memory bus. In particular, the attacker can observe memory addresses and (encrypted) data on the memory bus, in memory, or in EDB to generate data access patterns. Additionally, the attacker can log the time when these memory manipulations happen. The goal of the attacker is to learn extra information about the encrypted database from the leakage both revealed by hardware and the leakage function defined in Section V.

C. Design Intuition

As mentioned, Amjad et al. \[1\] proposed three backward private SGX-supported schemes: the Type-I scheme Fort, Type-II scheme Bunker-B, and Type-III scheme Bunker-A. The performance and security overview of these schemes can be found in Table I. Fort is the most secure while still relying on ORAM and thus we exclude it in this work. Bunker-A does not perform re-encryption and re-insertion after search and thus only achieves Type-III backward privacy. However, it still treats deletion as insertion, just like Bunker-B. Therefore, we only analyse the limitations of Bunker-B as follows.

Performance Analysis of Prior Work: The Update and Search protocols of Bunker-B are summarily presented in Algorithm I. As shown in Algorithm I, Bunker-B only requires $O(1)$ update computation complexity and $\alpha_w$ update $ocalls$: For each $(w, id)$, Bunker-B lets the enclave follow the same routine to generate tokens for addition and deletion and uses the generated token to update $M_I$ on the server (line 5 in Algorithm I). However, it causes high computation complexity $O(\alpha_w)$ and involves a large number of roundtrips (i.e., $\alpha_w$) during the search. In the Search protocol, the core idea of Bunker-B is to let the enclave read all records (associated with add or del) in $M_I$ corresponding to the keyword. Then, the enclave decrypts them and filters deleted $ids$ based on the operation. After query, the enclave re-encrypts non-deleted $ids$ and sends the newly generated tokens to the server for updates.
TABLE I: Comparison with previous SGX-supported schemes. $N$, $D$, and $W$ denote the total number of keyword/document pairs, total number of documents, and total number of keywords, respectively. $d_w$ presents the number of deleted documents. $n_w$ is the number of (current, non-deleted) documents containing $w$, $a_w$ is the total number of entries (including addition and deletion updates) performed on $w$, $d_w$ denotes the number of deletions performed on $w$. $r$ is the predefined number of necessary dummy entries to be inserted in oblivious operations. $v_d$ denotes the vector of a Bloom filter to verify the membership of $#d$ documents.

| SGX Scheme | Communication between enclave and server | Enclave Computation | Client Storage | Enclave Storage | BP Type |
|------------|----------------------------------------|---------------------|----------------|----------------|---------|
| Fort [1]   | $a_w$ | $O(n_w)$ | $a_w$ | $O(1)$ | $O(n_w + \sum_{w_u} d_w)$ | $O(1)$ | $O(1)$ | $O(W \log D)$ | – | I |
| Bunker-B [1] | $a_w$ | $O(n_w)$ | $a_w$ | $O(1)$ | $O(a_w)$ | $O(1)$ | – | $O(W \log D)$ | – | II |
| SXG-SE1 | $(d + d_w)$ | $O(n_w)$ | $n_w$ | $O(1)$ | $O(n_w + d)$ | $O(1)$ | – | $O(W \log D + d)$ | II |
| SXG-SE2 | $(d_w)$ | $O(n_w)$ | $n_w$ | $O(1)$ | $O(n_w + v_d)$ | $O(1)$ | – | $O(W \log D)$ | – | III |

* The complexity also requires $n_w$ ocalls (one-way trip) when sending query tokens to the server.

** The complexity also requires the size of a configurable Bloom filter vector.

† We note that the number of update ocalls is $n_w$ if the update is addition. Otherwise, deletion updates do not take any ocalls.

‡ If there is no deletion updates between two searches on different $w$, $d$ is cancelled. Then, the complexity is only $O(n_w)$.

These steps are summarised in lines 21-25 in Algorithm 1. We have implemented Bunker-B (see Section VI) and found that the scheme also has other limitations in practice as follows:

**Intensive Ecall/Ocall Usage:** Giving a document $doc$ with an identifier $id$ and $M$ unique keywords to the server, Bunker-B repeatedly performs the Update protocol with $M$ ecalls and then the same number of ocalls to insert tokens to the index map $M_I$. It indicates that the number of ecall/ocall for Bunker-B is linear to the keyword-document pairs for updates. In practice, a dataset can include a large number of keyword-document pairs (>$10^7$). As a result, Bunker-B takes $12 \mu s$ to insert one $(w, id)$ pair, and $2.36 \times 10^7$ ecall/ocalls to insert $10^6$ documents to the database. Similarly, deleting a doc in Bunker-B is the same as the addition, with the exception that the tokens contain $op = del$. Experimentally, Bunker-B takes $1.98 \times 10^6$ ecall/ocalls to delete $2.5 \times 10^5$ documents. The practical performance of Bunker-B can be found in Section VI. We also note that Bunker-B only supports deletion updates on the index map $M_I$ without considering deleting real documents. To do so, Bunker-B will need additional $d_w$ ocalls to request the server for the document deletion. This communication overhead is not mentioned in the previous work [1].

**Search Latency:** The re-encryption on non-deleted $ids$ per search makes Bunker-B inefficient. In particular, when the number of those $ids$ is large and the deleted ones is a small portion (adding $10^6$ documents and deleting $25\%$ documents), Bunker-B takes $3.2s$ to query a keyword (see Section VI).

**Technical Highlights:** Motivated by the above limitations of Bunker-B, we design SGX-SE1 and SGX-SE2 that are Type-II backward private schemes with: (1) reduced number of ecall/ocall when the client wants to add/delete a document, (2) reduced search roundtrips, and (3) accelerated enclave’s computation in search.

