SACK: Shielding Dynamic Attribute-based Access Control in Persistent Key-Value Stores

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ABSTRACT

Enforcing fine-grained access control is critical for secure key-value (KV) stores in cloud environments, yet classical attribute-based encryption incurs significant overhead. We present SACK, a shielded framework leveraging Intel SGX to enable efficient, dynamic attribute-based access control (ABAC) for KV stores in untrusted cloud environments, while ensuring confidentiality, integrity, and freshness. SACK decouples access control and data management by performing ABAC with hardware-assisted shielded execution and leveraging KV separation for secure, efficient, and crash-consistent KV storage. We implement SACK as a middleware system that can run atop general KV stores. Experiments show that SACK achieves high-performance KV operations and lightweight renewal of access rights.

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The source code, data, and/or other artifacts have been made available at https://github.com/adslabcuhk/sack.

1 INTRODUCTION

Modern cloud providers use high-performance persistent key-value (KV) stores to structurally organize data in KV pairs and serve multiple users in shared environments [24, 62, 82]. However, deploying KV stores in the cloud raises vital security concerns. First, there is a risk of unauthorized access to sensitive data by different users that have access to the same KV store [6]. While cloud providers isolate data across users with logical partitioning [10], the risk remains when users share the same physical infrastructure [79, 83, 97]. Second, cloud providers are often considered *untrusted* [74, 89]. Since cloud administrators have full control of storage infrastructure, insider threats are prevalent [15]. There are also concerns that legal frameworks (e.g., the CLOUD Act [66]) allow governments to request access to user data in the cloud without notifying affected users [32].

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This motivates us to protect cloud-hosted KV stores with *attribute-based access control (ABAC)* [28, 41], which provides fine-grained access management and prevents unauthorized access *without trusting the cloud*. ABAC characterizes a user's access rights by multiple *attributes* and defines access rules for KV pairs by *policies*. Users can access specific KV pairs only if their attributes satisfy a specified policy (see Section 2.1 for details). Enforcing ABAC on encrypted KV pairs can be done by *attribute-based encryption (ABE)* [11, 36, 73, 80], a public-key cryptographic primitive that encrypts data based on a policy and allows only authorized users (i.e., neither unauthorized users nor cloud providers) to decrypt data.

ABE, however, incurs substantial performance overhead. First, ABE relies on computationally expensive public-key cryptography, whose overhead increases as policy complexity grows. Also, ABE embeds policies into encrypted outputs and increases storage overhead. Furthermore, when a user's attributes are updated, ABE must re-issue private keys to other users sharing the same updated attributes and re-encrypt affected KV pairs, leading to excessive computational overhead [42, 95].

We present SACK, a shielded framework that enables efficient, dynamic ABAC for KV stores in untrusted cloud environments, while preserving essential security guarantees including confidentiality (i.e., data remains inaccessible to unauthorized parties), integrity (i.e., data remains intact), and freshness (i.e., only up-to-date data is processed). SACK's core idea is to decouple access control and data management. It leverages Intel Software Guard Extensions (SGX) [49] to manage attributes and policies and realize ABAC inside a hardware-assisted trusted execution environment (called an enclave). It extends KV separation [59] with security protection by storing the keys and metadata of KV pairs separately from values in different secure storage areas. It maintains high performance in core KV operations, including writes (i.e., inserting new KV pairs), reads (i.e., retrieving KV pairs by specific keys), scans (i.e., retrieving KV pairs over a key range; a.k.a. range queries), and updates (i.e., updating KV pair values). The shielded ABAC approach necessitates re-designs of garbage collection and crash consistency, which SACK addresses with security and efficiency guarantees.

SACK is implemented as a middleware system that can run atop general KV stores. As a case study, we deploy SACK atop RocksDB [27] and compare SACK with the state-of-the-art shielded KV store TWEEZER [51], which achieves confidentiality, integrity, and freshness, but without ABAC. SACK reduces the average write and read latencies of ABE's software implementation by 79.9% and 92.8% under a single attribute and policy, respectively. It also achieves throughput gains of 1.9× in update-heavy workloads and 5.4× in read-only workloads over TWEEZER, albeit being worse than TWEEZER in scans, and supports fast renewal of access rights.

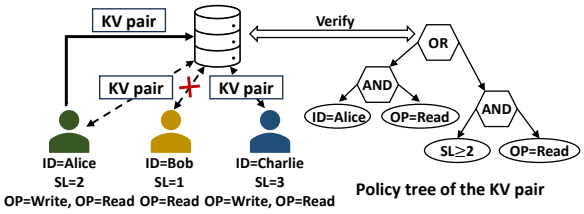


Figure 1: Example of ABAC.

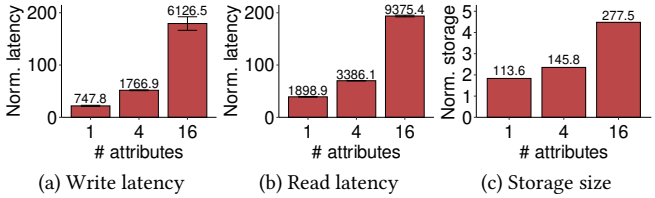


Figure 2: Normalized write latencies, read latencies, and storage size of ABE with respect to without ABE. We report absolute latencies (μs) and storage sizes (GiB) above the bars. Without ABE, the write and read latencies are 34.2μs and 48.4μs, respectively, while the total storage size is 61.9 GiB.

2 BACKGROUND AND MOTIVATION

2.1 Attribute-based Access Control (ABAC)

ABAC is essential for protecting KV stores against unauthorized access, by specifying the access rights of users to KV pairs in the form of *attributes*. We consider an organization with multiple users, where each user is associated with one or multiple attributes. Each attribute is represented as a string (`type=value`) defined by an *administrator* (i.e., a privileged user responsible for managing access rights and the KV store). For example, the administrator can define an attribute of type `identity` for user identification, and a user, say Alice, is assigned an attribute (`identity=Alice`).

Access rights are defined in *policies* represented in the form of a *policy tree*, which combines multiple attributes with logical operators (e.g., `AND` or `OR`). To check if a policy is satisfied, the policy tree recursively computes a Boolean value (true or false) for each node in a bottom-up manner. Each leaf node specifies the condition of an attribute and returns true if a user has an attribute whose value satisfies the condition (or false otherwise). Each non-leaf node represents a logical operator that combines the Boolean results of its corresponding sub-trees. The policy tree grants a user access if the root node returns true.

Figure 1 shows an example of ABAC, where users are associated with three types of attributes: (i) identity (`ID`), which specifies a user's name, (ii) security level (`SL`), a numerical value that specifies a user's privilege to access KV pairs (a higher value implies higher privilege), and (iii) operations (`OP`), which specify permitted operations on KV pairs (e.g., `Read` or `Write`). The policy tree indicates that Alice and Charlie have access rights since their attributes satisfy the conditions of the left and right sub-trees under the root node, respectively. Bob's access is denied since his `ID` does not match `Alice` and his `SL` is below 2.

2.2 Limitations of Attribute-based Encryption

Attribute-based encryption (ABE) [11, 36, 73, 80] is a public-key cryptographic approach for enforcing ABAC in untrusted environments. It encrypts data based on a policy tree, ensuring that only authorized users with permitted attributes can decrypt it, while unauthorized users cannot. At a high level, ABE assigns each user a private key derived from the user's associated attributes. It encrypts a data object based on the policy tree with a public key, and decrypts an encrypted data object only when the attributes for a user's private key match the policy tree. For formal cryptographic treatments of ABE, we refer readers to the literature [11, 36, 73, 80].

Realizing ABE in practical KV stores is non-trivial. We examine a naïve baseline that applies ABE to each KV pair and highlight three deployment-oriented limitations.

High performance overhead. Since ABE relies on public-key cryptography, it incurs much higher computational overhead in encryption and decryption than symmetric-key cryptography. The computational overhead increases with the number of attributes in the policy tree. To justify, we implement ciphertext-policy ABE [11] using OpenABE [96] and define a policy tree that combines attributes with the `AND` operator. We use YCSB [22] to issue ABE-protected reads and writes to RocksDB (v6.14.5) [27]. We load 64 M 1-KiB KV pairs with 24-byte keys and 1,000-byte values. We issue 5 M writes and reads following a Zipf distribution with a Zipfian constant of 0.99 (default in YCSB). To make KV pairs retrievable, we keep the keys of KV pairs intact and only encrypt and decrypt values using ABE. Figures 2(a) and 2(b) show the normalized write and read latencies with respect to without ABE, respectively (see Section 5.1 for testbed details). Even with a single attribute, ABE incurs write and read latency amplifications of 21.9× and 39.2×, respectively. Such amplifications increase with the number of attributes (e.g., 179.4× and 193.7× for 16 attributes), since the policy tree expands and increases encryption and decryption overhead.

