Sirius: Enabling System-Wide Isolation for Trusted Execution Environments

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Abstract

Hardware-assisted trusted execution environments (TEEs) are critical building blocks of many modern applications. However, the one-way isolation model introduces a semantic gap between TEE and its outside world, including conventional OSs and applications. This causes the most practical and ever-increasing set of attacks on TEE-enabled applications by exploiting various insecure interactions with the host OS and applications. Complex applications rely on many mechanisms on the host OS and TEE system; their complex interactions open a large attack surface that threatens both the trusted and normal worlds. To address this fundamental issue, we introduce Sirius, the first OS and TEE system to achieve system-wide isolation in TEEs. It enables fine-grained compartmentalization, strong isolation, and secure interactions between enclaves and kernel objects (e.g., threads, address spaces, IPC, files, and sockets). Sirius replaces ad-hoc and inefficient forms of interactions in current TEE systems with a principled approach that adds strong inter- and intra-process isolation and efficiently eliminates a wide range of attacks. We evaluate Sirius on ARM platforms, and find that it is lightweight (≈ 15K LoC) and only adds ≈ 10.8% overhead to enable TEE support on applications such as httpd, and improves the performance of existing TEE-enabled applications such as the Darknet ML framework and ARM’s LibDDSSec by 0.05% – 5.6%.

1 Introduction

Hardware-assisted trusted computing primitives such as ARM TrustZone [12], Intel SGX [23], AMD SEV [49] or Keystone [39] exist to establish strong security guarantees in the presence of malicious privileged code. These trusted execution environments (TEEs) assume a threat model in which only the CPU itself is trusted, not the host applications and OS. Therefore, the ideal in-enclave codebase should be small and verifiable with minimal interaction with the outside world [27].

However, in practice, TEEs are used in much more complex applications; secure payment [1, 10, 11, 67], databases [55], DRM [56], autonomous vehicle control [2], and privacy-preserving machine learning [31, 33, 34, 51, 59, 71]. These applications require bidirectional interfaces to enclaves (e.g., shared memory or RPC) and rely on the underlying untrusted system to interact with the external environment. But, existing OSs and TEE systems offer weak security guarantees and expect developers to guard all interaction layers. Hence, we observe severe attacks arising from ad-hoc security models for hosting enclaves on conventional OS.

Previous studies [35, 44, 61, 62, 68, 75, 81, 82] show a wide range of attacks (with and without root) on all primary TEE systems [23, 24, 30, 39]. For example, attackers take advantage of inadequate isolation in the shared address space between an enclave and its host application (see Figure 1). They can compromise host applications via horizontal privilege escalation (HPE) attacks [68], launch ROP attacks [17, 40] to extract cryptography keys and bypass remote attestation, or use BOOMERANG attacks [44] to gain control of the host OS by tricking the secure world into modifying host kernel memory. Attackers can also launch malicious threads inside the host application process to exploit synchronization vulnerabilities such as TOCTTOU [80, 81] or other type of COIN attacks [35] on enclave interfaces (Figure 1). This greatly limits the secure use of enclaves in a multi-threaded application. All these attacks are possible because of the underlying weak security model for sharing, unguarded

1 For simplicity, we use the terms TEE and enclave interchangeably.
shared kernel objects (e.g., address space, files, sockets), insecure threading and concurrent calls, and untrusted IPC/RPC interfaces.

Previous work focuses on reducing untrusted interactions between two worlds via in-enclave LibOSs [13, 15, 54, 72] that port unmodified applications entirely to enclaves via wrappers around the necessary host kernel system calls. For example, SGX-LKL [54] ports a large part of the Linux kernel into the enclave and provides encrypted communication channels. However, this approach has a high overhead, limited compatibility for complex applications, and does not protect the host kernel from the enclave. Compromised or malicious third-party enclaves can collect and leak sensitive data about the user and host system [45, 61] and transfer them through OS standard abstractions such as files or network sockets (Figure 1 ③④). Existing OSs and TEE systems offer no comprehensive protection against such attacks.

We present Sirius – a new set of kernel extensions and a TEE system – as a principled approach for mitigating these attacks in general-purpose OSs by supporting secure sharing, system-wide isolation, and fine-grained privilege separation. We aim to provide necessary abstractions for defenses layers to protect enclaves on one side and the host applications and OS on the other side. To build such a system, we need (i) a coherent security model based on mutual distrust; (ii) identifying the right abstractions to enforce fine-grained, efficient, intra-process privilege separation; and (iii) a new programming model for TEE-assisted applications to define fine-grained trust boundaries.

Since the host environment and TEE worlds have their own security requirements and software stack, extending centralized security models such as MACs [9], system call filtering [8], or namespaces only allows static coarse-grained security policies. We introduce a new security model – dubbed system-wide isolation in TEE-systems (SWIT) – that is inspired by decentralised information flow control (DIFC) [50]. Unlike classic IFC [25], DIFC allows every security principal to define trust boundaries via a set of labels drawn from a partially ordered set and allows communication if the labels satisfy an ordering. SWIT extends DIFC principles to work with TEE systems via: (i) low-overhead thread-granular enforcement of labels within fundamental kernel objects; (ii) isolation across multiple untrusting kernels on the same host; and (iii) secure label management and storage.