We achieve (1) by allowing the client to transfer the document to the enclave for document addition, instead of transferring $(w, id)$ pairs. This design reduces the number of ecalls to 1. We then use the enclave to store the latest states $ST$ of all keywords, where the state of a keyword

| Algorithm 1: Bunker-B [1]: Update and Search protocols |
|----------------------------------|
| 1 Update$(op, in) : \# op \in \{add, del\}, \text{ in } = (w, id)$ |
| 2 Client retrieves $st_w = (\text{version}, \text{count})$ from $st$; |
| 3 Send $(w, \text{version}, \text{count}, op, id)$ to enclave; |
| 4 Client updates $st_w = (\text{version}, \text{count} + 1)$ to $st$; |
| 5 Enclave generates an update token $u_k = (u, v)$; |
| 6 Enclave sends $u_k$ to the server; |
| 7 Server receives $u_k = (u, v)$ from the enclave; |
| 8 Server updates the map $M_I[w] = v$ |
| 9 Search$(w)$ : |
| 10 Client retrieves $st_w = (\text{version}, \text{count})$ from $st$; |
| 11 Client outputs $(w, \text{version}, \text{count})$ to enclave $st$; |
| 12 Client updates $st_w = (\text{version} + 1, \text{count})$ to $st$; |
| 13 Enclave receives $(w, \text{version}, \text{count})$ from client; |
| 14 Enclave generates query tokens $q_k = (u_1, \ldots, u_c)$, where $u_i := F_{K_1}(w|\text{version}|\text{count} + 1)$ |
| 15 Enclave sends $q_k$ to the server; |
| 16 Server returns the token to the list $L = \{(u_1, v_1), \ldots, (u_c, v_c)\}$; |
| 17 Server deletes all pairs in the $L$ from $M_I$; |
| 18 Enclave filters non-deleted $ids$ with $R = \{id : \text{token}(\text{id}, op =\text{del}) \in L\}$; |
| 19 Enclave returns $R$ to the client; |
| 20 Enclave resets $\text{count} = 1$ and re-encrypts $R$ with $f$ |
| 21 foreach $id \in R$: Generate a new token |
| 22 $u := F_{K_1}(w|\text{version} + 1|\text{count})$ |
| 23 $v := \text{Enc}(K_2, \text{id}|\text{op = add})$ |
| 24 Send $(u, v)$ to the server to update $M_I$; |
| 25 Enclave increase $\text{count} + 1 = 1$; |
is $ST[w] = count$. With this design, the enclave is able to generate addition tokens based on $ST$. Our experiments (see Section VI) show that this design improves $2 \times$ the addition throughput compared to Bunker-B. We note that it is negligible to store $ST$ in the enclave since it costs less than 6 MB to store the states of all keywords in the American dictionary of English\footnote{\(18 \times 10^7\) pairs \(\approx\) 380× Hamlet tragedy written by William Shakespeare} (assuming each keyword state item can take up 18 bytes in a dictionary map). Additionally, our schemes only require 1 \textit{recall} if the client wants to delete a document, by transferring that document \textit{id} to the enclave.

The SGX-SE1 scheme reduces the search roundtrips between the enclave and the server to \((d + d_u)\). The basic idea behind SGX-SE1 is to let the enclave cache the mapping between \(w\) and the deleted document \(id\). In particular, the enclave loads and decrypts \(d\) deleted documents to extract the mapping \((w, \text{id})\). It cleans the memory after loading each deleted document to avoid the memory bottleneck. After that, the enclave needs \(d_u\) roundtrips to retrieve the \(count\)s when the enclave filters those deleted \(id\). SGX-SE2 is more optimal by requiring only \(d_u\) roundtrips without the need for loading \(d\) deleted documents. To do this, SGX-SE2 uses a Bloom filter \(BF\) to store the mapping \((w, \text{id})\) within the enclave. Note that the \(BF\) can track \(1.18 \times 10^7 \times \sum \text{id}\) pairs with the storage cost of 34 MB enclave memory\footnote{\(18 \times 10^7\) pairs \(\approx\) 380× Hamlet tragedy written by William Shakespeare} with the false positive probability $P_e = 10^{-4}$. Our experiments (see Section VI) show that the search latency of SGX-SE1 is 30% faster than Bunker-B after inserting \(10^6\) documents and caching \(2.5 \times 10^5\) deleted documents. Moreover, SGX-SE2 is 2× faster than Bunker-B for the query after deleting 25% documents.

The proposed SGX-SE1 scheme improves the search computation complexity to $O(n_w + d)$. We note that the complexity is even amortised if there is no deletion updates between a sequence of queries. The reason is that the enclave only loads \(d\) document for the first query to update the mapping of all keywords in $ST$ with the deleted documents. Furthermore, the search computation complexity of SGX-SE2 is only $O(n_w)$. We note that testing the membership of \(d\) documents in the \(BF\) is \(v_\psi\) where \(v\) is the vector of \(BF\). Our experiments (see Section VI) show that Bunker-B takes 3.2\(s\) for queries after inserting \(10^6\) documents and deleting 25% documents while SGX-SE1 only takes 2.4\(s\) after caching those deleted documents. In addition, SGX-SE2 spends the least time (i.e., 1.4\(s\)), which is \(2 \times\) faster than Bunker-B.

\begin{itemize}
\item \textbf{D. SGX-SE1 Construction} \end{itemize}

The basic idea behind SGX-SE1 is to let the enclave store the latest states $ST$ of keywords and keeps the list $d$ of deleted document $id$s, in order to facilitate searches. Then, the enclave only loads the deleted documents for the first search between two deletion updates to update the mapping between deleted $id$s and tracked keywords. Subsequent searches between the two deletion updates do not require loading the deleted documents again. We note that the enclave clearly needs to remove $d$ after retrieving them in the first query to save the enclave’s storage. Once the enclave knows the mapping between the query keyword and deleted documents, it infers the mapping of the query keyword with the rest non-deleted documents, in order to generate query tokens. After that, the server retrieves documents based on the received tokens and returns the document result list to the client. The detail protocols of SGX-SE1 can be found in Figure 2. We explain the protocols further as follows:

