Let the Cloud Watch Over Your IoT File Systems

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Abstract

Smart devices produce security-sensitive data and keep them in on-device storage for persistence. The current storage stack on smart devices, however, offers weak security guarantees: not only because the stack depends on a vulnerable commodity OS, but also because smart device deployment is known weak on security measures. To safeguard such data on smart devices, we present a novel storage stack architecture that i) protects file data in a trusted execution environment (TEE); ii) outsources file system logic and metadata out of TEE; iii) running a metadata-only file system replica in the cloud for continuously verifying the on-device file system behaviors. To realize the architecture, we build Overwatch, a TrustZone-based storage stack. Overwatch addresses unique challenges including discerning metadata at fine grains, hiding network delays, and coping with cloud disconnection. On a suite of three real-world applications, Overwatch shows moderate security overheads.

1 Introduction

Smart devices, such as security cameras, voice assistants, and cleaning robots, emerge to be important cyber-physical systems. Unlike generic platforms such as PC, a smart device centers on a specific mission, e.g., capturing/analyzing videos or responding to voice commands. For engineering ease, they typically run commodity OSes such as Linux [63, 44, 84].

During operation, smart devices continuously generate data, e.g. video footage, floor maps, and flight logs. On one hand, the data is often confidential, e.g. for containing personally identifiable information; uploading the data to public cloud is often undesirable. On the other hand, the data often has high business value, e.g. for containing important traffic events; data loss should be prevented. Smart devices, in the face of limited memory and possible power failures, often write the data to local non-volatile storage and may retrieve the data for processing later. In this process, the data is handled by a storage stack which spans file systems, the block layer, and storage hardware, as shown in Figure 1(a). It is the storage stack’s responsibility to safeguard the data: not only keeping the data confidential but also assuring that the data has been correctly kept persistence and can be retrieved in the future.

Unfortunately, the storage stack on today’s smart devices is incapable of such guarantees. Vulnerabilities in file systems and their runtime environment, a commodity OS kernel, are not uncommon. The threats are further amplified by smart devices’ weak IT management, e.g. weak passwords and delayed security patches [57, 88, 56, 30]. Attackers, on-device or remote, may exploit vulnerabilities through the user/kernel interface or the interface exposed by privileged network services and hence compromise the smart device OS kernel. They may learn the data, inject fabricated data, or delete data covertly.

Prior solutions were inadequate in addressing these threats. Cryptographic file systems [28, 83, 89] are subject to Iago attacks from a compromised kernel [31]. They can only detect data integrity violation in retrospect which is less effective for memory-limited smart devices: upon the detection of violation, the data may already be lost permanently. File system checkers [49, 42] and kernel checkers [43, 22] look for violation of envelope behaviors and also do so in retrospect. These checkers often demand substantial CPU/memory resource, likely unavailable on smart devices. Kinetic disks [65] push the check logic down to storage hardware; it requires new hardware support yet to be seen on off-the-shelf smart devices.

Modern CPUs offer Trusted Execution Environments (TEE) which are strongly isolated from the commodity kernel. ARM TrustZone supports a TEE to fully own physical
memory regions and storage hardware, e.g. an eMMC RPMB partition [77]. While a TEE is already used for isolating program code that accesses security-sensitive data [48] and the underlying storage hardware, it sees difficulty in enclosing file systems, the largest portion of the storage stack. On one hand, commodity file systems are diverse, feature-rich, and have deep dependency on the kernel. Porting them into TEE would bloat the TEE with substantial file system and kernel code (as well as their vulnerabilities). On the other hand, reinventing new file systems for a TEE, commonly seen in today’s TEE-based systems [58, 8], gives away mature features of commodity file systems and fragments the file system ecosystem.

To achieve strong security properties while reusing existing file systems as much as possible, we follow the principle of least privilege [76] and take an outsource and verify approach: keeping any storage code out of TEE, as long as the code needs no access to data; verifying the outsourced code with a trusted party. This raises three primary questions.

First, how to identify a clean, narrow boundary for outsourcing? Rather than relying on sophisticated code analysis and slicing [69], our insight is that the boundary already exists in a commodity kernel: all file systems export generic interfaces to the page cache above and to the block layer below (see Figure 1(a)). The interfaces only contain several functions that work in a message-passing fashion. Hence, we partition the storage stack at these two interfaces and outsource file systems in between. This makes the current functional boundary a protection boundary.

Second, how can a file system operate properly when it is strongly isolated from the underlying storage? Our insight is that file systems, in principle, operate only on metadata but not file data. Hence, we keep file data inside the TEE while serving the metadata to the file system outside of the TEE.

Third, which party can be trusted for verifying the behaviors of outsourced file system? Our insight is that the cloud, with rigorous security management, offer a more trustworthy execution environment than smart devices. Therefore, we run a novel, metadata-only file system replica in the cloud; the replica’s sole goal is to validate the behaviors of the local file system. This is shown in Figure 1(b). At run time, the TEE sends any invoked file APIs to a pair of twin file systems: the local, untrusted file system (“evil twin”) and an in-cloud, trusted replica (“good twin”). The TEE may perform storage operations advised by the evil twin (fast), but will only accept the outcome when the good twin confirms the operations (slow).

The resultant advantages are threefold. We offer strong confidentiality: file data never leaves the on-device TEE (not even to the cloud). We bring the trustworthiness of the storage stack on smart devices to the level of its counterpart running in a rigorously-managed datacenter. We reuse unmodified commodity file systems and only add light code to the TEE.

To make the approach practical, we address multiple unique challenges: ensuring file data to flow only in TEE, discerning metadata at fine grains, hiding network delays, and continuing serving file access even when the cloud is disconnected. We build Overwatch, a concrete implementation based on ARM TrustZone with a suite of new designs. Our experiments show that Overwatch’s security mechanism incurs moderate overhead in representative smart device applications: 15%–45% increase in application latency and 5% loss in application throughput.