Sirius is the first system that comprehensively implements SWIT in a general purpose OS. Our new kernel extensions prove that it is possible to enforce fine-grained, strong security guarantees with reasonable overhead. The Sirius TEE programming model hides the complex details of the underlying information flow control enforcement from developers. It enables TEE hardware to guard complex multi-threaded use cases like the Apache webserver, the Darknet ML framework, and safety-critical applications such as autonomous vehicles or medical devices that rely on secure data distribution services. In summary, our contributions are:

- A new security model (§2): we introduce system-wide isolation in TEE-systems (SWIT) to enable fine-grained compartmentalisation and strong isolation at the inter- and intra-process levels.
- A new architecture and programming model (§3): we present the first kernel extensions across trusted and untrusted worlds that achieve SWIT within kernel objects like threads, address spaces, RPC, files, sockets, and pipes. Our APIs enable TEE-assisted applications to define thread-granular compartmentalisation with hierarchical trust relationships.
- Implementation and evaluation (§4, §5): we prototype Sirius on ARMv7-A platforms by modifying the Linux kernel and the popular TrustZone-based TEE system, OPTEE. Then, we evaluate it via microbenchmarks and real-world TEE-assisted applications, and show that it is efficient even for embedded devices with just a few megabytes of memory.

2 Overview

2.1 Threat Model

Sirius targets numerous userspace attacks caused by insecure interactions between enclaves and primary kernel objects (Figure 1). It assumes a userspace attacker, who can gain full control of a thread inside the host application, use OS services, memory operations, and spawn more threads up to the resource limits. The attacker tries to interfere with the interactions of other threads and
associated enclaves via crafted RPC requests, concurrent calls, shared memory access, or other process resources [35, 81]. She attempts to launch various attacks using the shared address space to extract other thread’s secrets or to gain full control of the host OS [17, 40, 44]. We also assume that it bypasses address space randomization techniques [63] by targeting the non-randomized runtime that handles transitions between the two worlds. These attack models are not mutually exclusive. They can be combined together to exploit more vulnerabilities. We also consider an attacker who can launch a malicious enclave or take control of a vulnerable enclave. The previous scenarios are also valid in this case. The attackers from both secure and normal worlds try to leak secrets through untrusted threads and other kernel objects such as files, network sockets, or IPC.

Sirius considers each userspace thread and enclave thread to be a security principle and enables them to define a wide range of security policies based on mutual distrust. We enforce each thread’s security policy to protect its secrets against unauthorized, accidental, and malicious access or disclosure. Therefore, the TCB consists of the host OS, TEE kernel and a security monitor, which perform this enforcement. It also assumes application developers correctly specify their policies through the Sirius userspace API. This work does not target microarchitectural covert or side-channel attacks [21, 36, 41, 60, 66, 74, 85, 88].

### 2.2 Information Flow Control for TEEs

Our security model, system-wide isolation in TEEs (SWIT), mitigates the many attacks against enclaves. We aim to enable threads, running on both normal and secure world kernels, to define trust boundaries over their resources (Figure 2). SWIT controls how information flows between threads on different kernels on the same host to ensure that only threads that should communicate can do so. It enables both kernels to collaborate for enforcing fine-grained compartmentalization across both worlds while providing an extra layer of defense for shared objects via a security monitor.

Security policies in SWIT are specified with secrecy and integrity tags, labels, and privilege capabilities. A tag has no inherent meaning, and a label is a set of tags. Privileges are represented in form of two capabilities \(\theta^+\) and \(\theta^-\) per tag \(\theta\), that are stored in each thread’s capability list \(C_t = C^+_t \cup C^-_t\) (\(\theta^+ \in C^+_t\) and \(\theta^- \in C^-_t\)). These capabilities enable adding or removing tags to or from labels (similar to Flume [38]). Therefore, each thread \(t\) has also secrecy \((S_t)\) and integrity \((I_t)\) labels, and a set \(D_t \subseteq C_t\) that stores all tags for which \(t\) has both privileges (full control). The normal kernel creates and stores all these lists for its own object, while the security monitor does the same for enclave-related objects. All label operations are done internally within the kernels; each kernel allows secrecy information flow from \(\alpha\) to \(\beta\) only if \(S_\alpha \subseteq S_\beta\), and allows integrity information flow if \(I_\beta \subseteq I_\alpha\). Unsafe operations such as declassification (removing a tag from a secrecy label) and endorsement (adding a tag to an integrity label) require the thread to be an owner or an authority (an acts-for relation [22]).

Enabling SWIT should not lead to new security threats, make the system too restrictive, or make it hard for developers to correctly define their security policies. It should not add large overhead to TEE systems that already feature expensive communications [83]. For example, hardening M:N threading across an application and enclave (e.g., our machine learning example in §5.2.2) should not lead to large labels and slow label propagation. Since shared objects between the two worlds are the most vulnerable parts of our threat model, no single kernel should be allowed to do unsafe operations on them (e.g., declassification and endorsement). Similarly, no thread should be able to manipulate persistent labels after a restart.

**Requirements:** To enable SWIT in a general-purpose OS we assume the presence of: (i) TEE hardware to isolate enclaves’ execution; (ii) a security monitor (SM) at a high privilege level to handle interactions between the two worlds; and (iii) secure persistent storage for enclave-related labels.

Widespread TEE hardware includes ARM TrustZone (TZ), Intel SGX, and AMD SEV. This paper focuses on TZ; however, our design is portable to x86 with straightforward engineering, where the security monitor can be emulated via the host hypervisor or a dedicated SGX enclave. We chose TZ for our prototype since its secure
world is more powerful than SGX enclaves, so exploited enclaves can lead to a full OS compromise. TZ does not directly support attestation as SGX does [23], which increases the possibility of hosting malicious enclaves. Also, billions of embedded devices use TZ-based TEEs, which requires enabling SWIT to be resource-efficient and not introduce the high overhead of a combination of techniques in compilers, sandboxing, and access control that previous x86-based TEE solutions have adopted.