\begin{itemize}
\item \textbf{In setup,} client communicates with enclave upon an established secure channel to provision $K = (K_{CS}, k_f)$ where $K_{CS}$ enables enclave to generate update/query tokens and $k_f$ is the symmetric key for document encryption/decryption. The enclave maintains the maps $ST$ and $D$, and the list $d$, where $ST$ stores the states of keywords, $D$ presents the mapping between keywords and deleted documents, and $d$ is the array of deleted $id$s. The server holds an encrypted index $M_I$, the map of encrypted state $M_s$, and the repository $R$ with $R[id]$ stores the encrypted document of document identifier $id$.
\item \textbf{In update,} the client receives a tuple \((op, \text{in})\), where it could be \((op = add, \text{in} = (\text{doc}, \text{id}))\) or \((op = del, \text{in} = \text{id})\). If the update is addition, the client encrypts $\text{doc}$ by using $k_f$ and sends that encrypted document to server. After that, the client sends \((op, \text{in})\) to the enclave. The enclave will then parse $\text{doc}$ to retrieve the list $L$ of \((w, \text{id})\). For each $w$, the enclave generates $k_w$ and $k_c$ from $K_{CS}$, and retrieves the latest state $c \leftarrow ST[w]$. The enclave will then generate $k_{id}$ from $c$ by using $H_1(k_w, c)$ with $H_1$ is a hash function. After that, the enclave uses $k_w$, $k_c$, and $k_{id}$ to generate encrypted entries \((u, v)\) and \((u', v')\) for $w$. In particular, the first encrypted entry, with \((u, v) \leftarrow (H_2(k_{id}, \text{id}), \text{Enc}(k_{id}, \text{id}))\), holds the mapping between $c$ and $id$ to allows the server retrieves $id$ based on given $u$ and $k_{id}$. The second encrypted entry, with \((u', v') \leftarrow (H_2(k_w, \text{id}), \text{Enc}(k_c, \text{c}))\), hides the state $c$ of documents. In this way, the client can retrieve the state $c$ of deleted documents upon sending $u'$ in search operation. In our protocols, $H_1$ and $H_2$ are hash functions, and $\text{Enc}$ is a symmetric encryption cipher. We note that enclave only sends a batch of \((T_1, T_2)\) to the server within one \textit{recall} per a document addition, where $T_1 = \{(u_{w_1}, v_{w_1}), \ldots, (u_{w_{|D|}}, v_{w_{|D|}})\}$ and $T_2 = \{(u'_{w_1}, v'_{w_1}), \ldots, (u'_{w_{|D|}}, v'_{w_{|D|}})\}$. Then, the server will update $T_1$ and $T_2$ to $M_I$ and $M_s$, respectively. If the update is deletion, the enclave simply updates $d$ by the deleted $id$ without further computation or communication to the server.
\item \textbf{In search,} the client sends a query $q$ containing $w$ to the enclave via the secure channel and expects to receive all the current (non-deleted) documents matching $w$ from the server. The enclave begins loading deleted encrypted documents in $d$ from the server in a sequential manner. By using $k_f$, the enclave decrypts those documents for checking the existence of $w$, and updating $D[w]$ if applicable. By leveraging $D[w]$, the enclave can retrieve the state list $st_{w_u} = \{c_{id}^d\}$, where $c_{id}^d$ is the state used when the enclave added the deleted document $id$ for $w$. After that, the enclave simply infers the states of non-deleted documents by excluding $st_{w_u}$ from the set of \(\{0, \ldots, ST[w]\}\). Finally, the enclave will compute the
query token $u$ and $k_{id}$ for these non-deleted documents, and send the list $Q_w = \{(u, k_{id})\}$ to the server. At the server, upon receiving $Q_w$, it can retrieve $id$, when decrypting $M_f[u]$ with $k_{id}$. Finally, the server returns the encrypted documents $Res = \{R[id]\}$ to the client.

Efficiency of SGX-SE1: In update, SGX-SE1 only takes $n_w$ ocalls to add all $n$ documents containing $w$ to the server, and no ocall for deletion due to the caching of deleted documents within the enclave. That efficiency outperforms Bunker-B since the latter requires an additional ocall per a deletion. However, we note that the asymptotic performance of SGX-SE1 is affected by $(d + d_w)$ search roundtrips. In particular, the enclave needs to load and decrypt deleted documents within the enclave. Thus, the search performance really depends on how large the number of deleted documents is at the query time. We will later compare our search latency with Bunker-B in Section VI.

E. SGX-SE2 Construction

According to Table 1, SGX-SE1 has $(d + d_w)$ search roundtrips and non-trivial $O(n_w + d)$ computation. One downside is that the enclave needs to spend time on decrypting deleted documents. Here, we present SGX-SE2, an advanced version of SGX-SE1, that reduces search roundtrips to $d_w$ and achieves better asymptotic and concrete search time $O(n_w + v_d)$. The main solution we make to SGX-SE2 is that we use a Bloom filter $BF$ within the enclave to verify the mapping between query keyword $w$ and deleted document $id$. In this way, SGX-SE2 avoids loading them from the server. Since $BF$ is a probabilistic data structure, we can configure it to achieve a negligible false positive rate $P_c$ (see Section VI). In Algorithm 2, we highlight the solution of SGX-SE2. We summarily introduce SGX-SE2 as follows:

In setup, SGX-SE2 is almost the same with that one in SGX-SE1 with the exception that the client also requires to initialise the parameters of $BF$. They are, $k_{BF}$, $b$, and $h$, where $k_{BF}$ is the key for computing the hashed value of $(w||id)$,
Algorithm 2: Protocols in SGX-SE2. The new instructions of SGX-SE2 is in blue