This paper makes the following contributions:

- Towards securing storage on smart devices, we conduct an analysis of their file IO, the attacks they face, and how existing solutions fall short in defeating attacks.
- We present a secure storage stack architecture for smart devices. It outsources file system logic and metadata while protecting file data. It runs a novel, metadata-only file system replica in the cloud for continuous verification. We analyze how the new architecture thwarts the aforementioned attacks.
- We build Overwatch, a concrete secure storage stack that incarnates the proposed architecture. Overwatch addresses system challenges with a suite of novel designs, including secure data path, metadata stencils, and emergency files.
- We demonstrate that Overwatch works with ext2 and f2fs, two popular, unmodified file systems. Atop Overwatch, we build multiple real-world smart device applications which show moderate security overhead.

2 Background & Motivations

2.1 TrustZone and its unique features

A Trusted Execution Environment (TEE) is isolated by hardware, as exemplified by Intel SGX [72] and ARM TrustZone [2]. Unlike SGX, TrustZone partitions all hardware resources of a System-on-Chip (SoC) into a normal (insecure) world and a secure world. In particular, the security of our system benefits from the following TrustZone features:

1) Physical memory partitioning. Unlike SGX where the untrusted OS maps memory pages to the TEE dynamically at runtime, TrustZone partitions the physical memory statically at boot time. The normal world is strongly isolated from the secure memory and therefore cannot mount controlled-channel attacks [85] against the latter.

2) IO partitioning. Unlike SGX where TEE accesses IO through the untrusted OS, TrustZone isolates peripherals by statically assigning them to different worlds at boot time. It does so by assigning IO interrupts and IO memory regions through the TrustZone Protection Controller. This allows the secure world to fully own on-device storage hardware, e.g. one SD card or a specific partition on an eMMC device [77]. We refer to such storage devices owned by TEE as secure disks1 in the remainder of this paper.

1While recognizing that smart devices often use flash-based storage, we
2.2 The storage stack

We use Linux, one of the most popular OSes for smart devices [16, 63, 44, 84], as the example. The storage stack is illustrated in Figure 1(a). At its top, the stack provides a Virtual File System (VFS) layer, which caches recent file data (via a page cache) and exports a set of common APIs for all file systems (e.g. ext3 or f2fs) to implement. All file systems invoke a common block layer, which serves block I/O requests from the former and accordingly drives the disk (through device drivers) below.

In response to a client’s file API invocation (e.g. “read 42 bytes from /local/data at offset 100”), VFS first attempts to serve the invocation from its page cache. Upon cache miss, VFS invokes the underlying file system, which translates the API invocation to disk block operations (e.g. “read from block 21”). The block operations are served by the block layer. In this process, the file system inspects metadata, e.g. inode table, for which it may trigger additional block operations. At the end, the kernel copies the read block data to the page cache and then the client’s buffer. File write is a mirror process.

2.3 File IO patterns on smart devices

Unlike general-purpose platforms such as servers and PCs, smart devices are single-purpose, e.g. security cameras for surveillance, robots for cleaning floors, voice assistants for responding to user commands. During operation, a smart device generates data pertaining to user interest or its own operation. Our study of multiple off-the-shelf smart devices (see Section 5 for details) reveals the following IO patterns which have strong implications on our security objectives.

User data is the focus of protection We use “user data” to refer to the data produced by smart device operations. Examples include captured videos, learnt user voice models, and robot operation logs. User data is often privacy-critical, e.g. user models may be tracked back to individuals; the data is often business-critical, e.g. captured videos may contain important crimes and accidents. It is crucial to prevent user data leakage and loss.

Besides user data, smart devices are preloaded with system data, e.g. program binaries or configuration files, often located in directories different from user data. System data has lower value for protection: one could dump the system data from any off-the-shelf smart device of the same model.

Directory structures are pre-defined On smart devices, the structures of file directories, including the tree topology, the numbers of subdirectories at each tree level, and the numbers of files in each subdirectory, are typically pre-defined at device development time. They cater to the device’s application logic and often remain unaffected by user data discussed above. One could learn the pre-defined directory structure by dumping the storage of off-the-shelf devices [84, 44].

We find this pattern in most, if not all, popular smart devices. i) Security camera systems, including WyzeCam [63] and MotioneyeOS [16], store captured videos as same-length footage, under directories organized by time ranges. ii) Voice assistants, such as the opensource Mycroft [7], keep each user-defined rule (“skill”) and the corresponding response in a dedicated directory; while operating, it stores captured voices as same-length clips under /tmp. Amazon Echo Dot, a commodity voice assistant, is likely to have similar behaviors based on the limited information revealed in reverse engineering [84]. iii) Robot cleaners, such as Xiaomi Mi, stores all the operation logs as well as the floor map in one specific directory [44]. iv) Drones, such as DJI Phantom 2, stores all sensor data (e.g. images with EXIF data) in a directory structure similar to security cameras [64].

Block access patterns are regular Being single-purpose, smart devices show regular block-access patterns as driven by their application logic, which again is orthogonal to user data.

Regardless of captured video contents, a security camera creates new directories periodically and keeps appending data to video files. During one operation, the cleaning robot keeps appending to log files; after the operation, it reads back log files sequentially and writes to a floor map file sequentially. A voice assistant periodically scans its “skill files” and write recorded audio samples to wav files sequentially.

Such regular access of file contents, combined with access to pre-defined directory structures, result in regular, repetitive block traces, e.g. querying the super block, read one metadata block and a fixed number of data blocks, and write one metadata block back.

Implications On smart devices, the user data resulted from device operation should be the focus of protection. By contrast, the system data, the directory structures, and the block access pattern, are pre-defined, can be learnt by analyzing off-the-shelf devices, and therefore have lower security values.

2.4 Security threats & design objectives

Smart devices suffer from common weakness of IoT, notably weak passwords and delayed security patches [79, 82]. Local and remote adversaries, through compromising the smart device OS, can break the security of user data.

Example attack paths are as follows. i) A local unprivileged adversary may exploit file system bugs to corrupt the file data [11, 12]. ii) Local unprivileged adversaries may exploit kernel vulnerabilities through the user/kernel interface [15]. iii) Remote adversaries may exploit may exploit vulnerabilities in privileged network services (e.g. an HTTP server [13]) or the kernel network stack [14]. For ii) and iii), a successful adversary either gain the root privilege or become capable of executing arbitrary code in the kernel context. She then replaces key functions in the file system, e.g. submit_bh() which moves data to/from the block layer. Her own malicious
substitute for the function may to reveal, modify, or drop the user data in the file system.