High storage overhead. In ABE, each value is encrypted by a public key under a policy and a random factor, such that (i) the policy tree is embedded in the encrypted value to reflect the policy and (ii) identical policy trees or values are mapped to different encryption results for *semantic security* (i.e., an adversary cannot infer the policy and the original value from the encrypted value). Figure 2(c) shows the normalized storage overhead with respect to without ABE. With 16 attributes, the storage blowup is 4.5×.

High attribute update complexity. ABE supports dynamic ABAC via attribute or policy updates. However, affected KV pairs must be re-encrypted under updated attributes and policies [42]. Also, we need trusted key management (which may be a third-party service) to coordinate the attribute update process, which complicates deployment.

2.3 Access Control with Shielded Execution

A natural way to address the limitations of the naïve ABE baseline (Section 2.2) is to use ABE to encrypt a small secret, which then serves as the symmetric key for encrypting the actual KV pairs. The main challenge is to retain strong security guarantees while preserving the performance of modern KV stores under realistic workloads. This motivates the use of *shielded execution*, which creates a hardware-assisted trusted execution environment (TEE) to achieve secure and efficient ABAC while preserving high KV store

performance. We focus on Intel SGX [49], which is supported by modern cloud providers [48] and Intel Xeon platforms [77]. SGX enables target applications to create their own shielded environments for fine-grained security protection, in contrast to other high-overhead TEE technologies (e.g., AMD SEV [2] and Intel TDX [46]) that create secure virtual machines (VMs) to run target applications. Even though VM-based TEE technologies can be used with lightweight secure VMs [55], they still incur higher overhead than SGX due to larger protection scopes.

SGX basics. SGX maintains an *enclave*, a trusted environment that ensures the confidentiality and integrity of in-enclave contents via hardware protection. An enclave is hosted inside an isolated memory region called the *enclave page cache (EPC)*, with a maximum size of 256 MiB in the earlier generation SGXv1 [43] and 512 GiB in the latest generation SGXv2 [45]. SGX provides two functions for secure interactions between applications in untrusted memory and the enclave: (i) *enclave calls (ECalls)*, which allow applications to securely access in-enclave contents, and (ii) *outside calls (OCalls)*, which allow the enclave to access external resources. Both ECalls and OCalls incur substantial context-switch overhead [39].

SGX supports *remote attestation* [49], which allows a remote entity to cryptographically verify an enclave's integrity and confirm that the enclave contains correct, unmodified code and data. Upon successful verification, a secure channel is established between a user and the enclave, and the user can securely access enclave services [49]. Note that remote attestation can be performed each time when a user connects to the enclave, and the secure channel is maintained throughout the session. If the connection is lost, the user can re-establish the channel via remote attestation.

For crash tolerance, applications can securely persist in-enclave contents to external storage via *sealing*, in which an enclave generates a secret *sealing key* for encrypting and authenticating data to be persisted [49]. To recover in-enclave contents from crashes, applications can restart the enclave, which decrypts sealed data with the same sealing key. The sealing key is bound to the specific hardware on which it was created on, so as to prevent direct migration of sealed data to a different machine. This hardware dependency is also enforced in public cloud services that support SGX [17].

Can simple access control work? SGX enables secure and efficient ABAC by hosting attribute and policy management within an enclave. The enclave securely maintains user attributes, verifies user authenticity via secure channels (e.g., SSL/TLS), and enforces access control based on policy trees. If access is allowed, the enclave securely processes authorized requests with the persistent KV store, thereby mitigating ABE's performance and storage overheads. Note that we do not consider putting the whole KV store inside the enclave (even with the large EPC size in the latest SGXv2 generation), as it cannot handle the increased data volume and address data persistence (which SGX does not support).

One naïve approach of implementing ABAC is to directly embed a policy identifier with each KV pair and keep the policy verification logic inside the enclave. This follows the idea of traditional POSIX-based access control for file systems [38], where a static set of access policies is attached to each file. However, this naïve approach is inadequate for KV storage, which has no hierarchical namespace for organizing access rights as in file systems, and incurs highly expensive access right updates under dynamic access control. For example, if two access policies are merged into one, the naïve approach needs to scan the entire KV store and update the identifier for each affected KV pair. This leads to significant I/O overhead.

3 SECURITY GOALS

SACK aims for four security properties: (i) *confidentiality*, KV pairs are encrypted in storage to prevent unauthorized access; (ii) *integrity*, any unauthorized change to attributes, policies, and KV pairs is detectable; (iii) *freshness*, all operations are performed using the latest attributes, policies, and KV pairs; and (iv) *dynamic ABAC*, attributes and policies can be securely renewed.

We consider an adversary that can compromise the KV store and one or multiple users. We host the enclave alongside the KV store. Even if the adversary compromises the KV store, it cannot access any in-enclave contents, but can access contents outside of the enclave, monitor ECall/OCall interactions, and tamper with KV pairs in storage. In addition, the adversary can compromise both the KV store and some users to launch collusion attacks, where the compromised KV store returns unauthorized KV pairs to the compromised users whose access rights have been revoked.

We make the following security assumptions. Users can authenticate the enclave via remote attestation (Section 2.3), while the enclave can authenticate users (e.g., via SSL/TLS). The enclave exports ECalls to add or remove users and dynamically update access rights for existing users and KV pairs. We do not consider access pattern leakage, from which an adversary can learn if two requests are from the same or different keys. We can mitigate such leakage via oblivious RAM [1, 34, 85], yet the performance overhead of oblivious RAM is significant and can reach 83× in SGX implementation [1]. We also do not consider denial-of-service attacks, which can be defended by rate-limiting requests issued by a user [63]. Furthermore, we do not consider known SGX vulnerabilities [13, 50, 87], which are already fixed by Intel [44] and protected by existing countermeasures [67, 70, 76].

4 SACK DESIGN

4.1 Design Goals and Overview

SACK enhances existing SGX-based KV stores (e.g., [8, 51]) with dynamic ABAC and general applicability, while preserving their core security features (i.e., confidentiality, integrity, and freshness). It aims for the following design goals.

- *Security guarantees:* SACK achieves confidentiality, integrity, freshness, and dynamic ABAC (Section 3).
- *Efficient use of SGX:* While SGXv2 supports a huge EPC size (Section 2.3), the actual available EPC space is limited by host memory. Thus, SACK carefully manages attributes and any metadata inside the enclave, while limiting ECall/OCall overhead.
- *Low storage overhead:* SACK should limit storage overhead introduced by security measures (e.g., encryption keys and metadata), and allow reclaiming the storage space of stale KV pairs, while preserving security guarantees.
- *Crash consistency:* SACK must still ensure crash consistency of both in-enclave contents and KV storage.
- *General applicability:* SACK is compliant with general KV stores and uses only the standard KV interface for storage management.

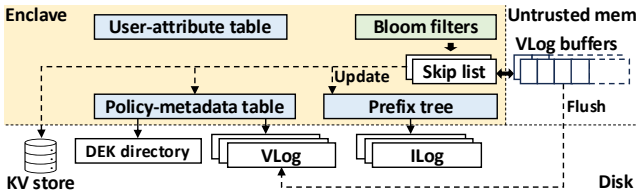


Figure 3: SACK's architecture.

Design novelty. SACK's core idea is to *decouple access control and data management*. It manages attributes and policies and evaluates users' access rights inside the enclave. Such shielded ABAC provides two key design features. First, instead of directly encrypting KV pairs by ABE, SACK uses ABE to manage secret keys (typically smaller than KV pairs) inside the enclave, where the secret keys are used to encrypt and decrypt KV pairs based on symmetric-key cryptography. This mitigates the computational overhead of ABE (based on public-key cryptography). Second, SACK enables lightweight dynamic access control by exporting enclave functions to securely update attributes and policies, thereby avoiding costly key re-issuing and data re-encryption in ABE.

To achieve secure, efficient data management outside of the enclave, SACK uses *KV separation* [59], which stores only keys and metadata in the KV store for indexing and values in separate storage space. The original motivation of KV separation is to improve indexing performance by keeping a small index structure (i.e., the *log-structured merge tree (LSM-tree)* [68]) with only keys and metadata. SACK preserves these performance benefits, and further securely and efficiently applies access control to value management. Note that SACK can be applied to other index structures beyond the LSM-tree, without modifying the index structure implementation.

Design trade-offs. The decoupled design of SACK incurs metadata overhead for separately managing access control and KV pairs. Its KV separation also incurs extra I/Os to separate storage space (as observed in [59]) and complicates crash consistency across the KV store and separate data structures.

Design roadmap. Figure 3 depicts SACK's architecture, including (i) external data structures hosted outside of the enclave (i.e., in untrusted memory and on disk) and (ii) in-enclave data structures. SACK incorporates various techniques: (i) lightweight renewal of access rights (Section 4.2), (ii) efficient freshness verification in reads (Section 4.3), (iii) garbage collection (GC) for encrypted data (Section 4.4), and (iv) crash consistency for both in-enclave contents and KV storage (Section 4.5). Finally, we provide security analysis (Section 4.6) and implementation details (Section 4.7).