For secure storage, we rely on the SM to encrypt a persistent storage area in its boot file system using a secure storage key (SSK), enclave storage key (ESK), and file encryption key (FEK). The per-device SSK is generated as a function of the unique hardware key and chip ID. The SSK must be stored in secure DRAM that is not accessible by the normal world, and will be used to derive the ESK.

3 Sirius Design and API

Sirius allows application developers to partition their code into multiple trusted components that would be executed inside enclaves. Normal world userspace threads launch these enclaves, and Sirius isolates all layers of interaction between those threads and enclaves by controlling the information flow across their kernel objects (RPC, shared memory, or other kernel objects). Before explaining the details of Sirius’s design, we illustrate at a high-level how Sirius establishes SWIT in Apache webserver (in Figure 3a).

Partitioning: The developer uses Sirius APIs to define two enclaves; an OpenSSL enclave to run cryptographic operations and a storage enclave to store private keys and certificates. The developer then defines the enclaves’ interfaces via a manifest. The build-system cross-compiles the manifest into separate executable enclave binaries and generates UUIDs for each based on the executable hash. This build generates per-enclave security keys, which are persistently stored by the SM.

Compartmentalization: The webserver needs to enforce mutual distrust between the OpenSSL enclave and the normal world. The enclave only needs access to the information required to establish a session key and no other user data. Sirius provides a new isolated memory compartment (IMC) API that enables thread-granularity shared memory protection between the webserver and enclave. Once the OpenSSL EVP code is modified to use this malloc-style memory allocator (§3.2), authorized threads in both worlds gain the convenience and performance of a shared-memory programming model that is only accessible by a subset of threads. Sirius also labels the private keys files for the TLS negotiations to not be accessible to webserver threads.

Enforcement: When the webserver starts, a single normal world thread can now launch the OpenSSL and storage enclaves and only that thread has the right label to interact with these enclaves. The secure kernel loads each enclave binary from the normal world into its dedicated address space in SEL0, similar to launching processes on Linux. The normal world thread then grants the OpenSSL enclave direct RPC access to the storage enclave, and proceeds to revoke its own access to the storage enclave. The normal world thread has now dropped its privileges and the storage enclave can only communicate with the OpenSSL enclave or its own encrypted filesystem.

The webserver uses a thread pool to handle incoming requests. The Sirius version can simply launch the same number of threads within the normal world (to handle external connections) and the OpenSSL enclave (to generate TLS session keys), and dynamically register memory regions so that the worker thread for a given connection only has access to its own session key. If a connection is compromised, that thread has no privileges to do anything beyond reading the one session key. If an enclave thread is compromised, it cannot leak its secrets to the outside world or access user data from the webserver.

We next explain the Sirius enclave lifecycle (§3.1) and
our memory compartmentalization mechanisms (§3.2). We do not describe the partitioning toolchain further, as it is largely consists of build system concerns.

### 3.1 Sirius Enclave Lifecycle

In Sirius, the security monitor (SM) runs in the highest privilege level (EL3). The normal kernel (NK) and secure kernel (SK) run in EL1 and SEL1. The application threads run in user-space processes in EL0 and enclave threads in SEL0. A normal world thread \( p \) calls \( s_{\text{create enclave}} \) to spawn an enclave (see Table 1 for the interface). The NK creates a random secrecy-tag \( x \) and adds it to the thread’s secrecy label \( S_p \) and ownership list \( D_p \). The NK then transfers the message to the SK via an SMC call (Figure 4 (a)). The SM creates and persistently stores a new tag \( y \) for the enclave and notifies the SK to assign both tags to a new enclave user-space thread \( e \), by updating its empty labels to \( S_e \{ x,y \} \) and \( D_e \{ y \} \). The SM enforces message safety from \( p \) to enclave \( e \) by checking that \( S_p - D_p = S_e \cup D_e \). The SM passes the \( y^+ \) capability to the NK for updating \( S_p \) to enable bidirectional calls (Figure 4 (b)).

Both threads have each other’s secrecy-tags but with only the plus capability. The SM is the only authority for declassifying (via \( s_{\text{declassify}} \)) an enclave tag as well as all shared objects between the two worlds. The SM checks the safety of all RPC requests between the two worlds. It ensures that no unauthorized thread can jump to an enclave entry. The SM drops unauthorized messages, and the NK kills the violating thread (Figure 4 (c)).

Each thread can grant privileges to another thread via \( s_{\text{grant}} \), and revoke previously delegated privileges by calling \( s_{\text{revoke}} \). The owner thread can also restrict any access or modifications of its object state by calling \( s_{\text{access disable}} \), which alters the object’s tag temporarily until \( s_{\text{access enable}} \) is called by the thread. This is a useful additional intra-process defense layer when adapting untrusted code or libraries. Child threads do not inherit labels by default (e.g., in the style of \( \text{fork} \)) as this makes it difficult to reason about security [14]. The parent thread can explicitly create a child with specified labels as an argument of \( s_{\text{create}} \).

Each normal thread can also use conventional Linux syscalls to access resources such as files, sockets, or pipes. We extend some syscalls such as open with extra flags (SLABEL/ILABEL) to create a labeled file, as are in \( c_{\text{lone}} \), create and pipe. Once labeled, Sirius controls the information flow within all operations on them via extended kernel abstractions (4.1.4). The other substantial new feature in Sirius is the intra-process memory compartmentalization, described next.