**Observation: cloud as a more trustworthy environment**

Like smart devices, the servers in datacenters also face threats from the vulnerabilities in their system software. Unlike smart devices, the servers are hosted in a more trustworthy environment. i) Datacenters follow rigorous standards [47] and mature protocols [74] in the face of incidents and vulnerability. By contrast, smart devices are often configured in batches and weakly [78]; their much delayed security patches leave a large window of attacks. ii) Datacenters can afford heavyweight security measures including frequent kernel introspection and regular file system checkers. By contrast, these measures are often unaffordable to a smart device, which only has a few CPU cores, a few GB DRAM, and limited power supply.

Fortunately, today’s smart devices are typically designed under the assumption of cloud connectivity for enriching their functionalities. This observation motivates us to secure the smart device storage with the assistance of the cloud.

**Objectives** *Strong confidentiality for file data.* We ensure that user data never leaves the on-device TEE. Catering to smart device file IOs (§2.3), we carefully choose to protect file contents, file names, and directory names; we do out protect directory structures and file system metadata including super blocks, allocation maps, and inodes; we do not protect block access patterns which are regular.

*Continuous assurance of data integrity and persistence.* We set to bring the trustworthiness of a storage stack running on smart devices to the level of its counterpart running in a rigorously-managed datacenter. At this level of trustworthiness, the storage stack ensures that: a successful read reflects the most recent write to the same file location; a successful fsync() implies that the data becomes persistent on the disk.

*Practicability.* We set to respect the diverse, mature file systems by reusing their code with little modification. We set to add as little code to TEE as possible; we set to keep the interface exposed by TEE as narrow as possible.

### 3  Security approach overview

**3.1  Scope**

**Target scenarios** We target smart devices for recording/analyzing environment data and/or serving human users; such devices are commonly seen in homes or offices, as exemplified by security cameras and voice assistants. We recognize the significance of mission-critical devices with tight control loops, but do not target it.

During operation, the smart devices generate data (“user data”) that is privacy-critical and/or business-critical; the smart devices store the data to files for persistence. We trust the TrustZone-based TEE on a smart device; the TEE already encloses a secure disk as well as app code (i.e. secure

| System                          | TCB | SG |
|--------------------------------|-----|----|
| Cryptographic FS [28, 83, 27]  | OS  | CI-|
| FS checkers [49, 42]           | OS  | I- |
| Kernel checkers [43, 22]       | TEE | C- |
| Outsource w/o verify [19, 80, 17, 48] | TEE | CI-|
| **Overwatch (this work)**      | TEE | CIP|

SG: security guarantees.

C: data confidentiality; I: data integrity; P: persistence assurance

Table 1: A comparison of existing solutions and this work

clients) that accesses the protected user data. We assume cloud connectivity but nevertheless design to cope with poor connectivity or even disconnection. We assume a “honest but curious” cloud service that execute timely patched, thoroughly checked file systems; however, we do not trust the cloud for data confidentiality.

**In-scope threats.** We consider malicious adversaries interested in learning user data and tampering with it. We assume powerful adversaries: it takes full control of the smart device’s OS, including the encompassed file systems, network stack, and any user processes atop the OS. The compromised file system may alter or covertly drop write requests; it may supply wrong data to read requests.

**Out-of-scope threats.** We consider the following threats out of scope: i) Exploitation of TEE kernel bugs [53, 4, 5]. ii) Physical attacks, e.g. snooping TEE’s DRAM access [25, 18]. iii) Availability attacks, e.g. a compromised OS could refuse to boot or deny requests from TEE; Many of these attacks are mitigated by prior work [61, 92, 35, 90] orthogonal to Overwatch. Note that controlled-channel attack [85] does not apply to ARM TrustZone as the latter’s page management is within TEE unlike Intel SGX.

### 3.2  Existing approaches are inadequate

Cryptographic file systems [28, 59, 45] guarantee data confidentiality/integrity but not file system correctness; they are also subject to Iago attacks [31] from a compromised kernel, e.g. by overwriting data blocks and hence causing permanent data loss. To enforce an envelope of file system behaviors, a file system can be certified through formal methods [32, 75] or checked at run time [52]. However, most commodity file systems are not built with formal methods; envelopes does not capture all possible file system behaviors; deploying per-file-system checkers into the smart device TEE is likely to increase the edge TCB and the overhead significantly [42, 49]. Data auditing [20, 73] proves data possession but not persistence. Non-repudiable IO [23] ensures that given disk reads or writes hit the disk while not asserting file system correctness. While much prior work can detect damicrobenchmarkta loss in retrospect, few techniques prevent it from happening.

To support TEE code for accessing storage, existing TEE-based systems take ad-hoc solutions: leaving the whole storage stack out of TEE and delegating file APIs to it [58, 19, 68],
pulling an entire storage stack to TEE, or hand-crafting a miniature stack (e.g. by only supporting a set of predefined files) [17, 48, 55]. Lacking systematic treatment, they suffer from Iago attacks, bloating TEE, and giving up decades of file system development, respectively. As file systems are tightly coupled with the kernel environment, pulling a whole file system into TEE would end up pulling most, if not all, of the kernel dependency (at least 30K SLoC): address space and page management (15K), memory allocator (7K), locking (8K), etc. This bloats the TEE codebase.

### 3.3 Our key ideas

Our observations are: i) although the file systems are complex, the data functions, i.e. page cache and block layer, are much simpler and hence fit TEE; ii) although file systems have disparate internals, they operate on storage data through a narrow, unified block interface; iii) compared to smart devices, the cloud offers a more trustworthy environment to file systems (§2.4).

Accordingly, we propose the following designs as illustrated in Figure 2.

1. **Protecting file data while outsourcing file system logic.** We partition the current storage stack: within TEE we isolate VFS, which tracks opened files and serves page cache, and the block layer, which guards a trusted disk² owned by TEE and all the data on the disk. We leave the unmodified code of commodity file systems (e.g. ext2) in the insecure world and consider the code untrusted (i.e. the “evil twin”).