1. \textbf{Setup}(λ):
2. \hspace{1em} Performs the same \textbf{Setup} in SGX-SE1;
3. \hspace{1em} Client initialises \( k_{BF} \leftarrow \{0, 1\}^λ \) and integers \( b, h \);
4. \hspace{1em} Client provisions \( (k_{BF}, b, h) \) to enclave;
5. \hspace{1em} Enclave selects \( \{H_j\}_{j \in [b]} \) for \( BF \);
6. \hspace{1em} Enclave initialises \( BF \leftarrow 0^b \);
7. \hspace{1em} Enclave does not maintain \( D \);
8. \textbf{Update}(op, in):
9. \hspace{1em} Performs the same \textbf{Update} in SGX-SE1;
10. \hspace{1em} if \( op=\text{add} \) then
11. \hspace{2em} for \( (w, id) \) do
12. \hspace{3em} for \( j = 1 : h \) do
13. \hspace{4em} \( h_j(w, id) \leftarrow H_j(k_{BF}, w || id) \)
14. \hspace{4em} \( BF[h_j(w, id)] \leftarrow 1 \);
15. \hspace{3em} end
16. \hspace{2em} end
17. \hspace{1em} end
18. \textbf{Search}(w):
19. \hspace{1em} Replacing lines 4-18 in \textbf{Search} in SGX-SE1 with following lines 20-29:
20. \hspace{1em} for \( id \in d \) do
21. \hspace{2em} if \( BF[H_j(k_{BF}, w || id)]_{j \in [b]} = 1 \) then
22. \hspace{3em} \( u' \leftarrow H_3(k_{w}, id) \);
23. \hspace{3em} \( v' \leftarrow M_j[u'] \);
24. \hspace{3em} \( c \leftarrow \text{Dec}(k_{w}, v') \);
25. \hspace{3em} \( st_w, \leftarrow \{c\} \cup st_w \);
26. \hspace{3em} delete \( M_j[u'] \);
27. \hspace{3em} delete \( R[id]; \text{ll delete doc} \)
28. \hspace{2em} end
29. \hspace{1em} end

and \( b \) is the number of bits in the BF vector (i.e., vector size), and \( h \) is the number of hash functions. Upon receiving the BF setting, the enclave initialises the BF and the set of hash functions \( \{H_j\}_{j \in [b]} \). In SGX-SE2, the mapping \( D \) between keywords and deleted \( ids \) is no longer needed within the enclave like that one in SGX-SE1.

In update, SGX-SE2 is also similar with SGX-SE1. However, if the update is addition, the enclave will compute a new member \( H_j(k_{BF}, w || id) \) to update BF.

In search, SGX-SE2 verifies the mapping between query keyword \( w \) and deleted \( ids \) by checking the membership of \( (w||id) \) with BF. If the mapping is valid, SGX-SE2 performs the same as SGX-SE1 to retrieve the state list \( st_w, = \{c^{del}_{id}\} \), where \( c^{del}_{id} \) is the state used for deleted \( ids \). After that, the enclave infers the states of non-deleted documents and computes query tokens to send to the server.

\textbf{Efficiency of SGX-SE2}: The scheme clearly outperforms SGX-SE1 in terms of search computation and communication roundtrips due to the usage of the Bloom filter. It avoids loading \( d \) deleted documents into the enclave, making the search roundtrip only \( d_{w} \). The scheme is even more efficient when \( |d| \) is large. The reason is that the cost of verifying a membership \( (w||id) \) is always \( O(1) \) under the fixed BF setting.

We note that checking \( d \) members in the BF is still more efficient than loading/decrypting their real documents. BF is also memory-efficient; therefore, one can configure its size to balance the enclave memory with the demand of large datasets.

\section{Security Analysis}

The only difference between SGX-SE1 and SGX-SE2 in term of security is that SGX-SE1 requires to load encrypted deleted documents to the enclave during the search. Therefore, our following analysis is almost identical to both schemes. We will state the difference between them wherever is necessary.

We denote \( D \) as our general scheme that could be SGX-SE1 or SGX-SE2. The security of \( D \) can be quantified through a stateful leakage function \( \mathcal{L} = (\mathcal{L}^{\text{Set}}, \mathcal{L}^{\text{Updt}}, \mathcal{L}^{\text{Srch}}, \mathcal{L}^{\text{hw}}) \). The first three components define the information exposed in \textbf{Setup}, \textbf{Update}, and \textbf{Search}, respectively. The latter one, \( \mathcal{L}^{\text{hw}} \), defines the inherent leakage of the used SGX enclave with the outputs from the enclave to the server. We now define \( \mathcal{L} \) and then formalise our security with analysis.

In \textbf{Setup}, \( D \) leaks nothing to the server except the data structure of \( M_I \) (i.e., the encrypted index), \( M_e \) (i.e., the encrypted map of keyword states), \( R \) (i.e., the empty repository of encrypted documents).

In \textbf{Update}(op = add, in), \( D \) leaks the data access pattern of encrypted entries to be inserted in \( M_I, M_e \), and \( R \). Otherwise, if \( op = \text{del} \), \( D \) leaks nothing under the secure channel established in \textbf{Setup}. Hence,

\[ \mathcal{L}^{\text{Updt}}(\{(op, in)\}) = \{(T_1, T_2, R[id_i])\} \]

where \( T_1 = \{(u, v)\} \) and \( T_2 = \{(u', v')\} \) present the collections of entries to be inserted in \( M_I \) and \( M_e \) respectively, and \( R[id_i] \) denotes an encrypted document to be inserted in \( R \) with label \( id_i \).

In \textbf{Search}(w), \( D \) leaks 1) the access pattern on \( M_e \) when the enclave queries the deleted states of \( w \), named \( \text{ap}_{M_e}(w) \), 2) the access pattern on \( M_I \) when the enclave queries non-deleted \( ids \), named \( \text{ap}_{M_I}(w) \), if \( D \) is SGX-SE1, and 3) the pattern on deleted documents \( d_w \), named \( \text{ap}_{R}(d_w) \). Then, formally

\[ \mathcal{L}^{\text{Srch}}(w) = \text{ap}_{M_e}(w) + \text{ap}_{M_I}(w) + |\text{ap}_{R}(d_w)| \]

We define \( \mathcal{L}^{\text{hw}}(M_I, M_e, R) \) as the hardware leakage during \textbf{Update} and \textbf{Search}. That includes memory access and location, the time log, and the size of the manipulated memory area.

\[ \mathcal{L}^{\text{hw}}(M_I, M_e, R) = (M_I, M_e, R)^{\text{Updt}} + (M_I, M_e, R)^{\text{Srch}} \]

This function outputs the trace \( \tau \) of \( (l, T, v, t) \), where \( l \) is the label input, \( T \) is a map data structure that could be \( M_I, M_e \), and \( R \), \( v \) is the value at \( T[l] \), and \( t \) is the time access of \( op \).

W.r.t. SGX-SE1, if \( l \) is an \( id \), the function will output the encrypted document \( e \) and the document size \( |e| \).