4.2 Access Control

Secret key management. SACK manages three types of secret keys for symmetric-key cryptography: the master secret K_M, the signature secret K_S, and a set of *data encryption keys (DEKs)* $\{K_p\}$, where each K_p is linked to a policy with the *policy ID (PID)* p. K_M is used to encrypt the keys of KV pairs for confidentiality under KV separation (Section 4.3), while K_S is used to generate a *hash-based message authentication code (HMAC)* for integrity checking. Both K_M and K_S are initialized during enclave bootstrapping and securely stored inside the enclave.

The DEKs are used for encrypting and decrypting KV pairs governed by policies based on symmetric-key cryptography. Instead of using a single DEK for all KV pairs, employing per-policy DEKs ensures strict isolation of KV pairs across different policies. This approach aligns with ABE, which encrypts data under distinct policies using logically distinct keys. When a new policy is created, the enclave randomly generates a new DEK linked to the policy. All DEKs are maintained in an external encrypted storage area called the *DEK directory*. They are protected by ABE and accessible only through the enclave when the attributes are satisfied under ABE.

SACK uses ABE to protect DEKs, as ABE enforces access control policies on encrypted data and systematically supports access right updates when attributes or policies change. With KV separation, SACK can achieve lightweight dynamic access control for access right updates, without scanning the entire KV store (Section 2.3).

To efficiently manage numerous policies, SACK hosts the DEK directory outside of the enclave, as the DEKs under ABE protection incur high storage overhead. For example, a 32-byte DEK encrypted with ABE expands to 564 bytes when the policy includes a single attribute, and 2,188 bytes when the policy includes 10 attributes.

Access management. SACK manages access control via two in-enclave structures: a *user-attribute table* and a *policy-metadata table*. The user-attribute table tracks the mappings between each user ID and the associated attributes. SACK allows only the administrator to update the user-attribute table (e.g., creating users and assigning attributes) using a secure authenticated ECall. Each attribute is represented as a string (`type=value`) (Section 2.1), and multiple attributes are concatenated with a delimiter '`|`'. Figure 4 shows the entry format of the user-attribute table. Each entry not only stores the mapping of the user ID and its associated attributes, but also caches the PIDs and the corresponding DEKs of the valid policies satisfied by the user's attributes. This saves the overhead of retrieving DEKs from persistent storage in subsequent KV operations.

The policy-metadata table references the DEK directory and VLogs (see Section 4.3 for details on VLog management) based on policies, each represented as a byte string encoded from its policy tree. Figure 5 shows the entry format of the policy-metadata table. Each entry in the policy-metadata table stores the PID p for locating DEKs (protected by ABE under the policy) in the DEK directory, as well as the HMAC of the DEK K_p. It also tracks the VLogs associated with the policy, identified by VLog IDs and verified by Merkle tree roots [61] (Section 4.3).

Upon receiving the first request from a user, the enclave checks the user's attributes from the user-attribute table and identifies all valid policies. It then retrieves the corresponding DEKs from the DEK directory using the PIDs, and caches the PIDs and DEKs in the user-attribute table for the user's subsequent requests.

Lightweight dynamic access control. For dynamic access control, SACK supports two primary cases of changes to access rights:

- *Case 1: Changing the access rights of users.* When a user's access rights change, the administrator updates the user's attributes in the user-attribute table. The enclave then drops the cached PIDs and DEKs that are no longer valid, and caches the new PIDs and DEKs under the updated attributes to enforce the user's new access rights. Note that the policy-metadata table remains intact.
- *Case 2: Changing the access rights to KV pairs.* When the access rights to a KV pair are updated (e.g., a new attribute is needed to

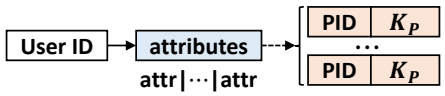


Figure 4: Entry format in the user-attribute table.

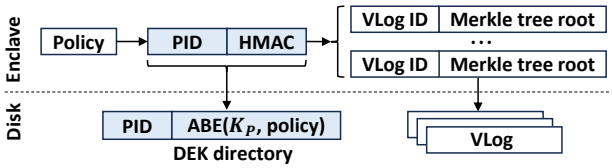


Figure 5: Entry format in the policy-metadata table.

access the KV pair), the administrator updates the corresponding policy in the policy-metadata table. SACK supports three types of policy updates: (i) changing the current policy to a new policy, (ii) transitioning from one policy to another existing policy, and (iii) merging two policies into a new policy (i.e., the original two policies become sub-trees of the new policy). In all cases, the enclave consolidates PIDs, DEKs, and VLogs into the resulting policy's metadata in the policy-metadata table. It also updates ABE-protected DEKs with the resulting policy in the DEK directory, by first retrieving DEKs based on the PIDs of the policies being changed, decrypting the retrieved DEKs with the attributes of old policies, and re-encrypting the DEKs with the resulting policy using ABE. Furthermore, it traverses the user-attribute table to identify the users that currently have access rights to the KV pairs under the old policy (based on the PID). It removes any cached PID and DEK if a user no longer retains access rights under the new policy.

Both cases achieve lightweight updates of access rights, as the currently stored KV pairs are unaffected. To avoid access violations, SACK temporarily suspends any requests during updates, but the suspension only lasts for a short duration as updates are lightweight. Currently, SACK does not support multiple policies for a KV pair. When a KV pair is rewritten with a new policy, the previous version of the KV pair (under the old policy) will be invalidated, and only the latest version is accessible under the new policy.

4.3 Data Management

KV separation. SACK adopts KV separation [59] to support operations for *general* KV stores. It stores the metadata records of KV pairs (called *KV-metas*) in the KV store, while storing encrypted KV pairs in multiple append-only *value logs (VLogs)* in persistent storage. Both the keys and values of KV pairs are encrypted for confidentiality, yet KV pairs should still remain searchable even after encryption. Thus, SACK deterministically encrypts the keys of KV pairs by the master secret K_M, so that identical unencrypted keys are mapped to identical encrypted keys for queries. It also probabilistically encrypts values by a random initialization vector [23] and K_p for the same policy with PID p, such that identical values are mapped to distinct encrypted outputs for semantic security.

Figure 6 shows KV separation and the VLog structure, where each KV pair is converted into a KV-meta and an encrypted KV pair. A KV-meta is identified by the encrypted key (encrypted by

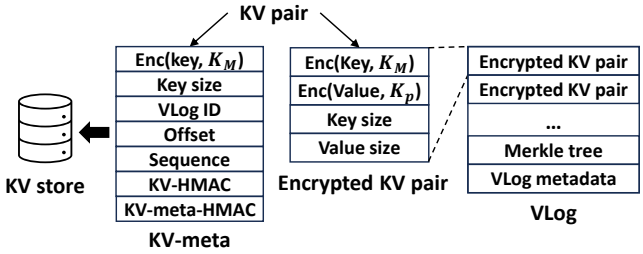


Figure 6: KV separation and VLog data structure.

K_M) and keeps multiple metadata fields for KV pair indexing and integrity verification: (i) the encrypted key size, (ii) the VLog ID (incremented each time a new VLog is created) for identifying the VLog holding the KV pair, (iii) the offset of the KV pair in the VLog, (iv) the sequence number of the KV pair, (v) the HMAC of the KV pair (called *KV-HMAC*), and (vi) the HMAC of all above metadata fields (called *KV-meta-HMAC*). Each VLog groups encrypted KV pairs under the same policy to mitigate overhead of changing access rights to KV pairs (Case 2 in Section 4.3), achieved by updating only VLog metadata in the policy-metadata table without traversing and updating all affected KV pairs. Each encrypted KV pair in a VLog includes the key and value sizes and the encrypted key and value (encrypted by K_M and K_p, respectively). Also, each VLog's end stores a Merkle tree formed by the KV-HMACs of all KV pairs in the VLog for integrity checking, plus the metadata fields including the PID, total KV pair size, and Merkle tree size.

To mitigate the enclave's context-switch overhead (Section 2.3), SACK adopts buffered writes [59] to trade immediate persistence for performance. It maintains *VLog buffers* in untrusted memory to batch small I/Os into a single large I/O. Each VLog buffer temporarily holds encrypted KV pairs under the same policy (note that SGX allows the enclave to directly operate on untrusted memory via memory addressing). When a VLog buffer is full, the enclave flushes encrypted KV pairs to disk with a single OCall. Also, the enclave maintains multiple *skip lists* to efficiently index unflushed KV pairs in VLog buffers (for reads).