2. **Exposing metadata to the untrusted local file system.** As the file system code needs to operate on the metadata (e.g. file system inode table, block bitmap, and directory structure), the storage substrate exposes an interface for the insecure world to access the metadata.

3. **Cloud as the verifier.** We run a trusted, lightweight replica of the same file system, i.e. the “good twin”, in the cloud. Its only responsibility is to validate the legitimacy of any storage operations that the untrusted edge file system suggests to execute. The cloud replica timely incorporates newest bugfixes, but no new file system features.

In this architecture, only the device TEE possesses the file data; both the device’s insecure world and the cloud work on their own metadata copies.

**Workflow** As shown in Figure 2, a secure client invokes file API (e.g. “write to file /local/data offset 42”). If the data happens to be in the secure page cache (1), the execution never leaves the TEE for consulting file systems. Upon cache miss, Overwatch sends the invocation to both the local file system (the untrusted evil twin) and the cloud replica (the trusted good twin), which both return storage operations resulted from the invoked API (e.g. “writing the given data [opaque reference] to disk block 42”) (23). Conceptually, only when the twins return the same operations, the secure block layer executes such validated operations on the protected storage (4). With this architecture, the good twin (remote) ultimately guarantees the security objectives, while the evil twin (local) is crucial to performance optimization, as will be discussed in Section 4.

**Security benefits** i) Our approach offers strong confidentiality over the file data. By exploiting TrustZone’s static partitioning of memory and IO hardware (§2), we ensure file data, as well as the memory and storage hardware containing the data, are strongly isolated from the rest of a smart device, including the commodity OS. The autonomy of TrustZone eliminates controlled channel attacks through page faults [17]. The file data is never disclosed to the cloud either, as the latter only operates on metadata. ii) Our approach offers high assurance of correctness: the assurance no longer depends on the integrity of local file system and OS that face high threats, but on the integrity of the cloud. By continuously validating the block-level activities at run time, it assures the apps that file data is safely kept persistent and can be readily read back.

## 4 Overwatch Design

Our security approach above takes a somewhat idealistic position. To realize the model and make it practical, we have addressed the following challenges with novel system designs.

1. How to make file data flow between the clients and the storage hardware without leaving TEE?
2. How should the TEE differentiate file data and metadata?
3. How to hide long network delays?
4. How to ensure consistency between twin file systems?
5. How to continue operating when the cloud is disconnected?

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²While recognizing that edge platforms often use flash-based storage, we use “disk” as a generic term for non-volatile storage
4.1 Secure data path

As discussed in Section 3.3, Overwatch incorporates in TEE the VFS and the block layer from the commodity OS. These layers are generic; compared to file systems, they are thinner, only adding 1K SLoC to the TEE code.

It has relatively simple responsibilities: manage file-related data structures (e.g., file descriptor table and page cache), and call into the file system-specific control functions. Hence, Overwatch also implements a simple yet generic virtual file system layer, Overwatch secure VFS (1). It provides a basic abstraction for opened files through a secure file descriptor table, and the protection of data through secure data path.

Secure file descriptor table To secure clients Overwatch presents POSIX file APIs. To do so, it keeps in TEE a file descriptor table, keeping track all opened files and their current access positions. When forwarding file APIs to the local file system, Overwatch obfuscates all file names and bookkeeps the mapping between the obfuscated file names exposed to the file system and the actual file names used by secure clients.

Secure page cache is where the Overwatch holds the recently accessed file data in memory. Similar to Linux’s page cache, the secure page cache is essentially a dictionary keeping (file, offset) → page, block_id. Any file API hits the cache will be served by the cache within TEE. Only upon a cache miss the Overwatch forwards the file API to the twins of file systems. The secure page cache only keeps user blocks not metadata blocks, which are manipulated by the local file system with untrusted contents.

And upon the delegated file operation returns, the verified blocks will be read from secure storage to fill corresponding pages. This is because the secure world never relies on the metadata to perform control path.

Secure block layer The block layer exposes a very narrow interface: copy data between a TEE memory address and a block on the secure storage. For read(), the block layer copies a disk block to the secure page cache, and then to a buffer supplied by the secure app; for write(), the block layer copies a secure app’s buffer to the secure page cache; for sync(), the block layer copies data from secure page cache to disk blocks.

What are metadata stencils? Metadata stencils, a compact data structure in TEE, encode the knowledge of metadata’s disk locations. Conceptually, for each block on the secure storage, a stencil specifies the bytes that represent metadata, e.g. “block 42: byte 0-127 [metadata]”. To serve a block read from the local file system, Overwatch consults the corresponding metadata stencil, reveals the metadata bytes, and redacts the remaining. Similarly, for a block write Overwatch only overwrites the data bytes. In practice, the metadata stencils are highly compact: file systems such as ext2/3 use separate disk blocks for metadata and data, allowing a one-bit stencil for each block; file systems such as BTRFS and F2FS may colocate metadata and data in the same block, yet we find only such blocks only constitute a small fraction.

How to generate metadata stencils? The metadata stencils are generated by parsing two on-disk data structures: the super block and inodes. The super block describes the usage of all live disk blocks; the inode structure describes any file data that may be embedded in an inode block. The two data structures are file system specific; their layouts are stable across different versions of the same file system, because a file system typically keeps its disk layout backward-compatible. Upon file system boots, a simple parser locates and parses the super block (identified by its well-known magic number) and inodes, establishing metadata stencils for all live blocks.

Who should generate the stencils? We have investigated the following two solutions. The cloud replica generates the stencils based on the metadata it possesses; it piggybacks the stencils to its validation responses. Overwatch runs on device without any file system-specific logic; it remains agnostic to the type of file system (e.g. ext2 or f2fs) running out of TEE. Overwatch can be deployed to the TEE once and remains sealed afterwards.

Alternatively, Overwatch may generates and maintains the stencils by itself. This requires Overwatch to incorporate a separate parser for each type of file systems it works with. Yet, data confidentiality is stronger: it completely depends on the TEE and independent of the cloud. We will test this solution in evaluation (§6).