### 3.2 Address Space Compartmentalisation

Our SWIT security model requires intra-process memory protection that is not provided in POSIX-based OSs. We designed a new memory compartmentalization abstraction (MCA) to efficiently overcome this limitation. It introduces isolated memory compartments (IMCs) and enforces IFC on these new address space objects to isolate them across threads in the same address space.

We introduce \( \text{vdom} \) as a contiguous segment of virtual memory (VM). Any virtual address can only belong to one \( \text{vdom} \), and threads can create one or multiple \( \text{vdoms} \) using \( \text{vdom create} \). Each thread creates one or more IMCs (via \( \text{imc create} \)), and the kernel assigns a new secrecy label to each. This enables different threads to have different privileges assigned for a shared \( \text{vdom} \). When a thread has the \( \theta^+ \) capability for IMC \( \theta \), it gains the privilege to access the IMC’s \( \text{vdoms} \) with the permission set by the IMC owner via \( s_{\text{imc grant}} \). Having the declassification capability allows the thread to modify the attached \( \text{vdoms} \) memory layout by adding/removing pages via \( \text{vdom mprotect} \), change IMC permissions via \( \text{vdom mprotect} \), or transfer the content to untrusted sources (e.g., copy to a file, or share with other thread).

Figure 4 (a) shows how both enclave \( e \) and thread \( p \) have access \( (m \in S_e \lor m \in S_p) \) to the shared IMC with two \( \text{vdoms} \), \( M_1 \) and \( M_2 \). Since the enclave is the owner...
The application uses `vdom_malloc` call to allocate contiguous memory blocks within the `vdom`, `vdom_free` to deallocate memory, or `vdom_mprotect` to change its permissions. The thread has fine-grained control over its IMCs and can even protect them against its own untrusted code (e.g., unsafe third-party libraries) through the `s_access_enable/disable` calls. The SM checks all the operations of an IMC that are shared or owned by an enclave thread. The NK does the same for enclave-independent IMCs, so applications can shield their secrets even from their enclave. Using `s_access_disable` restricts any IMC access or modification by accident or via malicious code; this is helpful for attacks inside a single thread. We later show how all these MCA features help to harden libraries such as OpenSSL with minimal in-enclave code (96% reduced enclave code) as an alternative to running it entirely inside an enclave (§5.2.1).

### 4 Implementation

Sirius builds the SWIT security model into the Linux kernel (§4.1) instead of userspace to minimise the TCB and avoid large overheads [38]. The secure world stack is implemented by extending OP-TEE (§4.2).

#### 4.1 Normal world kernel

Sirius adds a new security module in the Linux kernel (version 4.19.42) to govern information flows through fundamental kernel abstractions (§4.1.1). It adds new kernel- and hardware-backed virtual memory abstractions for intra-process isolation (§4.1.2, §4.1.3), and modifies other abstractions for enforcing DIFC within traditional kernel objects (§4.1.4).
### 4.1.1 Sirius security module

Our new Linux security module (LSM) implements a set of clear rules for enforcing SWIT within any primary kernel objects such as inodes, tasks, IMCs, and provides new security hooks (e.g., change_label, check_flow_allowed) that are used in the rest of the kernel to govern the information flow control. The LSM initialises required data structures such as the label registry that caches labels and capability lists per threads. We implemented a hash table-based registry to make operations (store/set/get/remove) on these data structures more efficient. The LSM also handles synchronisation for labeling operations using mutexes and atomic operations.

The LSM stores labels and metadata required for enforcing DIFC in each thread’s cred structure, and modified copy_creds and copy_process to disallow credential inheritance by allocating an empty cred per thread. LSM’s FS-specific hooks are used for managing inodes labels and enforcing the safe flow within files and directories; e.g., via the inode_permission and file_permission security hooks. The LSM provides similar hooks for DIFC enforcement within sockets and pipes, and IMCs.

#### 4.1.2 MCA implementation

We extend the kernel to support efficient intra-process address space isolation via the IMC abstraction. Each IMC maintains a secrecy label and has a private page global directory (pgd_t) that is loaded into the TTBR register during a context switch. Each of these private page tables can isolate vdoms as their permissions depend on the mapped IMC as shown below:

```c
struct vdom_struct {
    int vdom_id;
    struct mutex vdom_mutex;
    struct vm_segment *vdom_range;
    //operation bitmaps: set to 1 if imc[i]
    //is allowed to do this operation, 0 on
    DECLARE_BITMAP(imc_read, IMC_MAX);
    DECLARE_BITMAP(imc_write, IMC_MAX);
    DECLARE_BITMAP(imc_execute, IMC_MAX);
    DECLARE_BITMAP(imc_allocate, IMC_MAX);
};
```

Threads in a process share the same mm_struct that describes the process address space. Having separate mm_struct for threads would significantly impact system performance, as all the memory operations related to page tables should maintain strict consistency. Instead, MCA extends mm_struct to embed vdoms and IMC metadata within it as lightweight regions in the same address space. The pgd_t struct stores a per-IMC pgd_t for threads, and vdom_metadata and imc_metadata stores metadata for memory management and IMC.

The standard Linux kernel avoids reloading page tables during a context switch if two tasks belong to the same process. We modified check_and_switch_context to reload IMC page tables and flush related TLB entries if one of the switching threads owns an IMC. We further mitigate the flushing overhead using tagged TLB features and ARM memory domains (§4.1.3). We modify mmap.c to keep track of mapped vdom memory ranges and extend it with vdom_mmap/munmap operations.