KV-meta indexing. Keeping KV-metas in the KV store faces two challenges. First, encrypting the keys of KV pairs disrupts the ordering of the original unencrypted KV pairs, thereby hindering scans. Second, verifying the freshness of a KV pair becomes infeasible, as an adversary can compromise the KV store to return an older KV-meta version and break freshness. Note that HMACs in KV-metas cannot ensure freshness, as old KV-metas still have valid HMACs.

SACK separately manages KV-metas in multiple on-disk *index logs (ILogs)*, each containing KV-metas whose unencrypted keys share a common prefix. Figure 7 shows the ILog layout. Each ILog is identified by an ILog ID (incremented each time when an ILog is created) and comprises a *sorted part* and an *unsorted part*. The sorted part contains all KV-metas sorted by *unencrypted* keys for fast reads, while the unsorted part contains newly inserted KV-metas in an append-only manner to support fast writes. The unsorted part is merged into the sorted part when its number of KV-metas exceeds a threshold, while each ILog has a capacity (i.e., the maximum number of KV-metas that can be stored) and is split in GC when the capacity is reached (Section 4.4).

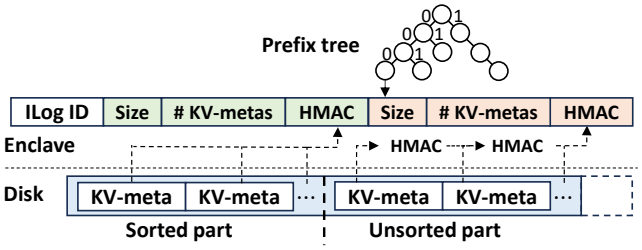


Figure 7: Prefix tree and ILogs.

SACK indexes KV-metas in all ILogs with a binary *prefix tree* inside the enclave (Figure 7). In the prefix tree, each leaf node corresponds to an ILog, while each root-to-leaf path represents a bit-level prefix of unencrypted keys in the ILog for lookups. Each leaf node contains the ILog ID and two metadata tuples, one for the sorted part and another for the unsorted part. Each metadata tuple contains the total size of KV-metas, number of KV-metas, and an HMAC that protects against ILog tampering. For the sorted part, the HMAC is computed from the KV-meta-HMACs of all KV-metas, while for the unsorted part, the HMAC is computed from the current HMAC and the KV-meta-HMACs of newly inserted KV-metas. SACK ensures freshness by verifying retrieved KV-metas based on ILogs and the prefix tree.

KV operations. SACK supports the basic KV operations, including writes, reads, scans, and deletes.

- *Writes.* Suppose that a KV pair is written under a policy with PID p. The enclave locates the DEK K_p and encrypts the key and value of the KV pair by K_M and K_p, respectively. It stores the KV-meta in a skip list and the encrypted KV pair in a VLog buffer. Both the skip list and the VLog buffer are associated with PID p. When the VLog buffer is full, the enclave flushes the contents in the skip list and VLog buffer to the KV store and the VLog associated with PID p, respectively. It also appends a Merkle tree to the VLog and flushes each KV-meta to the unsorted part of an ILog based on the prefix tree.
- *Reads.* Suppose that a KV pair is read. Based on the encrypted key (encrypted by K_M) of the KV pair, the enclave first checks if the skip lists and VLog buffers cache the KV pair; if not, it retrieves the KV-meta from the KV store and the encrypted KV pair from the corresponding VLog based on the VLog ID and offset in the KV-meta. It verifies the KV-meta using the KV-meta-HMAC. Also, it verifies the KV pair using the KV-HMAC, the Merkle tree in the VLog, and the Merkle tree root in the policy-metadata table. Finally, the enclave decrypts the encrypted KV pair by K_M and K_p and returns the results to the user, assuming that the user's attributes satisfy the policy with PID p. To verify KV pair's freshness, the enclave retrieves the corresponding ILog that contains the KV-meta, and verifies the ILog by the HMACs of both sorted and unsorted parts. Note that if the KV-meta has multiple versions, they are in the same ILog as SACK groups KV-metas by unencrypted keys. The enclave checks if the latest version matches the one retrieved from the KV store.
- *Scans.* SACK supports scans over ranges of unencrypted keys using the prefix tree and ILogs. Specifically, the enclave uses the prefix tree to retrieve all ILogs that contain KV-metas in the key range. It then decrypts the ILogs, sorts the KV-metas from both the sorted and unsorted parts by their unencrypted keys, and filters out invalid entries based on sequence numbers, so that all KV-metas within the specified key range are accurately identified. Like reads, the enclave verifies ILogs by the HMACs of both sorted and unsorted parts and retrieves encrypted KV pairs from the corresponding VLogs, and returns the latest versions of KV pairs (assuming that the user has access rights).
- *Deletes.* Similar to RocksDB's tombstone design [27], SACK deletes a key by writing a tombstone (a special KV-meta) to the ILog, so that the corresponding KV-metas of the deleted key are treated as invalid. It also issues a delete operation to the KV store. The tombstones in the ILogs and the corresponding KV pairs in the VLogs are later physically removed during GC.

Optimizing freshness verification in reads. To verify the freshness of a KV pair being read, the enclave retrieves the corresponding ILog and locates the KV-meta. This incurs significant I/Os as the ILog also contains KV-metas of other KV pairs. Also, the enclave performs HMAC verifications, which incur substantial computational overhead.

SACK introduces two types of Bloom filters (BFs) [12], namely *per-ILog insert BFs* and an *update BF*, to avoid accessing ILogs during reads for freshness verification. Our insight is that freshness verification is needed only when KV pairs are updated and have multiple versions. For newly inserted KV pairs, there is only a single version, so an adversary cannot replay outdated KV pairs without valid KV-metas from older versions. Note that these BFs are distinct from the SSTable BFs in RocksDB [27], which aim to eliminate reads to KV pairs that do not exist in SSTables. Instead, the BFs in SACK are tailored to identify newly inserted KV pairs and optimize freshness verification for updates.

Each per-ILog insert BF is allocated with a small memory budget (1.5 KiB by default (Section 5.1)) and stored in untrusted memory, so as to accommodate data growth (i.e., more ILogs) while maintaining a low false positive rate. The per-ILog insert BFs are loaded into an in-enclave least-recently-used (LRU) cache *on demand* for modifications to ensure integrity and freshness. They are authenticated by HMACs stored in the enclave, and the HMACs are updated when the per-ILog insert BFs are evicted from the enclave. On the other hand, the update BF always resides in the enclave.

When flushing a VLog buffer, the enclave checks if the key of a KV pair exists in the corresponding per-ILog insert BF. If the key is new (i.e., not present in the per-ILog insert BF), the enclave adds the key to the per-ILog insert BF; otherwise, the enclave adds the key to the update BF. To read a KV pair, the enclave checks the update BF. If the key does not exist, the enclave knows the key is new and will not access ILogs. Note that any false positive (i.e., a new key is treated as an updated one) does not compromise correctness, as the enclave still accesses ILogs and only incurs performance overhead.

Since not all reads will access ILogs with our BF optimization, an attacker may attempt to replay a deleted KV pair. Specifically, consider a key with only a single version (i.e., the key is not added to the update BF). If the key is deleted (with its tombstone written) but not yet physically removed by GC, the attacker can control the KV store, retrieve the KV-meta of the deleted key, replay the KV-meta to the enclave via the controlled KV store, and finally access the KV pair in the VLog that remains valid before GC. To

address this security issue, SACK also inserts deleted keys into the update BF during deletes. This ensures that any subsequent reads to a deleted key must access the ILogs, enabling the enclave to detect the deletion via the ILogs and stop the reads.

4.4 Garbage Collection (GC)

While the KV store has its own GC mechanism, SACK regularly performs GC on VLogs and ILogs to reclaim free space from stale KV pairs. SACK starts with the GC of ILogs and uses the results to guide the GC of VLogs. It also performs GC on BFs to prevent their saturation. It ensures confidentiality, integrity, and freshness during GC without compromising access control.

GC of ILogs. To maintain efficient reads to ILogs, SACK performs *sort-based GC* for an ILog to merge the unsorted part into the sorted part when the number of KV-metas in the unsorted part exceeds a threshold (e.g., 5% of the ILog capacity in our prototype). The enclave loads the whole ILog and sorts all KV-metas based on their decrypted keys. It removes stale KV-metas and keeps only the latest versions based on the sequence numbers of KV-metas. If the latest KV-meta is a tombstone (i.e., the key is deleted), the enclave removes all KV-metas of the deleted key. Finally, the enclave includes the sorted KV-metas into the sorted part and rebuilds the corresponding per-ILog insert BF based on all valid keys.

If the total number of KV-metas in an ILog reaches the capacity, SACK performs *split-based GC* to prevent the ILog from growing indefinitely. In the prefix tree, the enclave splits the leaf node corresponding to the ILog into two new leaf nodes and extends the prefix length by one bit. It also splits KV-metas into the sorted parts of the respective two ILogs, sorted by the decrypted keys. A new per-ILog insert BF is built for each new ILog based on all valid keys.

