Regulating Smart Personal Devices in Restricted Spaces

Rutgers University Computer Science Technical Report DCS-TR-715, July 2015

Ferdinand Brasser
Technische Universität Darmstadt

Daeyoung Kim
Rutgers University

Christopher Liebchen
Technische Universität Darmstadt

Vinod Ganapathy
Rutgers University

Liviu Iftode
Rutgers University

Ahmad-Reza Sadeghi
Technische Universität Darmstadt

ABSTRACT

Smart personal devices have become ubiquitous, and we increasingly rely on their use in our daily lives. Simultaneously, society is beginning to place restrictions on how these devices can be used in various environments. Such *restricted spaces* abound in today's society. For example, enterprises and federal offices that store sensitive information place restrictions on the use of cameras and microphones in smart devices. In classrooms, students are often disallowed from using smart devices during examinations. And in social settings, people are unwilling to have their conversations recorded by their friends wearing smart glasses. To date, these restrictions have been enforced using ad hoc methods.

In this paper, we present a systematic approach for restricted space hosts to remotely analyze and regulate guest device use in the restricted space. Policies governing device use are decided by the hosts that control the restricted space. These policies are enforced by a trusted mechanism that executes on the smart guest device. We present an implementation of our mechanism on smart devices equipped with the ARM TrustZone architecture. We also present candidate policies that show how device use can be regulated in a variety of restricted spaces.

1 INTRODUCTION

Over the last few years, we have witnessed an increase in the number and diversity of personal computing devices. These include smart phones, tablets, smart glasses, watches, and a variety of special-purpose embedded devices, such as health monitors and sensors. We can expect these devices to become integral parts of end-users' daily lives, *e.g.,* smart glasses used for prescription vision correction, and watches used as continuous health monitors. As a result of these developments, smart devices will come to be used in a wide variety of settings, such as the home, in social settings, and at school and work. End-users will carry these devices as they go, and expect them to connect and work with the environments at the places they visit.

As smart devices evolve, their computing power will continue to increase and so will the quality and diversity of periperhals available on them. While this is generally a desirable trend, there are environments in which highly-capable smart devices may be misused to gather and exfiltrate information from the environment, or smuggle unauthorized information into the environment. This may happen either through overt malice by the device owner, or unintentionally, via malicious apps accidentially installed on the device. Examples of such environments abound in today's society, and they impose a wide variety of policies (often unwritten) governing the use of smart devices. Enterprises typically forbid employees' personal devices from connecting to corporate networks or storing corporate data. Federal institutions and laboratories that process sensitive information place even more stringent restrictions, often requiring employees and visitors to place personal devices in Faraday cages before entering certain areas. In the classroom setting, students are often forbidden from using the aid of smart devices during examinations. Even outside work and school, there may be privacy concerns that restrict how smart devices are used. For example, certain restaurants and bars ban patrons from wearing smart glasses [44]. In social settings, people may be uncomfortable at the thought of their conversations being recorded by smart devices. We use the term *restricted spaces* to refer to such environments.

The mechanisms traditionally used to regulate device use in restricted spaces are ad hoc. Consider, for instance, the restricted spaces discussed above. In the enterprise setting, employees are given a separate work laptop/phone that can connect to the corporate network. They are also implicitly, or by contract, forbidden from copying data from these corporate devices onto their personal devices. In the federal setting, employees and visitors must undergo physical security checks to ensure that they are not carrying electronic equipment, while in the classroom setting, proctors enforce compliance. And in social settings, enforcement is informal and left to privacy-conscious patrons or hosts.

Going forward, such ad hoc methods will prove inadequate. First, our increasing reliance on smart devices will make traditional methods difficult to use. For example, it would not be possible to ask an employee or a student with prescription smart glasses to refrain from using the device. In this case, the right solution would be to allow the smart glass to be used as a vision corrector but regulate the use of its camera, microphone or WiFi interfaces. Second, the increasing diversity of smart devices will make it hard to identify policy violations (even if the devices are not used covertly). For example, there is already evidence that students cheat on exams by connecting to the Internet using smart phones [8]. Recent research has demonstrated even subtler methods to outsmart proctors via the use of smart watches [46]. And third, in enterprise settings, current trends indicate that employees may be encouraged to use their personal devices for corporate purposes. This *bring your own device* (BYOD) trend has numerous benefits, such as device consolidation and reducing the enterprise's cost of device procurement. With BYOD, it is imperative to ensure that employee devices adhere to corporate policies within the enterprise.

Given these reasons, we posit that a systematic method is needed to ensure that personal devices comply with the policies of the restricted spaces within which they are used. Such a method would benefit both the *hosts* who own or control the restricted space and the *guests* who use the smart device. Hosts will have greater assurance that smart devices used in their spaces conform to their policies. On the other hand, guests can benefit from and be more open about their use of smart devices in the host's restricted space.

In this paper, we present an approach for hosts to remotely regulate the use of smart guest devices in restricted spaces. Our approach recognizes that policies to govern device use vary widely