The kernel handle_mm_fault handler is extended to specially manage page faults in IMC regions, so an IMC privilege violation results in the handler killing the violating thread. The extended mm_struct thus contains the following extra metadata per process:

```c
struct mm_struct {
...
#define CONFIG_SW_MCA
    atomic_t num_vdoms; /* number of vdoms */
    atomic_t num_imcs; /* number of imcs */
    struct imc_struct *imc_metadata[IMC_MAX];
    struct vdom_struct *vdom_metadata[IMC_MAX];
    /*vdom Page tables per threads.*/
    pgd_t *pgd_imc[IMC_MAX];
    DECLARE_BITMAP(imc_inuse, IMC_MAX);
    DECLARE_BITMAP(vdom_inuse, IMC_MAX);
    int curr_using_imc;
    spinlock_t ptl_imc[IMC_MAX];
    struct mutex imc_metadataMutex;
#define...
};
```

#### 4.1.3 Hardware-backed MCA

We provide an optional optimization for our MCA implementation by utilizing ARM memory domains (MDs) [12] if supported by the hardware. ARM-MDs are a lesser-known memory access control mechanism that is independent of paging. Each page table first-level entry has 4 bits allocated to support 16 memory domains. Access control for each domain is handled by setting a domain access control register (DACR) in CP15, which is a 32-bit privileged register. Changing domain permissions are low cost and do not require TLB flushes, and any access violation causes a domain fault. The table below shows the four possible access rights for a domain.

| Mode   | Bits | Description                      |
|--------|------|----------------------------------|
| No Access | 00   | Any access causes a domain fault.|
| Manager | 1    | Full accesses with no permissions check. |
| Client  | 01   | Accesses are checked against page tables. |
| Reserved| 10   | Unknown behaviour.               |

The optimised MCA maps vdoms to hardware domains instead of separate page tables, and so supports up to 16 1MB-aligned vdoms. Sirius provides a separate set of kernel memory management functions similar to their Linux equivalents (e.g., do_mmap, do_munmap and do_mprotect) for mapping vdoms to hardware domains. Due to the reduced number of TLB flushes and faster context switches, using ARM-MDs improves the cost of
Sirius threading by 38% (§5.1). The hardware-backed MCA improves the performance of vdom_mmap/munmap by 48% due to the simpler mechanism of memory mapping to the memory domain instead of page tables. It also improves the performance of vdom_mprotect (1.14x faster than mprotect) if the requested permission change matches one of the supported hardware options; otherwise, the cost is the same as vdom_mprotect. The optimised MCA also has a more lightweight fault handler that utilise domain faults instead of full page faults.

4.1.4 Tracking flows within the kernel

We modified the VFS layer to enforce thread’s security policies within all operations on inode, file, and VFS address space objects; these kernel abstractions are used to perform operations on unopened files and file handles (including sockets and pipes). Most inode operations (e.g., create, link, mknod, mkdir, permission) require a lookup to find related inodes and dcaches; hence, we modified the kernel namei to disallow unauthorized information flow at early lookup stages.

We extended the open syscall with two new flags (SLABEL and ILABEL) that a thread can use to create a labelled file (e.g. O_CREAT | SLABEL) and added file/inode_permission security hooks on necessary places to disallow unauthorised file operations like read/write/stat/stat(seek). A malicious thread may also try to map a labelled file to an address space object via writepage. Sirius checks that labelled files are only be mapped to IMCs with the right labels via vdom_mmap.

The label of an inode protects its contents and its metadata. In a typical filesystem tree, secrecy increases from the root to the leaves. To ensure writing a new entry in a parent directory does not disclose secret information, we disallow a thread with secrecy label S{x} from creating a file with the same secrecy label in an unlabelled directory since it leaks information through the filename. The LSM lets a thread with non-empty labels S_p, I_p create a labelled file or directory with labels S_d, I_d, if the label change is safe and the thread can write to the parent directory with its current label. Sirius stores normal files’ labels in the extended attributes, or in the SM storage if the file is an enclave-shared/owned object.

We also modified the kernel to enforce DIFC in socket operations like create, listen, connect, sendmsg, and recvmsg. This was done by placing security hooks in those functions and at the end of the lookup process (e.g., socketd_lookup_light). All operations for unlabelled threads and unlabelled objects follow the traditional Linux access control mechanisms, so applications not using Sirius do not require any modifications. Similarly, Sirius controls information flow within pipes, so a thread may read or write to a pipe as long as its labels are compatible. Sirius does not allow a labelled thread to connect to a socket unless that thread has the declassification capability for the accessed secrets. Messages that cannot be delivered are rejected silently to avoid leaking information by returning errors.

4.2 Secure World Kernel and Monitor

We extend OP-TEE V3.4 secure kernel and monitor (optee_os), and the TEE driver (libTEEC) to enforce DIFC within enclave threads, RPC messages, and shared memory. The OP-TEE security model is based on GlobalPlatform [29] API parameter security checks. It checks RPC messages by validating arguments, buffer sizes, and directions flags at every layer of privilege (EL0, EL1, EL3, SEL1, SEL0). However, these checks have been bypassed many times [26]. For shared memory, OP-TEE checks the address range, cache attributes, and size of allocated memory chunks. This is also insufficient in many cases (§2.1); for example, to avoid BOOMERANG attacks, the authors extended OPTEE with the CSR-based pointer verification [44]. Our security model is based on fine-grained compartmentalisation and isolation rather than error-prone security checks.

Security Monitor: We first modified the optee_os security monitor (core/sm), which is the entry point of RPC messages between the two worlds and runs at the highest privilege level. We extended the monitor to label each enclave, and store labels and capability lists in sm_cred, a new data structure. IFC over RPC requests is enforced by adding a security module similar to our LSM (§4.1.1) to the SM. When an RPC is safe and leads to label changes, the monitor transfers its sm_cred data structure to the secure and normal worlds to each update their thread labels accordingly.