\textbf{Definition 1}: Let \( D \) denote our scheme that consists of three protocols \textbf{Setup}, \textbf{Update}, and \textbf{Search}. Consider the
probabilistic experiments \( \text{Real}_A(\lambda) \) and \( \text{Ideal}_{A,S}(\lambda) \), whereas \( A \) is a stateful adversary, and \( S \) is a stateful simulator that gets the leakage function \( L \).

\( \text{Real}_A(\lambda) \): The challenger runs \( \text{Setup}(1^\lambda) \) that involves the client, the enclave, and the server to initialise necessary data structures as presented in Figure [2]. \( A \) chooses a database \( DB = \{ \text{doc}_i \}_{i \in Z} \) and makes a polynomial number of updates (addition/deletion) with \( (\text{op}, \text{in}) \), where \( Z \) is a natural number of documents, and \( (\text{op} = \text{add}, \text{in} = \text{doc}_i) \) or \( (\text{op} = \text{del}, \text{in} = \text{id}_i) \). Accordingly, the challenger runs those updates with \( \text{Update}(\text{op}, \text{in}) \) and eventually returns the tuple \( (M_i, M_c, R)^{\text{update}} \) to \( A \). After that, \( A \) adaptively chooses the keyword \( w \) (resp. \( (\text{op}, \text{in}) \)) to search (resp. update). In response, the challenger runs \( \text{Search}(w) \) (resp. \( \text{Update}(\text{op}, \text{in}) \)) and returns the transcript of each operation. The challenger also returns \( (M_i, M_c, R)^{\text{search}} \) to \( A \). Finally, \( A \) outputs a bit \( b \).

\( \text{Ideal}_{A,S}(\lambda) \): \( A \) chooses a \( DB = \{ \text{doc}_i \}_{i \in Z} \). By using \( L^{\text{update}} \) and \( (M_i, M_c, R)^{\text{update}}, S \) creates a tuple of \( (M_i, M_c, R) \) and passes it to \( A \). Then, \( A \) adaptively chooses the keyword \( w \) (resp. \( (\text{op}, \text{in}) \)) to search (resp. update). The challenger returns the transcript simulated by \( S(L^{\text{search}}(w)) \) (resp. \( S(L^{\text{update}}(\text{op}, \text{in})) \)) with \( (M_i, M_c, R)^{\text{search}} \). Finally, \( A \) returns a bit \( b \).

We say \( D \) is \( L \)-secure against adaptive chosen-keyword attacks if for all probabilistic polynomial-time algorithms \( A \), there exist a PPT simulator \( S \) such that

\[
|Pr[\text{Real}_A(\lambda) = 1] - \Pr[\text{Ideal}_{A,S}(\lambda) = 1]| \leq \text{negl}(\lambda)
\]

Theorem 1: The scheme \( D \) presented above is \( L \)-secure according to Def. [1].

We now prove Theorem 1 by describing a PPT simulator \( S \) for which a PPT adversary \( A \) can distinguish \( \text{Real}_A(\lambda) \) and \( \text{Ideal}_{A,S}(\lambda) \) with negligible probability.

Proof: \( S \) first generates a random key \( \tilde{K} = (\tilde{k}_2, \tilde{k}_I) \) to simulate the key components that the enclave contains (see Figure [2]). Then, \( A \) executes \( \text{Search}(w) \) with \( w \), which is a random keyword, in order to obtain a query token \( q \) sent by the enclave. Then, \( A \) simulates addition tokens \( a \) for \( w \) based on \( K \) and \( L^{\text{new}}(M_i, M_c, R) \), and sends them to the enclave to receive the new update of \( (M_i, M_c, R) \). However, \( A \) cannot map which update token in \( a \) relates to \( q \). The reason is that the enclave keeps increasing the state \( ST[w] \). Hence, \( A \) cannot distinguish between the output of \( \text{Real}_A(\lambda) \) and the simulated output in \( \text{Update} \) and \( \text{Search} \) (forward privacy).

During \( \text{Search} \), if there were delete updates made in the past on deleted documents \( d \) with identifier list \( \{id_i\} \), \( A \) cannot know which keywords are inside the encrypted doc \( R[id_i] \). Also, \( A \) does not know when delete updates made since the enclave only requests \( d \) during \( \text{Search} \). The \( \text{ap}_{M_c}(w) \) does not reveal \( id_i \) (see \( \text{Search} \) in Fig [2]). However, \( A \) knows the time when the entry relating \( id_i \) added to \( \text{ap}_{M_c} \) via \( L^{\text{new}} \), and how many \( id_i \) in \( d \). Clearly, at the end of the protocol \( A \) knows how many current (non-deleted) \( id \) accessed. Hence, \( D \) is type-II backward privacy.

### VI. Implementation and Evaluation

**Experiment setup and implementation:** For evaluation, we choose two datasets: One is a synthesis dataset (3.2 GB) generated from the English keyword frequency data based on the Zipf’s law distribution, and the other one is the Enron email dataset (1.4 GB). A summary of the statistical features of the datasets is given in Table II.

We build the prototype of SGX-SE1 and SGX-SE2 using C++ and the Intel SGX SDK. In addition, we implement the prototype of Bunker-B as the baseline for comparisons, since its implementation is not publicly available. The prototype leverages the built-in cryptographic primitives in the SGX SDK to support the required cryptographic operations. It also uses the settings and APIs from the SDK to create, manage and access the application (enclave) designed for SGX. Recall that the SGX can only handle 96 MB memory within the enclave. Access to the extra memory space triggers the paging mechanism of the SGX, which brings an extra cost to the system (average 5 \times as reported in [41]). To avoid paging in our prototype, our prototypes are implemented with batch processing to tackle with the keyword-document pairs, which splits a huge memory demand into multiple batches with smaller resource requests. The batch processing enables our prototypes to handle queries with large memory demands.

On the other hand, the prototype should avoid too many \( \text{ecall} \)s/\( \text{locals} \) as it incurs the I/O communication cost between the untrusted and the trusted application (enclave). In the following experiments, we set the batch size to 100,000 for all schemes, which can avoid triggering paging while minimising the number of \( \text{ecall} \)locals in the system.