4.2 Metadata stencils

Based on our idea of only exposing metadata (§3.3), the TEE serves metadata to the untrusted file system code (Figure 2 6). In doing so, Overwatch must i) reject any request to file data; ii) redact the metadata that contain user information (e.g. directory name) before serving; iii) serve metadata in clearext if it contains no user information. It is worth noting the metadata includes directory links (but not directory names), which is required by the file system for walking file paths. To do so, Overwatch must know metadata’s disk locations, for which it relies on metadata stencils.

4.3 Memoizing verified file-block mapping

Unlike write(), an uncached and trusted read() is synchronous. Because Overwatch will have to wait for the cloud to return validated blocks to proceed, it inevitably incurs latencies that worsens linearly with elongated network delays and suffers much from unstable network connections. To optimize for such cases, our key insight is to reduce the remote validation by memoizing the file offsets with their corresponding verified data blocks and return the data blocks directly to the application.

Our rationale is that, the mappings from file offsets (i.e. the input of file system execution) to locations in page caches
and disk blocks (i.e. the output of file system execution) will remain valid until future file API invocations alter the file system metadata.

It works like a cushion to the secure page cache: whenever a page in the secure page cache gets evicted due to limited memory size, Overwatch memoizes the blocks and file offset that map to the spilled page. And after read() misses the search in page cache, it will then search among the memoized disk blocks and return the trusted data blocks if it finds the corresponding blocks. Also, it implies that the read from the offset within the same disk blocks will not require remote validation, either. For instance, in serving two consecutive reads at the same file at offset 42 and 128, the Overwatch avoids invoking the file system and the cloud for the second read, because the two offsets are known to map to the same block and the mapping is unchanged. We will evaluate this mechanism in Section 6.4.

4.4 Hiding network delays

Overwatch incorporates the following mechanisms. Essentially, it exploits the untrusted local file system for speed and relies on the trusted cloud replica for correctness.

Overlapping network/storage delays Overwatch executes storage operations from the (untrusted) local file system as soon as they become available; the Overwatch rolls back the operations if it receives dissonance from the cloud later. By doing so, the Overwatch overlaps the network latency (typically tens to a few hundred ms) with the local storage latency (typically a few to tens of ms).

Overlapping network/computation delays As described before, Overwatch provides POSIX file APIs to its clients. It further provides an option for the clients to observe the outcome of unvalidated storage operations.

Our rationale is to give the clients opportunities to handle unvalidated (and hence untrusted) file data with their own logic. For instance, the camera code may process unvalidated images it reads from storage while the validation is still pending. For read(), Overwatch returns the requested data to the client and indicates the data is yet to be validated; for write(), Overwatch checkpoints the blocks to be modified (in case of future rollbacks) and taints the modified blocks and pages as untrusted (in case of future read from them). In case the cloud rejects the data operations, Overwatch rolls back to the earlier version without the modifications.

To support the option, Overwatch introduces a light interface augmentation, by adding two flags to existing file APIs. In open(), Overwatch supports a new untrusted flag, indicating that any subsequent access of this particular file will return with the results from the local file system without waiting for the remote operation to complete. In select(), Overwatch supports a new validation flag which serves as a validation barrier. Overwatch will block the caller client until all pending validations pertaining to this file are completed. The new flags are simple yet sufficiently powerful to support overlapping between computation and network delay. Section 6 will present a case study.

4.5 Coping with emergencies

Emergency file for cloud disconnection Overwatch supports clients to write a fixed amount of data reliably without any remote validation. This is important for keeping time-critical user data persistent, e.g. an image frame containing a person’s face of interest. To do so, during file system initialization and while the cloud is connected, Overwatch creates an emergency file and pre-allocates all its blocks and remembers all its data blocks by memoization, as described in Section 4.3. As the mappings between file offsets and disk blocks are all known to the storage substrate, it can safely access the file without consulting the cloud. The size of the emergency file is configurable to the device user.

Maintaining crash consistency Overwatch applies 2-phase commit (2PC) protocol [10] to maintain consistency between the two file systems on the edge and the cloud. On the local smart device, for on each file operation that changes the metadata (e.g. write to a new file) Overwatch piggybacks an additional commit request to the cloud; on the cloud, when Overwatch receiving the file operation and the commit request, Overwatch executes the file operation but saves the modified metadata into a temporary file and piggybacks an ok to commit message with the block requests. Then after receiving the message, the smart device executes the verified block requests and sends the final commit message to the cloud. Lastly, only upon receiving the final commit from the edge should the cloud write the modified metadata persistently to its storage. In this way, if the device crashes (e.g. due to power failure) before executing the file operations, the cloud will not receive the final commit and thus will not update its copy of metadata; however, if it’s due to temporary disconnection, on the next successful connection, the smart device will resend the commit, thus allowing the cloud to update its copy, keeping both copies consistent.

4.6 Maintaining the cloud replica

A metadata-only file system The cloud replica of local device’s file system, called Overwatch file system (OFs), runs in the cloud to verify the block requests of the untrusted file systems on the smart device. OFs has the same control logic as the local file system but operates only on the metadata (i.e., inode table, block bitmap, inode bitmap, etc. in the ext family). Its initial metadata is replicated when the local file system is first initialized (e.g., when mkfs). Since then, the subsequent replication of metadata is performed by replaying each file operation sent by the smart device, where the consistency is
We have built Overwatch v4.9 to forward the delegated file operations to the twin of the untrusted file system. We implement the metadata stencil by porting only 300 lines of code from libext2 and libf2fs. 2) passing metadata to the cloud, the in-TEE operation verifier (shown in Figure 2) receives the block requests generated by OFS and verifies those issued by the untrusted OS. As discussed, Overwatch delegates file operations to both the untrusted file system and the cloud replica (OFS). Upon receiving the file operation, OFS executes the file operation by consulting and manipulating its replica of metadata; as a result, it generates a sequence of block requests, and responds to the operation verifier with those block requests. The operation verifier compares generated block requests. The matching block requests (i.e. both the requested block number and request type are the same) result in a successful data read/write while failure leads to data roll back, as discussed in Section 4.4.

5 Implementation

We have built Overwatch in 5K lines of C code (reported by Sloccount [81]). We implement the following major Overwatch components, which are agnostic to specific file systems.