Secure Kernel: The unmodified OP-TEE secure kernel assigns a static number of threads for each enclave (CFG_NUM_THREADS). Execution of enclave threads is tied to the execution of the caller thread and scheduled by the Linux kernel. The secure kernel uses several L1 translation tables (one spanning 4GB) and some smaller tables spanning 32MB. The large translation table handles secure kernel mappings (TBR1), and the small tables are assigned per thread and map enclave contexts to its dedicated VM. We also extend the secure kernel to enforce IFC within enclave threads, RPCs, and memory objects.

Enclave Userspace: We replaced the OP-TEE shared memory mechanism with an IMC-assisted one via new ioctl calls to the OP-TEE driver (e.g., TEE_IOC_SHM_SIRIUS_ALLOC). We also added support
for the enclave-side versions of the MCA. Enclave threads now benefit from the fine-grained shared memory protection described in the Linux MCA (§4.1.2).

The original OPTEE supports a limited encrypted storage mechanism using a (non-POSIX) interface to the Linux filesystems. While useful for storing enclave-related keys, it is impractical for applications with moderate I/O requirements (§5.1). We extended OPTEE to provide labeled access to the Linux FSs, allowing enclave threads to control their files without high overhead.

5 Evaluation

We have so far explained how Sirius implements SWIT to guard applications partitioned across normal and secure worlds (§4). Sirius reduces the overhead of DIFC significantly by: (i) enforcing and tracking labels in the kernel abstractions rather than userspace; and (ii) adding a new abstraction for address space compartmentalisation to achieve intra-process memory isolation (§4.1.3). We next examine the impact of these choices, with microbenchmarks (§5.1) and poring applications (§5.2).

Our evaluation is done on Raspberry Pi 3 Model B [7] with a 1.2 GHz 64-bit quad-core ARM Cortex-A53 processor with 32KB L1 and 512KB L2 cache memory, running a 32-bit unmodified Linux kernel version 4.19.42 and glibc 2.28 as the baseline. We modified Linux to implement SWIT within the normal world (§4.1). Our kernel patch only adds ≈ 10K LoC, of which the Sirius LSM (§4.1.1) is ≈ 5.4K new LoC and the MCA modifies ≈ 2.5K LoC within the virtual memory layer (§4.1.2). The hardware-backed MCA required fewer changes as it bypassed much of the existing Linux code by using hardware domains (§4.1.3). The remaining changes are mostly done to VFS and networking layers (§4.1.4). We extended OPTEE V3.4 to implement SWIT within the secure world. Our modifications add ≈ 2K LoC to the security kernel and monitor, and ≈ 3K LoC to the TEE driver and userspace API.

5.1 Microbenchmarks

What is the overhead of Sirius on a baseline Linux kernel? How much does the Sirius LSM affect the performance of general OS services such as filesystem, networking, threading, and memory operations? How effective is the use of hardware memory domains for optimizing MCA?

Linux: We used LMbench 3.0 [46] to evaluate the overall overhead of our Linux modifications compared to the baseline kernel (Figure 5a). The results show that enabling Sirius on all file systems causes ≈ 1.2x slowdown. Figure 5b shows that Sirius protection is ≈ 81x faster than the OPTEE secure storage mechanism, which uses a heavyweight forwarding mechanism to the Linux. The Sirius labelling approach has reasonable overhead, and makes it far easier to securely share resources across the host application and enclave. Latency overhead is ≈ 0.7% on LMbench networking benchmarks.

Threading: We tested the cost of creating and joining (using waitpid) Sirius threads using clone with the new SLABEL flag that creates a secrecy-tagged thread. We also run pthread and fork microbenchmarks on the baseline kernel. The table below shows the average latency (µs) of 100000 runs with 1MB and 2MB heap sizes.

| Operation     | fork  | pthread | s_clone | hw s_clone |
|---------------|-------|---------|---------|------------|
| Launch (1MB)  | 280.24| 31.17   | 51.80   | 31.98      |
| Join (1MB)    | 832.45| 1.10    | 3.78    | 1.70       |
| Launch (2MB)  | 331.40| 31.51   | 51.83   | 32.1       |
| Join (2MB)    | 1126.69| 1.13   | 3.82(3) | 1.78       |

Forking is far more expensive than baseline threads with shared address space. The Sirius threads are slower than pthreads due to the overhead of our MCA-based memory isolation, but with our hardware-backed MCA optimization, Sirius threads add only 2.5% overhead com-
pate to pthreads. This highlights the importance of utilizing HW-based VM tagging for optimizing MCA.

**Enclave operations:** Our changes to OP-TEE replaced checks spread throughout it with SWIT-enabled enclave operations that improves flexibility and performance. The table below reports the average of 20000 runs of our microbenchmark that shows Sirius secure world is ≈ 8.3% faster than unmodified OPTEE with baseline Linux.

| Latency (µs) | OP-TEE | Sirius SK |
|-------------|--------|-----------|
| create enclave | 99.82 ± 0.02 | 93.95 ± 0.01 |
| delete enclave | 30.02 ± 0.01 | 30.10 ± 0.01 |
| enclave calls (ecall ocall) | 22.68 ± 0.01 | 20.14 ± 0.03 |

**Memory allocation:** We next test our memory compartmentalisation overhead, first for shared memory allocation. We test baseline OP-TEE, and the BOOMERANG [44] CSR code that adds additional pointer verification to OP-TEE, with our IMC-based approach. The following results show that Sirius shared memory protection outperforms both by ≈ 16% and ≈ 31%, respectively, while providing stronger and thread-granularity address space isolation.