The prototypes are deployed in a workstation equipped with SGX-enabled CPU (Intel Core i7-8850H 2.6 GHz) and 32 GB RAM.

#### A. Performance evaluation on the synthesis dataset

**Insertion and deletion:** First, we evaluate the time for insertion and deletion under three different schemes. In this evaluation, we follow a reversed Zipf’s law distribution to generate the encrypted database of our synthesis dataset, and we measure the runtime for adding one keyword-document pair into the encrypted database of different schemes. As shown in Table III, Bunker-B takes 21 \( \mu \)s to insert one pair, which is faster than our schemes (23 \( \mu \)s and 26 \( \mu \)s) when
the number of keyword-document pairs equals the number of documents. The reason is that the insertion time of the above three schemes is bounded by the I/O (eccall/localcall) between the untrusted application and the enclave. For Bunker-B, the I/O cost is linear to the number of keyword-document pairs (see Section IV-C for details), while the one for our schemes is linear to the number of documents. Also, our schemes involve more computations (PRF, Hash) and maintain more data structures (Bloom filter), which require more time to be processed. Nonetheless, when inserting $1 \times 10^6$ documents, our schemes only require 7 µs and 8 µs respectively to insert one keyword-document pair, which is $2 \times$ faster than Bunker-B (12 µs). In the above case, the number of keyword-document pairs is $10 \times$ larger than the number of documents, which implies that Bunker-B needs $10 \times$ more I/O operations (eccall/localcall) to insert the whole dataset comparing to our schemes (see Table IV for details). Note that the real-world document typically consists of more than one keyword. Hence, our schemes are more efficient than Bunker-B when dealing with a real-world dataset (see Section VI-B).

For deletion, the performance of Bunker-B is identical to that for insertion (12 µs), because deletion runs the same algorithm with different operations. For our schemes, the deletion process only inserts the document id into a list, and the deletion operation is executed by excluding the deleted id during the query phase. Thus, our schemes only need 4 µs to process one document in the deletion phase.

**Query delay:** Next, we report the query delay comparison between Bunker-B and our schemes to show the advantage of using SGX-SE1 and SGX-SE2. To measure the query delay introduced by keyword frequency and the deletion operation, we choose to query the top-25 keywords after deleting a portion of documents. In our first evaluation, we insert $2.5 \times 10^5$ documents and delete 25%, 50% and 75% of the documents, respectively. Fig. 3 illustrates the query delays when deleting 25% of documents: For the most frequent keyword, Bunker-B needs 1.3 s to query while SGX-SE2 only needs 654 ms. Although SGX-SE1 takes 5 s to perform the first search, it also caches the deleted keyword-document pairs inside the enclave and performs deletion on documents during the first query. As a result, the rest of the queries are much faster, as the number of ocalls is significantly reduced (900 µs if we query the most frequent keyword again). Even for the 25-th most frequent keyword, SGX-SE1 (159 ms) and SGX-SE2 (155 ms) are still $40 \times$ faster than Bunker-B (221 ms). Bunker-B is always slower than SGX-SE1 and SGX-SE2 in the above case as it requires to re-encrypt the remaining 75% documents after each query. Compared to Bunker-B, SGX-SE1 and SGX-SE2 only access the deleted 25% files and exclude the corresponding token of deleted files before sending the token list (see Section IV-E). With the increase of the deletion portion, the difference of the query delay between our schemes and Bunker-B becomes smaller as Bunker-B has fewer documents to be re-encrypted after queries. When 75% of the documents are deleted, our schemes still outperform Bunker-B when querying the keywords with a higher occurrence rate (see Fig. 5). However, their performances are almost the same when querying the 25-th most frequent keyword, i.e., about 400 ms for three schemes, because Bunker-B only re-encrypts a tiny amount of document id (almost 0).

The second evaluation shows the query delay when inserting all $1 \times 10^6$ documents into the encrypted database. The major difference between this experiment and the previous one is that the SGX-SE1 scheme requires more than 128 MB to cache the deleted documents, which triggers paging. As shown in Fig. 4a, SGX-SE1 needs 10 s to cache the deleted documents. When processing the query that contains a large number of documents (e.g., the second most frequent keyword), SGX-SE1 (2.4 s) is almost $2 \times$ slower than SGX-SE2 (1.4 s). Nonetheless, their query performance is still better than Bunker-B, which takes 3.2 s to answer the above query. When our schemes delete a larger portion of documents (see Fig. 4b and Fig. 4c), the query delay of SGX-SE1 and SGX-SE2 is very close, since SGX-SE1 only refers to the small deletion information cached in the enclave while SGX-SE2 requires to check the Bloom filter for each deleted document.

**Communication cost:** The next evaluation demonstrates the impact of I/O operation (eccall/localcall) on the performance of different schemes. As shown in Table IV, Bunker-B needs $10 \times$ more eccall/localcall operations than our schemes. Consequently, although both Bunker-B and our schemes generate and store the encrypted keyword-document pairs at the end, our schemes can achieve a better performance for insertion, because our schemes rely on less I/O operations. This result is consistent with the average insertion time reported in the insertion and deletion part. In terms of the deletion operation, Bunker-B needs almost $30 \times$ more I/O operation than ours (see Table V). Moreover, the deletion in our schemes only

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**Table IV:** Number of eccall/localcall for adding $1 \times 10^6$ documents for different schemes.

| Deletion % | Bunker-B | SGX1 | SGX2 |
|------------|----------|------|------|
|            | eccall | localcall | eccall | localcall | eccall | localcall |
| 25%        | 1.18 $\times 10^6$ | 1 $\times 10^6$ | 1 $\times 10^6$ | 1 $\times 10^6$ | 1 $\times 10^6$ | 1 $\times 10^6$ |
| 50%        | 1.12 $\times 10^6$ | 1.1 $\times 10^6$ | 5 $\times 10^6$ | 0 | 5 $\times 10^6$ | 0 |
| 75%        | 1.16 $\times 10^6$ | 1.16 $\times 10^6$ | 7.5 $\times 10^6$ | 0 | 7.5 $\times 10^6$ | 0 |