1) The Overwatch runtime within on-device TEE. We build it atop OP-TEE OS v2.6 [68], where we add 3K for new implementation and reuse the exception handling and RPC facility to handle world switch. We emulate the secure storage as a ramdisk. We implement the metadata stencil by porting only 300 lines of code from libext2 and libf2fs. Block requests from the untrusted file system are verified sequentially.

2) A small kernel module in the smart device kernel (Linux v4.9) to forward the delegated file operations to the twin of file systems. It sets up shared memory as the secure communication channel, and establishes the network connection with the cloud. To support multiple commodity file systems, we also modify loop device driver of the on-device Linux kernel.

3) A secure communication channel between the TEE and the local file system. The channel passes messages through shared memory which has a fixed size of 4KB. The channel serves two purposes: 1) passing file APIs and block requests. Invocations to file APIs are identified by \(<\text{op, fd, flag, count, name}\>$. Block requests, resulted from untrusted file system’s execution, are a sequence of block numbers represented by 32-bit integers. 2) passing metadata blocks. Overwatch serves metadata block requests after they are checked against the metadata stencil. For read, Overwatch reads the requested metadata blocks from the secure storage and deposits it in the communication channel, which will be collected by the untrusted file system, write is a mirror process.

4) A cloud server for running the metadata-only file system replica. We implement the server in a straightforward way, which keeps listening, parsing, and executing the file operations from the smart device on the file system replica. Since the server must respond to smart devices with block operations, we run a privileged service on the server to extract the block operations to the user space. Note that an alternative is to use userspace block device (BUSE [1]), which does not require a privileged service on the cloud server.

Smart device applications Atop Overwatch, we build three applications derived from real-world smart devices:

1. A cleaning robot (Robot) for house cleaning [44]. We derive the workloads from Xiaomi Vacuum Robot [3]. When cleaning, the robot sequentially updates a log file every 200ms; each entry is 32-byte 3-tuple containing coordinates (x, y) and the angle. After cleaning, the robot reads back the whole log file, reconstructs the cleaning map using SLAM in PPM format; each pixel of the map is 5cm in physical world and a typical map size is therefore tens to a few hundred KB. At last the robot writes back the map file to disk. We fix the log size to 512KB and map size to 256KB.

2. A voice assistant (Voice) for interacting with user speech commands [7]. We derive the workloads from Mycroft [7]. When starting, the voice assistant first loads a set of user-defined rules, called skills, to respond to user speech; each skill is a directory under ~/.mycroft/ containing a .voic and a .intent file to identify the intent of user, a .dialog file to respond to user, and a .json file to describe the skill; every 2s the device will scan the three skill files using fstat in case any modification or updates. After boot, it listens to the user speech in the background, records the audio, and stores the recording as a wav file under /tmp; it then runs speech to text transcription (STT) and responds to user according to the STT results and existing skill.

3. An intelligent camera (Camera) for license plate recognition. We derive the workloads from intelligent traffic systems. As the surveillance goes on, the camera periodically captures and saves images (1080P in JPG format). Every other 10 seconds, it reads in the saved images and runs license plate detection algorithm on them; on the images, the algorithm detects canny edge, dilates them, and then find license plate blobs. Finally, it draws bounding box around detected plate blobs and saves the resulting image. We use images from UFPR-ALPR dataset [66]. For the application, we ported to TEE SOD [9], a popular embedded computer vision library.

These applications serve as our macrobenchmarks.
Table 2: A comparison between the source of Overwatch and that of the Linux storage stack, showing that Overwatch reduces the on-device TCB significantly.

6 Evaluation

In this section, we seek to answer the following questions:
1. How does Overwatch reduce TCB and thwart attacks?
2. What is the security overhead of Overwatch?
3. How does Overwatch’s API augmentation (§4.4) impact programmability and reduce overhead?

6.1 Security Analysis

6.1.1 TCB analysis

On-device TCB size Table 2(a) shows a breakdown of the Overwatch source code, which only adds 4K SLoC to the TCB. The size of the Overwatch binary is 52KB, a small fraction (3.3%) of the entire OP-TEE binary.

TCB interfaces The Overwatch secure runtime only exports two functions: one for issuing file API requests (to both file system twins) and one for receiving block requests from the untrusted local file system. Two worlds share no state; all messages and the enclosing arguments are passed by value.

Comparison to alternative TCB Compared to enclosing the entire Linux storage stack in TEE (the source count listed in Table 2(b), Overwatch significantly reduces the storage stack’s on-device TCB by 16×. This is because Overwatch completely excludes the file system logic (ext2 and f2fs in our example) from the TEE and implements compact data functions for the TEE.

6.1.2 Attacks thwarted by Overwatch

Table 3 shows an overview of major attacks that target an smart device to compromise our security guarantees.

Iago attack. As disclosed in [31], a compromised kernel can forge return results of system services, subverting the efforts of prior approaches that delegate file operations to an untrusted file system [58, 68]. For example, when prior approaches delegate open("/ofs.txt") to the untrusted file system, a compromised file system may request TEE for user data blocks instead of the only required metadata blocks of "ofs.txt", hence resulting in sensitive information leakage.

Overwatch defeats Iago attack in the following way: first, the metadata stencil ensures only metadata can pass over to the untrusted file system with any inline user data erased. Second, the operation verifier verifies each resultant user block request with the cloud, which ensures the legitimacy of user block requests. Lastly, the user block data always stays in secure page cache and is never disclosed to the untrusted world. Hence, with these components as a package, Overwatch defeats Iago attack in a straightforward way.

Page fault & cache side-channel attack. Page fault attacks are usually launched against SGX [86], since a compromised SGX driver is able to modify page attributes belong to SGX enclave and cause page faults to infer the memory access pattern. However, by exploiting TrustZone, Overwatch is by design immune to such an attack because TEE memory is physically isolated and thus transparent to normal world. Therefore, normal world is unable to tamper with TrustZone memory, and to launch page fault attacks. To defeat cache side-channel attack, Overwatch fully confines cached read/write to Trustzone, and flushes its cache before switching back to the normal world. As a result, no cache contention between secure world and normal world can occur to launch cache side-channel attack [91], hence Overwatch thwarts cache side-channel attack.