During the GC of ILogs, the enclave records stale KV-metas and tombstones in a temporary file, called *GC-Log*, which is stored outside of the enclave and protected by an in-enclave HMAC against tampering.

GC of VLogs. During idle periods, SACK suspends KV operations, and the GC of VLogs removes stale KV pairs based on the GC-Log and updates indexes with new KV-metas for remaining KV pairs in the affected VLogs. Those remaining KV pairs are written to new VLogs and the policy-metadata table is updated. SACK always performs the GC of *all* ILogs first to ensure that stale KV pairs are fully removed, and the update BF is reset only after the GC of VLogs is completed. The new enclave version is then persisted, and the GC-Log and affected VLogs are reclaimed to ensure reliable crash recovery (Section 4.5).

GC of BFs. To prevent BF saturation, SACK rebuilds per-ILog insert BFs during ILog GC based on all valid keys in the ILogs. It also resets the update BF after VLog GC is completed. All KV operations are temporarily suspended until the GC of BFs is done, yet the suspension time is very short.

4.5 Crash Consistency

Crash consistency requires a KV store to maintain correct and recoverable storage even after a system crash. SACK employs VLogs for write-ahead logging as in KV separation [59] and maintains crash consistency among the enclave, KV store, VLogs, and ILogs. It also maintains integrity and freshness during crash recovery.

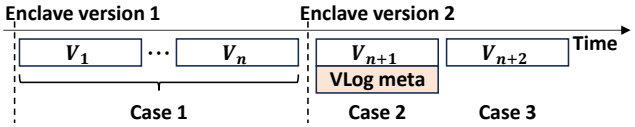


Figure 8: Crash recovery for VLogs.

Enclave sealing. The contents of in-enclave structures are protected by sealing (Section 2.3), yet frequent sealing incurs high overhead. Thus, SACK seals the entire enclave and persists the sealed enclave at a low frequency (e.g., every hour). It further applies sealing to the metadata of any new VLog created and flushed (i.e., the VLog ID, policy, and Merkle tree root). It keeps the sealed VLog metadata until the sealed enclave is persisted.

Enclave versioning. SACK keeps an *enclave version count (EVC)* in the enclave to track the number of times the enclave has been sealed. When the enclave is sealed, the EVC is incremented and persisted in the sealed enclave. The EVC is initialized with a random number when the enclave is first created, and is sent to all users during enclave sealing. Thus, a user can verify the EVC of the enclave and ensure that only the latest enclave is used.

Crash recovery for ILogs. In crash recovery, SACK unseals the latest sealed enclave and recovers ILogs to be consistent with the latest sealed enclave. The enclave reads each ILog included in the prefix tree (restored from the latest sealed enclave), and verifies the HMACs of both sorted and unsorted parts. Note that the GC of an ILog may occur after the latest sealing, so the enclave may not track removed KV-metas after being unsealed. Thus, the enclave uses the GC-Log (Section 4.4) to recover any removed KV-metas.

Crash recovery for VLogs. Figure 8 shows how SACK handles crash recovery for VLogs. Suppose that there exists a sequence of VLogs $V_1, V_2, \cdots, V_n, V_{n+1}, V_{n+2}$ and a crash happens, and there are three cases: (i) $V_1, V_2, \cdots, V_n$ are generated before the enclave is sealed; (ii) V_{n+1} is generated after the sealed enclave and its VLog metadata is sealed; and (iii) V_{n+2} is generated after the sealed enclave, but its VLog metadata is not yet sealed before the crash happens. Now, SACK restarts from the crash. It unseals the latest sealed enclave, recovers the Ilogs, and checks the consistency of all VLogs on disk. It handles the three cases as follows:

- *Case (i):* The policy-metadata table in the latest sealed enclave records $V_1, V_2, \cdots, V_n$, all of which are persisted. Thus, there is no special recovery action.
- *Case (ii):* SACK unseals V_{n+1}'s metadata, and verifies V_{n+1} on disk based on V_{n+1}'s Merkle tree. If V_{n+1} is valid, SACK decrypts all KV pairs in V_{n+1}, rewrites KV-metas into the KV store and ILogs, and updates the VLog ID of V_{n+1} and Merkle tree root in the policy-metadata table; otherwise, SACK discards the invalid V_{n+1}. Note that ILogs (recovered to the latest sealed enclave) now have consistent KV-metas with VLog V_{n+1}.
- *Case (iii):* Since SACK cannot verify the authenticity of V_{n+2} without the sealed metadata, it discards V_{n+2}.

4.6 Security Analysis

We discuss how SACK maintains its security properties (Section 3).

Confidentiality. An adversary can have access to any data outside of the enclave, including external structures (Figure 3 in Section 4.1)

and the sealed enclave (Section 4.5). SACK encrypts all sensitive contents (e.g., KV pairs, DEKs, and sealed enclave) to prevent unauthorized access. Note that the keys of KV pairs are deterministically encrypted to preserve searchability (Section 4.3), and non-sensitive contents (e.g., metadata fields of KV-metas) are unencrypted. Also, an adversary may monitor the enclave's ECalls/OCalls and disk I/Os to learn the access pattern of KV pairs, or infer the ordering of KV pairs from the sorted parts of ILogs. Nevertheless, they do not introduce additional information leakage about the values of KV pairs, which are probabilistically encrypted for semantic security (Section 4.3). Also, since the ordering across ILogs is independent of the ordering of keys in each ILog, the leakage of ordering of KV pairs is limited to individual ILogs and cannot be used to deduce the ordering of all KV pairs.

Integrity. SACK can detect any tampering against encrypted KV pairs, KV-metas, and DEKs via HMAC-based verification. It also enforces integrity for the sealed enclave via SGX sealing (Section 4.5).

Freshness. SACK prevents any adversarial attempt to reuse outdated KV pairs, KV-metas, or DEKs. It ensures freshness mainly through ILogs, by only returning KV-metas with the latest sequence number. Also, it protects ILogs via HMAC-based integrity verification and ensures that ILogs are not maliciously modified and are up-to-date with in-enclave contents. Furthermore, it prevents forking [56] and rollback [71] attacks by ensuring that only the latest version of a sealed enclave is used (Section 4.5) (via the EVC broadcast to all users during enclave sealing).

While SACK uses BFs (Section 4.3) to mitigate freshness verification overhead for reads via ILogs, the BFs will not introduce any security concern. As SACK only resets BFs after VLog GC is done (Section 4.4), all invalid KV pairs are removed and the in-enclave metadata are updated. Even though the KV pairs are later updated, no old KV pairs can pass integrity checks, and the updated KV pairs will be treated as newly inserted KV pairs.

Dynamic access control. SACK securely manages users' attributes and all access rights defined by policies inside the enclave. Even if an adversary has access to the DEK directory or knows the attributes of a compromised user, SACK prohibits the adversary from feasibly decrypting ABE-protected DEKs or modifying any policy to grant unauthorized access to other non-compromised users. Note that a malicious administrator can assign unauthorized attributes to a user to gain illicit access to KV pairs, yet it can still be mitigated by requiring multiple administrators to manage access control and approve changes to attributes or policies [57].

4.7 Implementation Details

We implement SACK as a middleware system that runs atop general KV stores and supports both SGXv1 [43] and SGXv2 [45]. We adopt Intel SGX as Intel currently occupies over 60% of the server CPU market [72] and provides the most comprehensive encryption, integrity, and freshness guarantees [60]. The implementation can be adapted to other TEEs with a similar programming model (e.g., ARM TrustZone [86] and RISCV-V Penglai [25]) that separate trusted and untrusted components and export function calls to access them securely.

Our SACK prototype is written in C++ and consists of 19 K lines of code. It leverages third-party libraries for major operations, including OpenABE-1.0 [96] for ABE, SGX SDK 2.21 [49] and the corresponding SGX SSL [47] for SGX enclave management, and OpenSSL 1.1.1u [30] for cryptographic operations. It implements HMACs based on SHA3-384 (as in TWEEZER [51]), and symmetric-key encryption based on AES-256 in cipher feedback mode. It uses xxHash [18] as the hash function for BFs (Section 4.3) and indexes the HMACs of per-ILog insert BFs by ILog IDs via a hash map in the enclave. We adopt standard performance optimization techniques, such as parallelizing I/O operations with multi-threading and batching multiple reads to a VLog during scans. SACK processes incoming KV operations regardless of whether they originate from a single or multiple users, so as to ensure proper functionality in multi-user scenarios.

SACK caches the matched policy IDs inside the EPC for active users. If the EPC is full, some cached data can be securely swapped out via the SGX page swapping mechanism, which is natively supported by SGX without manual intervention.

SACK can be deployed atop general KV stores. Our evaluation focuses on RocksDB [27] (Section 5), yet our current prototype also supports other KV stores, including BerkeleyDB [69] with B-tree-based and hash-based storage backends, B^ϵ-tree-based SplinterDB [21], and the LSM-tree-based LevelDB [35]. Our evaluation findings also hold for other KV stores.