![Memory allocation graph](image)

**Memory protection:** We measure the cost of memory protection for baseline Linux where protection is per-process, and on Sirius threads where protection is per-thread and either implemented in software (§4.1.2) or hardware (§4.1.3). The next graph shows the average results of 10000 runs of our microbenchmark comparing the cost of vdom_mprotect with mprotect on baseline kernel. The results show vdom_mprotect is 1.12x slower than mprotect, but the hardware-backed Sirius vdom_mprotect is 1.14x faster than baseline for some permissions (none and r/w) that supported by DACR register and do not need a TLB flush (§4.1.3).

5.2 Protecting Applications with Sirius

Sirius aims to make the usage of TEE systems more widespread in conventional applications, as well as improve the security of existing TEE-assisted applications.

We chose three applications to comprehensively adapt to the Sirius APIs. Firstly, the popular Apache httpd can be adapted to run with reasonable overhead under Sirius (§5.2.1). Then we port two popular TEE-assisted applications – a machine learning framework (§5.2.2) and DDS-based control system (§5.2.3), and show how our system-wide isolation improves their security and performance at the same time. Figure 3 illustrates the ported architecture of all three applications.

**5.2.1 Apache httpd and OpenSSL**

We earlier described the architecture of the enclave-protected httpd in Sirius (§3). We built a TEE-assisted OpenSSL using two enclaves, and only modified ≈ 2.4K LoC out of ≈ 533K LoC. The ported httpd protects all private keys, session keys, and certificates and operations on them from any unauthorized thread by defining SWIT-based trust boundaries in both normal and enclave worlds. It forbids a malicious enclave thread from transferring secrets through uncontrolled channels to another enclave, or via untrusted memory, or via a file or networking sockets. A malicious httpd worker thread cannot compromise the enclave by crafting RPC requests or modifying shared memory or even by gaining root privilege unless also compromising the host kernel and security monitor to obtain the right labels. It also provides in-depth mutually distrustful isolation of stored data, metadata, and binaries on the host filesystem for both enclaves and httpd.

We modified OpenSSL libcrypto to support a protected heap via a shared IMC owned by our EVP_enclave. All the data structures that store private keys (EVP_PKEY) now use the Sirius vdoms memory operations such as vdom_malloc/free that is replace with original CRYPTO_malloc/free. The EVP_enclave thread is the owner of this protected heap. Sirius protects the secrets that are being processed in this memory region, usually via cryptography operations such as EVP_Encrypt/DecryptUpdate or pkey_rsa_encrypt/decrypt. The main httpd thread grants the plus capability to the EVP_enclave for communication with the storage_enclave to store encrypted

See CVE-2019-0211 or CVE-2019-0217, among others.
content, keys, and certificates inside storage that is labeled to be hidden from other threads. The EVP_enclave thread is also the owner of all the OpenSSL files and directories (e.g., OPENSSLDIR) to restrict unauthorised or accidental information leaks.

Figure 6 shows the overhead of ApacheBench applied against the original OpenSSL library on a baseline kernel and the Sirius-assisted httpd. ApacheBench ran with a timeline of 5 minutes for each request size, with the TLS1.2 DHE-RSA-AES256-GCM-SHA384 algorithm cipher suite. The results show that Sirius-enabled httpd adds \( \approx 10.8\% \) overhead on multithreading benchmark. This is a very reasonable overhead for an application that now gains fine-grained isolation with defense-in-depth layers to protect its secrets against threats from both the normal and secure world, which was not possible without Sirius.

5.2.2 Privacy-preserving ML

TEE-assisted ML frameworks such as DarkneTZ [48] are designed to avoid membership inference attacks (MIA) [65] against ML models and training data [33, 58, 76]. We modified DarkneTZ to protect it against attacks that require even finer-grained compartmentalisation.

Darknet is a heavily multithreaded application that launches many threads for training and processing sensitive data that could potentially misbehave. Sirius ensures that only authorised threads can issue queries to the enclave, providing another layer of protection against MIA attacks. Sirius labels the ML models stored in the host filesystem to be hidden from any untrusted thread and restricts enclaves from transferring the models or any processing data to untrusted sources.

We ported OPTEE-based DarkneTZ to Sirius with only minor modifications (318 LoC) to provide full-system security guarantees. We modified the Darknet classifier (classifier.c) to launch secrecy-tagged threads for communicating with enclave layers and used regular threads for the rest of the data loading logic. We utilized Sirius-guarded RPC and shared memory operations, and protected all sensitive resources such as config (/cfg), models (/models), and data (/data) on the host OS.

We evaluated the performance using AlexNet, which has five convolutional layers. We train a model with four layers outside and one layer inside an enclave using CIFAR-100 [37] for both training and inference. CIFAR-100 includes 50k training and 10k test images belonging to 100 classes. The table below shows the Sirius overhead compared to OP-TEE and the baseline when all layers run in the normal world.

| Operation    | Baseline (µs) | Sirius (µs) | OPTEE (µs) |
|--------------|---------------|-------------|------------|
| training     | 75234         | 78486       | 85354      |
| pre-trained  | 68753         | 73987       | 76453      |
| inference    | 33.23         | 36.32       | 38.45      |

Sirius outperforms OPTEE-based DarkneTZ by \( \approx 5.6\% \) and on average adds \( \approx 9.2\% \) overhead compared to baseline Darknet, despite the improved layers of isolation and amount of data flowing across the normal and secure worlds.