What can be learnt by eavesdroppers?
- The cloud server and the local OS, by running the twin file systems, are able to access metadata which we set to reveal (§2.4). They access directory and file names in encrypted form but cannot decrypt them. They observe file API invocations with API semantics only (§2.4). They observe uncached block access activities, while most of block accesses are cached in TEE and hence invisible. They cannot touch file data.
- A network-level eavesdropper observes encrypted network traffic to/from the smart device. She can infer the activities of file access and block access without knowing which files/blocks are accessed.

6.2 Methodology

Test setup We test Overwatch on Hikey [6], an ARM-based development board, as the smart device. We choose this board for its good support for TrustZone. The details of Hikey are summarized in Table 4. We run an x86 machine as the cloud
Table 4: The test platform used as a smart device

server. The two machines are connected by Ethernet in an isolated LAN. We use Linux traffic control (tc) on the x64 machine to emulate different network conditions.

We test Overwatch with ext2 and f2fs, with two commodity, unmodified file systems; we choose them to represent different levels of complexity: while ext2 is classic and simple, f2fs is modern and feature-rich.

We run a suite of macrobenchmarks and microbenchmarks. Prior to each run, we reboot both devices in order to have a cold cache. As the current TrustZone TEE lacks device drivers for flash storage, we use ramdisk in TEE as the secure disk. We cap the ramdisk performance at 4K IOPS, which typical in today’s low-cost flash.

Macrobenchmarks To understand Overwatch's end-to-end impact, we run the applications described in Section 5. We define overhead metrics for applications based on their objectives. For Camera, we study its loss of throughput in image processing. For Voice and Robot, we study the extra delays they experience in each mission, i.e. data logging and map reconstruction, and responses to user voice commands respectively. We test under a spectrum of typical network delays according to recent study [54].

We show Overwatch’s impacts on latency of Robot and Voice as they are latency-sensitive. We then shift the focus on its impacts on throughput of Camera. This is because compared with Robot and Voice whose workloads are lightweight data logging, Camera is more compute-intensive and thus stresses throughput more.

Microbenchmarks To understand the overhead of Overwatch’s on-device security mechanisms, we run a series of stress tests. We run Iozone v3.482 [29], a widely adopted file system benchmark suites for Linux. We configure Overwatch to bypass validation with the cloud replica while still keeping all on-device mechanisms on. To exclude the benefit of cache and observe the security overhead, we set the O_DIRECT flag in file APIs to force each read/write hit the Overwatch. We then compare Overwatch with native, insecure file systems which run in the normal world atop ramdisk.

6.3 Application security overhead

Our results show Overwatch adds moderate overhead to the representative smart device applications.

Application latency increase Overwatch adds moderate latency overhead to the application, considering different network delay and on-device security hardening.

Overall, at the common latency segment (50ms), Overwatch incurs as little overhead as 15% in Robot (f2fs). Overwatch achieves such low overhead due to the asynchronous writes – the application does not block while waiting for the blocks to be verified. Moreover, the secure page cache facilitates trusted read without going to the cloud, it saves significant RTT in the Robot benchmark where the whole log is read back for map reconstruction. In Voice, Overwatch incurs 45% overhead. This is because Voice requires three fstat in each run, which is sensitive to the network delay due to its synchronous nature. (§5)

Application throughput loss As shown in Figure 3, in a broad latency spectrum, Overwatch causes the throughput of Camera to drop by no more than 5%. The low overhead is due to two factors: 1) for read, the storage architecture which caches recently produced image data, reducing consultation with the cloud replica and the secure disk; 2) for write, most operations are asynchronous and hence effectively overlap with the application’s processing of subsequent images.

Network bandwidth usage Overwatch incurs light overhead in network bandwidth usage, as the smart device and the cloud only exchange compact validations instead of actual file data. Even in Camera, our most data-intensive application, the smart device uses uplink/downlink bandwidth at 3.7 KB/sec and 2.6 KB/sec respectively, which are minor as compared to typical wireless bandwidth today (hundreds KB/sec) [54].

Cloud server overhead In running the file system replica, the cloud server sees negligible CPU overhead as the execution is bound by network delays. Possessing only metadata, the replica is also space-efficient. To support a 4GB disk on device, the metadata stored by the cloud replica are up to 12MB for f2fs, and up to 65MB for ext2. This implies that every 1TB cloud storage server can support up to 87k and 16k smart device instances running f2fs and ext2, respectively.

6.4 Security overhead under stress test

We run the aforementioned stress test to understand the overhead of Overwatch's on-device components.

Overhead of Overwatch execution Overwatch’s on-device security mechanisms introduce noticeable overhead: because of them, the throughput of microbenchmark drops by 25% on average (24% for sequential and 26% for random). Between the two commodity file systems we tested, f2fs experiences higher overhead (33% on average) than ext2 (18% on average), likely due to the former’s more sophisticated logic and hence more (sometimes 10x) block requests.

Impact of metadata stencil. The metadata stencil examines each outgoing block served to the local file system. For ext2 in which file data and metadata do not co-locate on the same block, checking a block against its metadata stencil is simply examining a flag (§4.2). This incurs minor overhead, e.g. compared to native-ext2, the sequential read throughput of
**Figure 3:** Overwatch’s impact on application performance under different network latencies (x-axis). Red dashed line: native performance when applications run on insecure file systems. The two additional Overwatch versions show secure cache and overlapping network/storage operations contribute to reduce the overhead.

**Figure 4:** Microbenchmark performance of Overwatch compared with native, insecure file systems. Benchmark: Iozone [29]. Read/write size = 4KB. O_DIRECT flag set.

Overwatch-ext2 drops by 18%. However, for f2fs in which file data and metadata may co-locate, applying metadata stencil requires to redact inline file data in the outgoing block. This reduces throughput by up to 41%, shown in the bottom figures of Figure 4 (a) and (c).

Cross-world invocations cause low delays. It only takes few thousand nanoseconds for the normal world file system to receive file APIs sent by the TEE, and vice versa. In a file API (e.g. fstat) that must invoke both local/cloud file systems synchronously, the cross-world invocation delay is negligible as compared to the network delay (in milliseconds). Within a cross-world invocation, the world switch takes around 49ns. Memoizing validations effectively reduces network trips and hence overhead. We demonstrate this with the benchmark, which writes 512KB to the file and read them back for processing; this is similar to Robot benchmark and the write-read back for processing pattern can be commonly found in other edge processing devices. As shown in Figure 5, memoizing reduces latency significantly, by up to 291%. The saving is more pronounced with smaller secure page cache. This is because even an access to a file offset misses the page cache and has to hit the secure disk, Overwatch still knows which block...
the offset maps to and can safely skip consulting local/cloud file systems. The saving is substantial because consulting the cloud file system is much slower than accessing the secure disk.