5 EVALUATION

We evaluate SACK's performance and resource usage. As there is no existing SGX-based KV store that supports dynamic access control for more fair comparisons, we mainly compare SACK with TWEEZER [51], a state-of-the-art SGX-based KV store that provides confidentiality, integrity, and freshness guarantees but lacks dynamic access control and general applicability. TWEEZER extends RocksDB [27], which manages KV pairs in the LSM-tree. It protects KV pairs with symmetric-key encryption and per-KV-pair HMACs. It applies KV separation within each data block (the storage unit of an SSTable) and reorganizes key blocks and value blocks for fine-grained encryption and authentication, yet it still keeps complete KV pairs within the LSM-tree. It needs to perform LSM-tree compaction and maintain LSM-tree metadata inside the enclave, so it cannot be directly applied to general KV stores without re-engineering their index structures. In contrast, SACK separates value storage from the LSM-tree, significantly reducing the LSM-tree size and achieving strong security guarantees without modifying the index structure (Section 4.1). This design ensures compatibility with various KV stores (e.g., hash-based KV stores) (Section 4.7). We also compare SACK against ABE in Exp#2 and Exp#6, where ABE's results are referenced from Figure 2 (Section 2.2) due to its significantly higher overhead than SACK and TWEEZER.

5.1 Methodology

Testbed. SACK is compatible with both SGXv1 and SGXv2, yet the open-source TWEEZER prototype supports SGXv1 only, but not SGXv2, as reported by TWEEZER's authors [64]. Thus, for fair comparisons with TWEEZER, we mainly conduct our evaluation on an SGXv1 server. The server has a six-core Intel Core i5-8400 2.8 GHz CPU, 32 GiB RAM, 128 MiB EPC memory, and a 1 TiB PCIe 3.0 NVMe SSD. It runs Ubuntu 18.04.6 LTS with Linux kernel

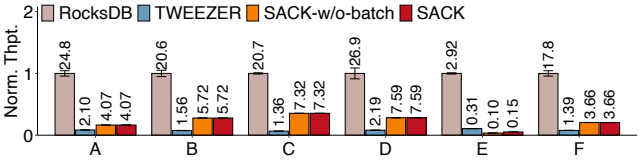
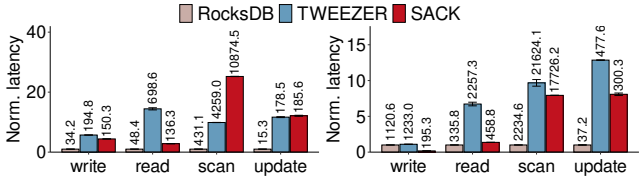


Figure 9: Exp#1 (Performance under YCSB core workloads). We plot the throughput normalized by RocksDB's. We also report the absolute throughput in KOPS above each bar.



(a) Normalized average latency (b) Normalized P99 tail latency

Figure 10: Exp#2 (Performance of KV operations). We plot latency results normalized by RocksDB's. We also report the latencies in microseconds above the bars.

4.15.0-213-generic, as required by TWEEZER. We run TWEEZER on SCONE [5] version 5.4.0[37].

Default configurations. We run SACK atop RocksDB v6.14.5 [27] as in TWEEZER for fair comparisons. We follow the default settings of RocksDB and TWEEZER. For SACK, we configure the capacities of a VLog and an ILog to store at most 1,000 KV pairs and 1,000 KV-metas, respectively. We set eight VLog buffers. We configure the BFs with three hash functions each. We configure the per-ILog insert BF size as 1.5 KiB, which yields a theoretical false positive rate of less than 1% for 1,000 KV-metas per ILog. Similarly, we set the update BF size as 16 MiB, which provides a theoretical false positive rate of less than 1% for 10 M unique updates. In addition, we cache per-ILog insert BFs with a 1 MiB in-enclave LRU cache.

We focus on a single attribute and a single policy for access control to isolate system variables and incrementally validate core mechanisms. We also evaluate the impact of a varying number of attributes and policies in Exp#7.

Workloads. We generate workloads using YCSB [22]. By default, in each experiment, we first load 64 M 1-KiB KV pairs composed of 24-byte keys and 1000-byte values into storage. We then generate 5 M requests for each workload. The requests follow a Zipf distribution with a Zipfian constant of 0.99 (default in YCSB). We report the average results across five runs, with error bars representing 95% confidence intervals based on the student's t-distribution (we omit error bars from line charts for brevity).

Additional experiments. In the technical report [78], we present additional evaluation results, including the effects of in-enclave LRU cache sizes for per-ILog insert BFs, value sizes, ILog and VLog capacities, database volume, and SSTable BFs. We also evaluate the compatibility of SACK with SGXv2 and various KV stores.

5.2 Results

Exp#1 (Performance under YCSB core workloads). We compare RocksDB, TWEEZER, and SACK using six YCSB core workloads [22]: A (50% reads, 50% writes), B (95% reads, 5% writes), C (100% reads), D (95% reads, 5% writes), E (95% scans, 5% writes), and F (50% reads, 50% read-modify-writes). All workloads (except D) follow a Zipf distribution, while Workload D reads the most recently written KV pairs.

Figure 9 shows that SACK achieves throughput gains of 1.9-5.4× over TWEEZER across all workloads except Workload E. SACK's throughput gains are mainly due to KV separation and reduction in EPC paging for reads (Exp#5), and increase with the read ratio (e.g., 1.9× in A and 5.4× in C). However, SACK has 51.6% lower throughput than TWEEZER in Workload E due to KV separation, as it requires extra reads from multiple VLogs (the scan overhead is also observed in [59]). Our batched-read VLog optimization for scan operations (Section 4.7) mitigates this overhead and increases Workload E's throughput by 50%, from 0.10 KOPS (i.e., SACK-w/o-batch) to 0.15 KOPS (i.e., SACK). Overall, the average throughput drop of SACK over RocksDB (without security protection) is 6.7×, while that of TWEEZER is 12.5×.

Exp#2 (Performance of KV operations). We evaluate the average and 99th-percentile latencies for specific KV operations, including reads, writes, scans, and updates. We first load 64 M 1-KiB KV pairs, followed by issuing 5 M requests for each type of KV operations under a Zipf distribution with a Zipfian constant of 0.99. For scans, the scan length is 100 KV pairs as in YCSB Workload E.

Figure 10 shows that compared with TWEEZER, SACK reduces average write and read latencies by 22.8% and 80.5%, respectively, but increases average scan and update latencies by 155.3% and 4.0%, respectively (Figure 10(a)). The latency increase stems from reads to separate VLogs and from GC overhead. Compared with RocksDB, SACK incurs 2.8-25.2× higher average latencies due to added cryptographic features. The latency increase is the most in scans, consistent with Workload E in Exp#1. With the batched-read VLog optimization (Section 4.7), SACK's average scan latency decreases from 13.8 ms (not shown in the figure) to 10.9 ms.

For 99th-percentile tail latencies (Figure 10(b)), SACK consistently maintains lower tail latencies than TWEEZER across all KV operations, with an average reduction of 54.7%. Notably, although SACK has higher average scan latencies, it has lower tail latencies for scans due to 19.9× EPC paging reduction (Exp#5). Disabling the batched-read VLog optimization increases SACK's scan tail latency by 80.8% to 32.0 ms (not shown in the figure). Compared with RocksDB, SACK has 82.6% lower tail latencies in writes as KV separation reduces the LSM-tree size, while it has higher tail latencies in reads, scans, and updates. Compared with ABE (Figure 2 in Section 2.2), SACK reduces average write and read latencies by 79.9% and 92.8%, respectively, under a single attribute and policy, as it employs lightweight symmetric-key encryption instead of public-key-based ABE.

Exp#3 (Performance breakdown). We provide a performance breakdown for multiple steps of writes, reads, and GC. We report the time of processing 1 MiB of KV pairs for each step based on the workloads in Exp#2. Table 1 shows the breakdown results. For writes, the most time consuming step is ILog updates, which account for 46.0% of total write time. The reason is that the KV-metas of written KV pairs may reside in different ILogs, and the enclave needs to recalculate and update HMACs after appending KV-metas to ILogs. For reads, the most time-consuming step is fetching KV-metas from ILogs, where the enclave retrieves the whole ILog for

Table 1: Exp#3 (Performance breakdown). We show the average results (in milliseconds/MiB) and 95% confidence intervals for different steps of writes and reads.