**Table V:** Number of eccall/localcall for deleting a portion of documents after adding $1 \times 10^6$ documents.

| Deletion % | Bunker-B | SGX1 | SGX2 |
|------------|----------|------|------|
|            | eccall | localcall | eccall | localcall | eccall | localcall |
| 25%        | 1 | 2 | 1 | 290,011×11 | 1 | 11 |
| 50%        | 1 | 20 | 1 | 590,011×10 | 1 | 10 |
| 75%        | 1 | 21 | 1 | 790,011×11 | 1 | 11 |

*: It includes the ocall for caching and deleting the encrypted documents.
TABLE VII: Average time (\(\mu s\)) for adding a keyword-doc pair from Enron dataset and removing 25\% documents under different schemes.

| Operation          | Bunker-B | SGX-SE1 | SGX-SE2 |
|--------------------|----------|---------|---------|
| Insertion          | 12       | 7       | 8       |
| Deletion (25\%, 129,305 documents) | 12 | 4 | 4 |

to store the necessary information for deletion. For SGX-SE1, it caches all the document id in the enclave, which leads to notably high memory usage (e.g., 304 MB when deleting 25\% documents, and 355 MB when deleting 75\%). The memory resource requests in SGX-SE1 triggers the paging mechanism of the SGX, resulting in a larger query delay as presented above. SGX-SE2 successfully prevents the paging by using the Bloom filter. After applying a Bloom filter with the false positive rate \(10^{-4}\), SGX-SE2 only needs 34 MB to store all keyword-document pairs (1.18 \times 10^7 pairs) and maintains a low query delay over the large dataset.

### B. Performance evaluation on the Enron dataset

We use a real world dataset to illustrate the practicality of the proposed scheme. Since the bulk deletion (e.g. delete 50\%) is rare in the real world, we only focus on the setting with a small deletion portion. Therefore, in the following experiments, we insert the whole Enron dataset and test the average runtime for insertion/deletion as well as the query delay with a small deletion portion (25\%).

**Insertion and deletion:** As described in Section VI-A our schemes are more efficient for the insertion and deletion if the number of keyword-document pairs is larger than the number of documents. The evaluation result on the Enron dataset further verifies our observation: as shown in Table VII our schemes only need 7 \(\mu s\) and 8 \(\mu s\) respectively to insert one keyword-document pair while Bunker-B needs 12 \(\mu s\) to do
In this paper, we leverage the advance of Intel SGX to design and implement forward and backward private dynamic searchable encryption schemes. We carefully analyse the limitations of the recent theoretical constructions and propose new designs to avoid the bottleneck of the SGX enclave. We present a basic scheme and then further optimise it for better performance. We implement prior work and our schemes, and conduct a detailed performance comparison. The results show that our designs are more efficient in query latency and data deletion.

VII. Conclusion

REFERENCES

[1] G. Amjad, S. Kamara, and T. Moatuz, “Forward and Backward Private Searchable Encryption with SGX,” in EuroSec ’19, 2019.
[2] V. Bindschaedler, P. Grubbs, D. Cash, T. Ristenpart, and V. Shmatikov, “The Tao of Inference in Privacy-protected Databases,” Proc. VLDB Endow., vol. 11, no. 11, pp. 1715–1728, 2018.
[3] G. Borges, H. Domingos, B. Ferreira, J. Leito, T. Oliveira, and B. Portela, “BISEN: Efficient Boolean Searchable Symmetric Encryption with Verifiability and Minimal Leakage,” Cryptology ePrint Archive, Report 2018/588, 2018.
[4] R. Bost, “Sophos - Forward Secure Searchable Encryption,” in ACM CCS’16, 2016.
[5] R. Bost, P.-A. Fouque, and D. Pointcheval, “Verifiable Dynamic Symmetric Searchable Encryption: Optimality and Forward Security,” Cryptology ePrint Archive, Report 2016/062, 2016.
[6] R. Bost, B. Minaud, and O. Ohrimenko, “Forward and Backward Private Searchable Encryption from Constrained Cryptographic Primitives,” in ACM CCS’17, 2017.
[7] F. Brasser, S. Capkun, A. Dimitrienko, T. Frassetto, K. Kostiainen, and A.-R. Sadeghi, “DR.SGX: Automated and Adjustable Side-Channel Protection for SGX using Data Location Randomization,” in ACSAC’19, 2019.
[8] F. Brasser, U. Müller, A. Dimitrienko, K. Kostiainen, S. Capkun, and A.-R. Sadeghi, “Software Grand Exposure: SGX Cache Attacks Are Practical,” in USENIX WOOT’17, 2017.
[9] D. Cash, P. Grubbs, J. Perry, and T. Ristenpart, “Leakage-Abuse Attacks against Searchable Encryption,” in ACM CCS 15, 2015.
[10] D. Cash, J. Jaeger, S. Jarecki, and C. Jutla, “Dynamic Searchable Encryption in Very-Large Databases: Data Structures and Implementation,” in NDSS’14, 2014.
[11] D. Cash, J. Jaeger, S. Jarecki, C. Jutla, H. Krawczyk, M.-C. Rosu et al., “Dynamic Searchable Encryption in Very Large Databases: Data Structures and Implementation,” in NDSS’14, 2014.
[12] D. Cash, S. Jarecki, C. Jutla, H. Krawczyk, M.-C. Rosu, and M. Steiner, “Highly-Scalable Searchable Symmetric Encryption with Support for Boolean Queries,” in CRYPTO’13, 2013.
[13] D. Cash and S. Tessaro, “The Locality of Searchable Symmetric Encryption,” in EUROCRYPT’14, 2014.
[14] P. Christian, V. Kapil, and C. Manuel, “EnclaveDB: A Secure Database using SGX,” in IEEE S&P’18, 2018.
[15] V. Costan, I. Lebedev, and S. Devadas, “Sanctum: Minimal Hardware Extensions for Strong Software Isolation,” in USENIX Security ’16, 2016.
[16] R. Curtmola, J. Garay, S. Kamara, and R. Ostrovsky, “Searchable Symmetric Encryption: Improved Definitions and Efficient Constructions,” in ACM CCS’06, 2006.
[17] I. Demertzis, D. Papadopoulos, and C. Papamanthou, “Searchable Encryption with Optimal Locality: Achieving Sublogarithmic Read Efficiency,” in CRYPTO 18, 2018.
[18] I. Demertzis, S. Papadopoulos, O. Papapetrou, A. Deligiannakis, and M. Garofalakis, “Practical Private Range Search Revisited,” in ACM SIGMOD’16, 2016.
[19] I. Demertzis and C. Papamanthou, “Fast Searchable Encryption with Tunable Locality,” in ACM SIGMOD’17, 2017.
[20] I. Demertzis, R. Talapatra, and C. Papamanthou, “Efficient Searchable Encryption Through Compression,” Proc. VLDB Endow., vol. 11, no. 11, pp. 1729–1741, 2018.
[21] H. Duan, C. Wang, X. Yuan, Y. Zhou, Q. Wang, and K. Ren, “LightBox: Full-stack Protected Stateful Middlebox at Lightning Speed,” in ACM CCS’19, 2019.