### 6.5 A case study of using the augmented API

```c
for (i = 0; i < N_FILES; i++) {
    /* Allow read to return untrusted data*/
    fd_in = open(in[i], O_RDONLY);

    /* Determine data size for read*/
    fstat(fd_in, &stat);

    /* Read untrusted data*/
    ret = read(fd_in, buf, stat.st_size);

    /* Make image */
    img = make_image(buf, IMG_JPG);

    /* Processing untrusted data, slow. */
    ret = detect_license(img, buf, &sz);

    /* Wait for validation*/
    ret = select(fd_in, VALIDATION, ...);

    if (ret == SUCCESS) { /* validated */
        /* Write results to new file */
        write(fd_out, buf, sz);
    } else { /* validation failed */
        /*... discard compute results...*/
    }

    close(fd_in);
    close(fd_out);
}
```

Listing 1: Code example showing the use of untrusted reads. The augmented API is highlighted in bold and red.

**Overwatch** gives applications an option to access file data before validation arrives (§4.3) and hence hide network latency. To understand the entailed programming burden and performance reward, we build a revision of the camera application. The application open a series of input image files, runs license detection on them, and write results to output image files. In the new version, the application opens input images files by specifying the `untrusted` flag (line 3, 4). When the application reads in images, **Overwatch** therefore returns the data as soon as the local file system gives the block numbers. As the application gets the untrusted image data, it computes, and executes a validation barrier (line 17). Only on successful validation (i.e. the vision algorithm has executed on a correct input image) will the application write back the processed image (line 20). With minor source changes, the application overlaps the vision compute with network delay in validating a read.

Figure 6 shows the application latency reduction as the reward from handling the untrusted data. With fully trusted read/write, the application incurs 26% higher latency as compared to a native execution baseline; with untrusted read, that overhead is reduced to 8%. Note that, the use of untrusted file access is optional.

### 7 Related Work

We next discuss related work that is not covered so far.

**Defending against untrusted OSes with TEE** Recent research has recognized OSes as untrusted [31] and examined various countermeasures against them, e.g. by relying trusted hypervisors [33, 71, 52] and trusted compilers [37]. To protect important software components against untrusted OSes, many systems use TEEs. Haven [24] protects unmodified apps and ports FAT32 into an SGX enclave. Scone [19] secures containers with TEE. Graphene [80] ports a library OS to protect apps in TEE. Oblviate [17] exploits ORAM to keep file operations in TEE oblivious. TrustShadow [48] focuses on protecting memory integrity of apps, and delegates syscalls to an untrusted OS. Similar to them, we do not trust the OSes, and use TEE to shield critical execution; unlike them, we focus on file system and propose new partitioning between data functions and control functions for protection; we also support multiple commodity file systems.

Much work uses TEEs (mostly TrustZone) to enforce system software invariants. TZ-RKP [21] intercepts and examines control-critical instructions (e.g., pagetable update); Sprobes [43] checks kernel integrity to guard its code integrity. Like much of them, we build on TrustZone; different from them, we do not enforce any invariant for ensuring integrity but instead verifying with the cloud. Trustgyges [40] exploits TEE to hide file data from an untrusted smartphone OS. It neither partitions the storage stack nor use the cloud for validation.

**Replicated execution.** The idea of replicated execution
we focus on using the cloud for security without disclosing Trustworthy file systems. We implement Overwatch replica of the file system in the cloud, which continuously validate the behaviors of the on-device file system. We execute a metadata-only integrity, and assured persistence. Following an outsourcing of data confidentiality, smart devices offer weak security guarantees. We propose a new storage architecture to provide data confidentiality, from commodity file systems. We execute a metadata-only persistent on local storage. The current storage software on them, we do not trust the commodity kernel but reuse its file system logic. Cryptographic file systems are also designed to them, we do not trust the commodity kernel but reuse its file system logic. Cryptographic file systems are also designed for distributed computing. Plutus supports file-sharing on untrusted storage with cryptographic key distribution and management. SiRius further guarantees freshness using Merkle tree. SUNDR detects tamper on files on untrusted servers. While such prior work and apply it to file systems to our knowledge. Replicated execution is also used for resource efficiency. Tango, MAUI, and Clonecloud offload compute-intensive code from smartphones to the cloud. Like them, we exploit the collaboration of cloud and the local device; unlike them, we focus on using the cloud for security without disclosing user data. Knockoff ships IO traces from clients to the cloud for creating multiple versions of disk image. Similar to it, Overwatch exchanges file/block requests with the cloud; unlike it, Overwatch does not upload file data but use the cloud as the verifier for file system behaviors.

**Trustworthy file systems.** A traditional approach to keeping file data confidential is through cryptographic file system, either stackable or integrated natively. Compared to them, we do not trust the commodity kernel but reuse its file system logic. Cryptographic file systems are also designed for distributed computing. Plutus supports file-sharing on untrusted storage with cryptographic key distribution and management. SiRius further guarantees freshness using Merkle tree. SUNDR detects tamper on files on untrusted servers. While such prior work and Overwatch share the goal of file system security for networked computers, Overwatch offers strong security guarantees, e.g. assured persistence, and therefore introduces different techniques.

8 Conclusions

Smart devices produce security-critical data and keep them persistent on local storage. The current storage software on smart devices offer weak security guarantees. We propose a new storage architecture to provide data confidentiality, integrity, and assured persistence. Following an outsource-and-verify approach, we isolate file data in TEE, shielding it from commodity file systems. We execute a metadata-only replica of the file system in the cloud, which continuously validate the behaviors of the on-device file system. We implement Overwatch and analyze its security properties. We demonstrate that Overwatch works with commodity file system and incurs moderate overhead. Overwatch represents a new design point for storage stacks.

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