Steps		Writes
Generate KV-meta		19.66±0.04
Encrypt KV pairs		23.08±0.09
Build Merkle tree		3.48±0.02
Update BFs		32.15±0.13
Flush VLogs		0.72±0.10
Update ILogs		70.81±0.14
Update KV store		3.99±0.07
Steps		**Reads**
Query BFs		4.78±0.04
Fetch KV-meta	Query KV store	33.22±0.55
	Query ILogs	477.42±13.61
Read value from VLog		38.16±0.08
Access control checking & Decryption		16.46±0.07
Verify integrity and freshness		42.56±0.08
Steps		**Scans**
Query ILogs		34.59±0.10
Read values from VLogs		55.35±0.21
Access control checking & Decryption		10.06±0.02
Verify integrity and freshness		15.66±0.04
Steps		**GC**
GC of ILogs		6.43±0.08
GC of VLogs		45.16±1.55

each KV-meta and performs HMAC verification. Nevertheless, the BFs significantly save access to ILogs in reads (Exp#8).

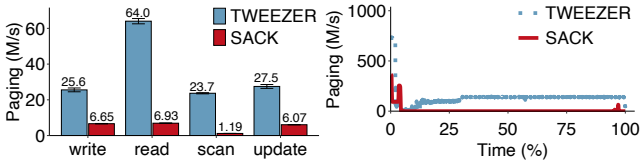
In contrast, scans read 100 sequential KV pairs at a time (0.1 MiB per scan), while reads fetch one KV pair (1 KiB) per operation. Thus, the most time-consuming step for scans is reading values scattered across multiple VLogs, even for sequential keys. The overhead is exacerbated by the large data transfers between the enclave and untrusted memory, which amplify context-switch ovrehead due to the limited EPC size. On the other hand, querying ILogs is faster in scans than in reads, since ILogs store contiguous KV-metas. Also, the access control checking, decryption, and integrity verification are faster in scans than in reads, as their processing can be batched for multiple values.

For GC, ILog GC is efficient, while VLog GC is more time-consuming as it needs to verify data integrity and update the KV-metas of valid KV pairs in both ILogs and the KV store. VLog GC runs in system idle periods to limit its overhead to normal operations (Section 4.4).

Exp#4 (Crash recovery performance). We evaluate SACK's crash recovery performance. We load 64 M 1-KiB KV pairs into SACK and issue 5 M writes as in Exp#2. We crash SACK after issuing about 2.5 M writes using the `kill -9 processID` command. We restart SACK to initiate recovery and measure the times of various recovery steps. Table 2 shows SACK's crash recovery performance. The enclave unsealing, ILog recovery, and VLog recovery account for 1.3%, 38.6%, and 60.1% of total recovery time. During VLog recovery, ILog updates are the most time-consuming step as they involve HMAC recalculations and KV-meta rewriting.

Table 2: Exp#4 (Crash recovery performance). We show average latencies and 95% confidence intervals for different steps.

Steps		Time
Unseal enclave		6.68 ± 0.06 s
Recover ILogs		194.72 ± 0.66 s
Recover VLogs	Fetch KV pairs	15.73 ± 2.86 s
	Decryption	31.32 ± 3.60 s
	Verify KV pairs	45.42 ± 5.23 s
	Update BFs	40.94 ± 4.94 s
	Update ILogs	101.73 ± 14.06 s
	Update KV store	10.32 ± 1.07 s
Recovery time		504.69 ± 38.64 s



(a) Average paging rates (b) Paging rate in reads

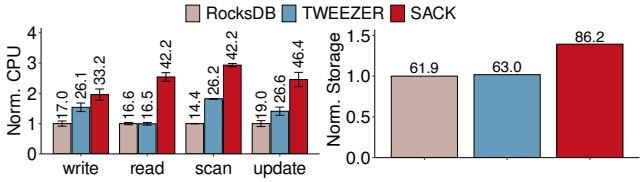
Figure 11: Exp#5 (Enclave usage).

Exp#5 (Enclave usage). We analyze SACK's EPC usage, assuming a scenario of 64 M 1-KiB KV pairs, 1,000 users with 16 attributes each, and 2^{16} policies. The EPC usage is calculated based on the following persistent data structures:

- *User-attribute table:* We assume 4 bytes for the user ID and 16 bytes for an attribute string. We do not consider the cached PIDs and DEKs. Thus, the user-attribute table size is (4 + 16 × 16 (attributes)) × 1,000 (users) ≈ 0.25 MiB.
- *Policy-metadata table:* We assume 256 bytes for a policy string (using 16 attributes), 4 bytes for a PID, 48 bytes for a DEK HMAC, 4 bytes for a VLog ID, and 48 bytes for a Merkle tree root, and each policy corresponds to one VLog. The policy-metadata table size is (256 + 4 + 48 + 4 + 48) (bytes) × 2^{16} (policies) = 22.5 MiB.
- *Prefix tree:* We assume 4 bytes for each ILog ID, 4 bytes for each size entry, 4 bytes for the number of KV-metas, and 48 bytes for HMAC in both sorted and unsorted parts. Thus, each leaf node has 116 bytes. Also, each non-leaf node has 24 bytes (three pointers for referencing the parent node and two child nodes). Assuming 64 M KV pairs and 1,000 KV-metas in each ILog, there are 64 K ILogs, which imply 64 K leaf nodes and 64 K non-leaf nodes for a binary prefix tree. The prefix tree size is about 8.5 MiB.
- *SACK BFs:* We assume 17 MiB (1 MiB for the in-enclave LRU cache for per-ILog insert BFs and 16 MiB for the update BF). Additionally, HMACs (48 bytes each) for per-ILog insert BFs are indexed by 64 K ILog IDs (4 bytes each) and account for (4 + 48) (bytes) × 64 K ≈ 3.3 MiB. The total size is 20.3 MiB.

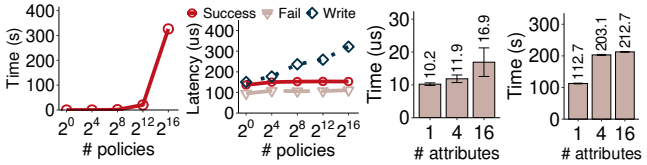
We do not consider skip-lists for indexing KV pairs in VLog buffers (Section 4.3) as they are temporary (with less than 1 MiB of EPC). Thus, the total EPC size for SACK's persistent data structures is about 51.6 MiB.

We also evaluate the EPC paging overheads of TWEEZER and SACK. We use `sgxtop` [29] to measure the page rate in Exp#2 (a higher paging rate means higher overhead). Figure 11 shows that SACK reduces the EPC paging rate of TWEEZER by 74.0%,



(a) CPU usage (b) Storage size

Figure 12: Exp#6 (Server resource usage). We report results normalized by RocksDB's. We report the absolute CPU usage (%) and storage size (GiB) above the bars.



(a) Initialization (b) Avg. latency (c) Updating (d) Rekeying

Figure 13: Exp#7 (Impact of the number of policies). In figure (b), "Success" and "Fail" denote whether a read successfully retrieve a KV pair or is denied due to insufficient access rights, while "Write" denotes write operations.

89.2%, 95.0%, and 77.9% in writes, reads, scans, and updates, respectively (Figure 11(a)), as it maintains small-size data structures in the enclave, while TWEEZER maintains SSTables' metadata in the enclave for LSM-tree management. Figure 11(b) examines the paging rates over the time of issuing reads in TWEEZER and SACK. SACK incurs paging mainly at the beginning and end of reads, which correspond to the initialization of in-enclave data structures and the enclave sealing when all reads are completed for crash consistency (Section 4.5), respectively. In contrast, TWEEZER performs paging throughout reads to manage SSTables' metadata.

Exp#6 (Server resource usage). We compare the CPU usage and storage sizes of RocksDB, TWEEZER, and SACK in our server using the workloads in Exp#2. We disable compression in all systems (the default setting in RocksDB). We collect CPU usage using the Linux system `proc` files every 1 s. We also collect storage sizes using the `du -s --bytes` command at the end of evaluation.

Figure 12(a) shows that SACK incurs 95.3-193.1% higher CPU usage than RocksDB, as it performs additional cryptographic operations. SACK also incurs higher CPU usage than TWEEZER due to the extra operations for enforcing access control and managing VLogs and ILogs.

Figure 12(b) shows that SACK incurs 39.3% more storage space than RocksDB, mainly due to (i) KV-metas stored in the KV store and ILogs and (ii) Merkle trees in VLogs. Specifically, SACK's storage comprises: (i) enclave states and DEKs (0.04 GiB), (ii) persistent per-ILog insert BFs (0.23 GiB), (iii) ILogs (8.84 GiB), (iv) underlying KV store (8.95 GiB), and (v) VLogs (68.2 GiB) (not shown in the figure). In contrast, TWEEZER shows only 1.8% more storage size than RocksDB. Our observed storage overhead is much less than reported in TWEEZER's paper as it enables compression for plain KV pairs in RocksDB [51], while we disable compression. Compared to ABE (Section 2.2), SACK reduces storage overhead from 83.5% to 39.3%, as it removes the embedding of policies within KV pairs.