[22] B. Fisch, D. Vinayagamurthy, D. Boneh, and S. Gorbunov, “IRON: Functional Encryption Using Intel SGX,” in ACM CCS’17, 2017.

[23] B. Fuhr, R. Bahmani, F. Brasser, F. Hahn, F. Kerschbaum, and A. Sadeghi, “HardIDX: Practical and Secure Index with SGX,” in DBSec’17, 2017.

[24] J. Ghareh Chamani, D. Papadopoulos, C. Papamanthou, and R. Jalili, “New Constructions for Forward and Backward Private Symmetric Searchable Encryption,” in ACM CCS’18, 2018.

[25] J. Götzfried, M. Eckert, S. Schinzel, and T. Müller, “Cache Attacks on Intel SGX,” in EuroSec’17, 2017.

[26] D. Gruss, J. Lettner, F. Schuster, O. Ohrimenko, I. Haller, and M. Costa, “Strong and Efficient Cache Side-channel Protection Using Hardware Transactional Memory,” in USENIX Security’17, 2017.

[27] M. Hähnel, W. Cui, and M. Peinado, “High-Resolution Side Channels for Untrusted Operating Systems,” in USENIX ATC’17, 2017.

[28] S. Kamara, C. Papamanthou, and T. Roeder, “Dynamic Searchable Symmetric Encryption,” in ACM CCS’12, 2012.

[29] S. Lai, S. Patranabis, A. Sakzad, J. K. Liu, D. Mukhopadhyay, R. Steinfeld et al., “Result Pattern Hiding Searchable Encryption for Conjunctive Queries,” in ACM CCS’18, 2018.

[30] X. Lei, A. X. Liu, R. Li, and G. Tu, “SecEQP: A Secure and Efficient Scheme for SkNN Query Problem Over Encrypted Geodata on Cloud,” in IEEE ICDE’19, 2019.

[31] R. Li, A. X. Liu, A. L. Wang, and B. Bhushadhuvar, “Fast Range Query Processing with Strong Privacy Protection for Cloud Computing,” Proc. VLDB Endow., vol. 7, no. 14, pp. 1953–1964, 2014.

[32] F. McKeen, I. Alexandrovich, A. Berenzon, C. V. Rozas, H. Shafi, V. Shanbhogue et al., “Innovative Instructions and Software Model for Isolated Execution,” in HASP’13, 2013.

[33] P. Mishra, R. Poddar, J. Chen, A. Chiesa, and R. A. Popa, “Oblix: An Efficient Oblivious Search Index,” in IEEE S&P’18, 2018.

[34] M. Naveed, S. Kamara, and C. V. Wright, “Inference Attacks on Property-Preserving Encrypted Databases,” in ACM CCS’15, 2015.

[35] O. Oleksenko, B. Trach, R. Krahn, A. Martin, C. Fetzer, and M. Silverstein, “Varys: Protecting SGX Enclaves from Practical Side-channel Attacks,” in USENIX ATC’18, 2018.

[36] S. Shinde, Z. L. Chua, V. Narayanan, and P. Saxena, “Preventing Page Faults from Telling Your Secrets,” in ACM AsiaCCS’16, 2016.

[37] D. Song, D. Wagner, and A. Perrig, “Practical Techniques for Searches on Encrypted Data,” in IEEE S&P’00, 2000.

[38] E. Stefanov, C. Papamanthou, and E. Shi, “Practical Dynamic Searchable Symmetric Encryption with Small Leakage,” in NDSS’14, 2014.

[39] E. Stefanov, M. van Dijk, E. Shi, T.-H. H. Chan, C. Fletcher, L. Ren et al., “Path ORAM: An Extremely Simple Oblivious RAM Protocol,” in ACM CCS’13, 2013.

[40] S.-F. Sun, X. Yuan, J. Liu, R. Steinfeld, A. Sakzad, V. Vo et al., “Practical Backward-Secure Searchable Encryption from Symmetric Puncturable Encryption,” in ACM CCS’18, 2018.

[41] M. Taassori, A. Shafiee, and R. Balasubramanian, “VAULT: Reducing Paging Overheads in SGX with Efficient Integrity Verification Structures,” in ACM ASPLOS’18, 2018.

[42] S. Wu, Q. Li, G. Li, D. Yuan, X. Yuan, and C. Wang, “ServeDB: Secure, Verifiable, and Efficient Range Queries on Outsourced Database,” in IEEE ICDE’19, 2019.

[43] Y. Xu, W. Cui, and M. Peinado, “Controlled-Channel Attacks: Deterministic Side Channels for Untrusted Operating Systems,” in IEEE S&P’15, 2015.

[44] Y. Yarom and K. Falkner, “FLUSH+RELOAD: A High Resolution, Low Noise, L3 Cache Side-Channel Attack,” in USENIX Security’14, 2014.

[45] Y. Zhang, J. Katz, and C. Papamanthou, “All Your Queries Are Belong to Us: The Power of File-Injection Attacks on Searchable Encryption,” in USENIX Security’16, 2016.