5.2.3 Secure DDS

Security-sensitive IoT applications such as autonomous vehicles or medical devices use TEE-assisted data delivery service (e.g., ARM LibDDSSec) enclaves for security-critical tasks. Sirius hardens LibDDSSec handlers for authentication, protecting data samples, secret sharing, and certificate operations, which all require secure interactions with the normal world. The changes ensure that all shared data from other nodes are protected while being processed (via IMC) and while at rest (via labeled files). Only trusted threads can exchange safety-sensitive messages, control messages, critical system data (e.g. emergency start/stop), and sensor data (e.g. temperature, laser, camera).

We modified dsec_ca.c to replace the OPTEE RPC and shared memory with Sirius-protected operations. Sirius restricts any node from leaking private content
They have often been missing defense-in-depth, and one via principled approach. Based privilege separation [19, 43, 64, 79], mandatory based isolation [18, 20], namespaces [3–5, 53], capability-based techniques for compartmentalisation using process-ically one of the main jobs of OSs. There are various layers of defense both in normal and enclave worlds and intra-process levels, so applications can architect various layers of (§2.1). Sirius is the first OS and TEE system that considering the large attack surface that Sirius defends proving the security of applications, these systems are not filterings [8] for sandboxing enclave malware. Despite improving the security of applications, these systems are not considering the large attack surface that Sirius defends against (§2.1). Sirius is the first OS and TEE system that offer collaborative system-wide isolation at both inter- and intra-process levels, so applications can architect various layers of defense both in normal and enclave worlds via principled approach.

**Related Work & Discussion**

Our goal with building Sirius has been to understand how to securely integrate TEE hardware, which is now prevalent in modern systems, on conventional OSs. Existing solutions have explored some aspects, but have not considered system-wide isolation for complex applications. They have often been missing defense-in-depth, and one attack breaks through the TEE protections and results in data compromise (§1).

**TEE systems:** There are several TEE systems such as Intel’s SGXSDK [23], Microsoft’s Open Enclave [24], Komodo [27], Google’s Asylo [30], OP-TEE [6], Sanctuary [52], and Keystone [39] that enable enclave-assisted computations. Also, in-enclave LibOSs [13, 15, 70, 72] ports a large portion of OS personality inside enclaves for running unmodified applications entirely to enclaves. EnclaveDom [47] utilizes Intel MPK to provide memory isolation within such monolithic in-enclave LibOSs, and MPTEE [89] uses Intel MPX for providing protected shared memory for SGX enclave-enabled applications. SGXJail [82] uses process-based isolation and syscall filtering [8] for sandboxing enclave malware. Despite improving the security of applications, these systems are not considering the large attack surface that Sirius defends against (§2.1). Sirius is the first OS and TEE system that offer collaborative system-wide isolation at both inter- and intra-process levels, so applications can architect various layers of defense both in normal and enclave worlds via principled approach.

**OS-assisted solutions:** Providing isolation is historically one of the main jobs of OSs. There are various techniques for compartmentalisation using process-based isolation [18, 20], namespaces [3–5, 53], capability-based privilege separation [19, 43, 64, 79], mandatory access controls (MACs) [43, 84], and syscall filtering [8]. Despite working well for protecting the host OS, they are not designed to protect multiple independent and mutually untrusting kernels running, as is the case in the TEEs. Sirius is the first system to work alongside these in Linux and without large per-process protection overhead [38, 77] or reliance on a specific language [57]. Many systems provide intra-process memory protection [16, 28, 32, 42, 69, 73, 78]. Our MCA offers efficient intra-process isolation as a part of Sirius’s system-wide compartmentalisation goals. DIFC-based systems [38, 77, 87, 87], and in particular HiStar [86], inspired our work; However, these systems are not designed to achieve Sirius’s goals for providing system-wide compartmentalisation in TEE systems on conventional OSs.

Our experience with building Sirius has shown a sweet spot for the adoption of DIFC as the core of our SWIT model to enable mutually-distrustful isolation between trusted and untrusted worlds; this allows both worlds to combine their features without leaking information. However, this was not practical without (i) our kernel extensions to reduce the overhead of labeling within Linux kernel abstractions, and in particular, within address space objects; and (ii) our APIs to hide the underlying complexities that allow our ported applications to gain many layers of protection and very natural integration with Linux programming facilities.

When porting applications to Sirius, we learned two important lessons on the usability of Sirius: Firstly, since DIFC works best when a clean definition of trust boundaries is possible. The right set of APIs that enables applications with simple compartmentalisation and seamless labeling, such as our extension to existing kernel syscalls, plays a significant role in adopting complex applications. In particular, in TEE systems, a typical target application already has a relatively clear sense of its secrets (for example, private keys or data models) to isolate inside enclaves, as well as its coarse-grained trusted and untrusted partitions; this is a perfect match for defining even more powerful trust boundaries. Secondly, it turned out to be straightforward to compartmentalise security-sensitive memory pieces of TEE-assisted applications using our intra-process MCA. For instance, after partitioning enclave and untrusted components, we only needed one or two IMCs for shared memory and another IMC for isolating the rest of the application from its enclaves. In our experience, we never needed more than 16 IMCs, so we could gain the performance advantages of our hardware-backed MCA support that utilizes hardware memory domains for VMA tagging.
7 Conclusion

We have presented Sirius, the first system that establishes system-wide isolation by enforcing fine-grained information flow control within enclaves and kernel objects. Sirius provides a pragmatic solution by selectively extending the Linux kernel and introducing new abstractions where needed. We have ported applications to Sirius that would otherwise not have fully benefited from TEE hardware, and also shown both performance and security improvements in existing TEE-assisted applications.

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