Exp#7 (Impact of the number of policies). We evaluate SACK's performance by varying the number of policies. We define 16 attributes (`attr=i`, where $1 \leq i \leq 16$) and generate up to 2^{16} policies by randomly selecting different subsets of the 16 attributes. Since practical ABAC systems typically limit the number of policies (e.g., fewer than 10,000) for efficient access control [40, 90], the range of policies considered here reflects real-world use cases. We load 64 M 1-KiB KV pairs and evenly assign them to different policies. We focus on a single user with a single attribute (`attr=1`) to analyze its performance when accessing a KV store that contains KV pairs with mixed attributes and policies. We let the user issue 5 M reads or writes.

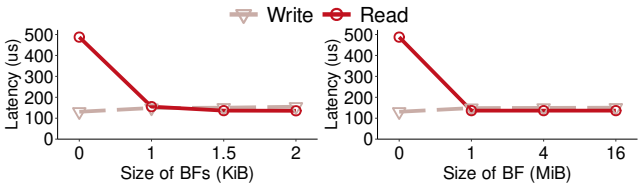
Figure 13(a) shows the initialization time for a different number of policies, starting from when a user connects to the system until the enclave caches all associated PIDs and DEKs in the user-attribute table. The initialization time increases from 8 ms to 326.4 s when the number of policies increases from 1 to 2^{16}. SACK decrypts the DEK by ABE for each policy that contains at least one of the user's attributes, so as to cache the DEK in the user-attribute table. Note that this is only a one-time process when the user first connects to SACK or when its attributes are updated (i.e., Case 1 in Section 4.3), and it does not affect subsequent KV operations.

Figure 13(b) shows the average write latency and the average read latencies for the scenarios when the user has the access rights to successfully read the KV pairs and otherwise. As the number of policies increases from one to 2^{16}, the latency for successful reads increases from 136.3 μs to 152.9 μs, and that for failed reads increases from 95.1 μs to 111.1 μs. The latency for failed reads is 29.3% lower than successful reads, as it does not need to fetch DEKs and decrypt KV pairs. As the number of policies increases, the average write latency increases from 150.3 μs to 321.8 μs. The reason is that the number of available VLog buffers are limited, so VLog buffers are flushed more frequently as more policies are involved, leading to more context switches and disk I/Os. Nevertheless, the latency increase remains acceptable, and the write latency remains much lower than in ABE (Figure 2 in Section 2.2).

With 2^{16} policies, SACK maintains strong read efficiency: its average latency for successful reads remains 78.1% lower than TWEEZER's (Exp#2), while its average write latency is 65.2% higher.

Figure 13(c) shows the time to update a varying number of attributes of a user (i.e., Case 1 in Section 4.3) in the user-attribute table. When the user's number of attributes increases from one to 16, the updating time slightly increases from 10.2 μs to 16.9 μs. Note that after updating attributes, the enclave needs to re-initialize the user-attribute table to cache the DEKs for the new attributes before any KV operations, and the overhead is analyzed in Figure 13(a).

Figure 13(d) shows the rekeying time when some policies are updated (i.e., Case 2 in Section 4.3), in which DEKs with outdated policies are decrypted and re-encrypted with new policies by ABE. Here, we consider the cases where one, four, and 16 attributes are updated, and renew the affected policies that involve at least one of the updated attributes (the affected policies account for 48.8%, 91.6%, and 100% of all policies, respectively). We observe that the rekeying time increases from 112.7 s (for one updated attribute) to 212.7 s (for all 16 updated attributes). Note that the rekeying time does not depend on the storage size of KV pairs, and renewing a single DEK for a policy takes only 3.4 ms.



(a) Varying sizes of IBF, UBF=16 MiB, Cache=1 MiB

(b) Varying sizes of UBF, IBF=1.5 KiB, Cache=1 MiB

Figure 14: Exp#8 (Impact of the sizes of BFs). We vary the sizes of per-ILog insert BFs (IBF) and update BF (UBF), while fixing the in-enclave LRU cache for per-ILog insert BFs (Cache) as 1 MiB. A zero size means BFs are disabled.

Exp#8 (Impact of the sizes of SACK BFs). We evaluate various sizes of per-ILog insert BFs and update BF (Section 4.3) on SACK's read performance. We load 64 M 1-KiB KV pairs and issue 5 M reads. The SSTable BFs of RocksDB are disabled by default (as in RocksDB and TWEEZER). Note that we have also evaluated the effects of various in-enclave LRU cache sizes for per-ILog insert BFs (Section 4.3) and SSTable BFs in the technical report [78].

Figure 14(a) shows that as the per-ILog insert BF size increases, the write latency increases from 130.9 μs (without BFs) to 154.9 μs (2 KiB per-ILog insert BF) as fewer per-ILog insert BFs are cached, while the read latency decreases by 72.2% from 487.5 μs (without BFs) to 135.6 μs (2 KiB per-ILog insert BF) as larger per-ILog insert BFs reduce false positives and ILog reads. Notably, even without BFs, SACK's read latency is still 30.2% lower than TWEEZER (Exp#2).

Figure 14(b) shows a similar trend for the update BF, where the write latency increases from 130.9 μs (without BFs) to 150.3 μs (16 MiB update BF), while the read latency decreases to an average of 136.3 μs (across 1 MiB, 4 MiB, and 16 MiB update BF). The read latency is stable as it only queries the update BF (Section 4.3), while the overall false positive rate mainly depends on the per-ILog insert BF size as the read-only workload has no updates.

To maintain SACK's performance, we recommend users to configure the per-ILog insert BF size according to the ILog capacity and a fixed false positive rate (e.g., 1%) (computed following [12]). For the update BF, we provide two practical strategies: (i) fix the update BF size and adjust the frequency of VLog GC (which resets the update BF) based on the observed update rate; or (ii) fix the VLog GC frequency and adjust the update BF size based on the expected number of updates within the time window between two VLog GC cycles. For example, a 16 MiB update BF can support up to 10.9 M updates with a 1% false positive rate, while increasing its size to 32 MiB doubles the capacity to 21.7 M updates.

6 RELATED WORK

Software-based access control in KV stores. Traditional KV stores implement cryptography-based access control in software [19, 20, 31, 33]. Attribute-based group key management (AB-GMK) [65] lowers the overhead of ABE-based ABAC, and has been used for access management for user certificates [88] and enforcing access control in relational databases [81]. It uses attributes to manage group membership and control access to DEKs, which are used to protect data with symmetric encryption. While SACK adopts a similar approach to protect DEKs with ABE and encrypt data symmetrically, it targets persistent KV stores, decouples policy enforcement from data storage, and leverages SGX to achieve confidentiality, integrity, freshness, and dynamic ABAC. In contrast, AB-GMK offers access control and data confidentiality, but does not natively guarantee integrity or freshness.

Shielded execution for relational databases. Shielded execution has been extensively studied in relational databases, both in academia [9, 26, 58, 75, 92, 93] and industry [3, 16, 98]. TrustedDB [9], ObliDB [26], EnclaveDB [75], SQL Server [3], GaussDB [98], and ApsaraDB [16] execute SQL statements inside an enclave with privacy protection. VeDB [93] uses a native monotonic counter of TEEs and a trusted timestamp for verifiable endorsement. HEDB [58] protects sensitive data against smuggling attacks. SecuDB [92] is a multi-granularity, privacy-preserving, and tamper-resistant relational database within Intel TDX. Our work targets KV stores, with higher performance and scalability than relational databases.

Shielded execution for persistent KV stores. Shielded execution has been applied to in-memory KV stores for secure and fast data access [7, 14, 52, 91, 94], while our work targets persistent KV stores. Concerto [4] stores incremental hashes of reads and writes in the enclave to verify the integrity of KV pairs. VeritasDB [84] provides a secure proxy that uses Merkle B+-trees and SGX to verify data integrity of server responses before forwarding them to clients. TEE-KV [53] applies SGX to blockchains to store transactions in external KV stores. SPEICHER [8] uses SGX in LSM-tree-based KV stores and designs asynchronous trusted monotonic counters to ensure confidentiality, integrity, and freshness. TWEEZER [51] improves the I/O performance of SPEICHER with per-KV-pair message authentication for fine-grained integrity protection. SACK further supports dynamic access control with SGX and outperforms TWEEZER via KV separation (Section 5.2). A closely related work is Pesos [54], which uses SGX and trusted storage (Kinetic Object Storage) to achieve user-defined policy-based access control. In contrast, SACK does not rely on trusted storage. It also supports policy renewal and is compatible with general KV stores.

7 CONCLUSIONS

SACK is a shielded framework that enables secure and efficient dynamic access control in cloud-hosted KV stores. It decouples access control and data management, by managing attributes and policies inside an SGX enclave and leveraging KV separation for secure and efficient data management. Experiments demonstrate SACK's performance efficiency in KV operations and low overhead in access control. Future work includes enhancing SACK with faster scans, recovery, and policy renewal mechanisms, and supporting distributed KV stores with low performance overhead.

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