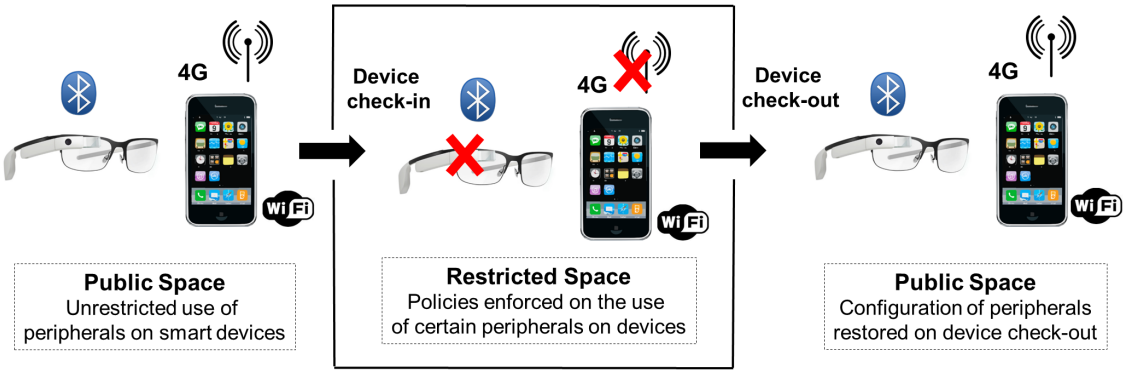


Figure 1: An overview of our restricted space model. Guests "check-in" devices when entering restricted spaces. During check-in, hosts inspect, analyze and modify the configurations of these devices in accordance with their usage policies. In this example, the host restricts the use of the camera on the smart glass, and the 4G data interface on the smart phone. However, the glass can continue to use its Bluetooth interface to pair with the smart phone, while the phone can use WiFi. When guests leave the restricted space, they "check-out" their devices, which the host then restores to their original configurations.

across restricted spaces, and therefore cleanly separates policy from mechanism. Policies are specified by hosts and could, for instance, require guests to prove that their devices are free of certain forms or malicious software, or restrict the use of certain peripherals on the devices, *e.g.,* camera, WiFi, 3G/4G.

The enforcement mechanism itself is implemented on the guests' device(s) and simply enforces the host's policies. This mechanism must have three key properties. First, it must be *trusted* by both hosts and guests, and is therefore part of the trusted computing base (TCB). Hosts trust the mechanism to correctly enforce policies on guest devices. On the other hand, guests trust the mechanism to authenticate hosts. Host authentication is important because malicious or untrusted hosts could otherwise abuse the mechanism to compromise guest security and privacy. Second, the mechanism must have the ability to *inspect* guest devices and *make configuration changes* to enforce hosts' policies. And third, the mechanism must be *minimal*, and not bloat the size of the TCB executing on guest devices.

We describe an approach to implement this enforcement mechanism using *remote memory operations* on the guest device. Hosts use these operations to remotely inspect and modify the memory contents of the guest device based on its policies. The host must be able to ensure that these operations are performed correctly on the guest device. Thus, we cannot rely on the guest's operating system to enforce these operations because it may be malicious (or compromised by malware). We therefore rely on *trusted hardware* in the guest's device to provide a root of trust, which provides the host with the desired assurances. In particular, our prototype uses the ARM TrustZone architecture [6] as the root of trust. Devices that use the ARM TrustZone are now commercially available and widely deployed [11]. We rely on the ARM TrustZone to bootstrap trust in our mechanism's TCB, which executes on the guest.

The use of trusted hardware enables our approach to offer an attractive feature—using the ARM TrustZone, a guest device can prove to the host (using *verification tokens*, introduced in Section 4.5) that it was policy compliant for the duration of its stay in the restricted space. Malicious guest devices, which may have violated the host's policies in the restricted space, will not be able to provide such a proof, and can therefore be apprehended by the host. The ability to handle malicious guest devices is a significant difference from prior projects with related goals [48, 51, 52], which have assumed that the guest devices are benign and will not attempt to bypass the host's policies within the restricted space.

To summarize, the main contributions of this paper are the following:

- *Restricted space model.* We introduce the restricted space model for smart personal devices (Section 2). This model is of independent interest due to the growing number of environments that restrict smart device use. We also present multiple examples of policies that may be enforced in restricted spaces (Section 3).
- *Enforcement mechanism.* We present the design of a mechanism for hosts to enforce policies on guest device use (Section 4). Our mechanism allows hosts to remotely inspect and control a guest device using a simple interface with two operations: remote memory reads, and remote memory writes. The mechanism allows hosts to request a proof from guest devices that they are policy compliant; only compliant devices can provide a proof that will be acceptable to the hosts. Finally, the mechanism ensures that only authenticated hosts can control guest devices, and provides a vetting service that allows guests to check the safety of the host's requests (Section 6).
- *Prototype implementation.* We demonstrate a prototype implementation of the mechanism using the ARM TrustZone hardware as a root of trust on guest devices. Our design/implementation is minimal, thereby ensuring a small TCB on guest devices (Section 5).

2 RESTRICTED SPACE USAGE MODEL

We now provide an overview of the restricted space model, motivate some features of our enforcement mechanism, and describe our threat model.

2.1 Overall Workflow

Check-in. As depicted in Figure 1, when a guest enters a restricted space in which he wishes to use his devices, he "checks-in" each of his devices during entry. During check-in, the guest device communicates with the host's policy server for the following tasks:

(**1**) *Authentication.* The authentication step allows the guest and host to mutually identify each other. We assume that both the guest and the host have cryptographic credentials (*e.g.,* public/private key pairs) that can be validated via a trusted third party, such as a certifying authority. The host and the guest mutually authenticate

each other's credentials in the standard way, for example, as is typically done during SSL/TLS handshakes.

The host's policies are enforced by a mechanism that executes in the guest. As previously discussed, this mechanism is part of the TCB, and must therefore not be tampered by the guest. We rely on secure hardware on the guest device (the ARM TrustZone) to ensure this property. In particular, we rely on the secure hardware to detect and prevent any attempts to tamper with the TCB on the guest. This can be ensured using a special boot-time protocol implemented atop the secure hardware.

It is important to note that this TCB is *not* the end-user's usual work environment on the device, *e.g.,* the traditional Android, iOS or Windows environment with apps. Rather, the TCB is an environment that is created and distributed by a trusted entity, such as the device vendor, and executes in isolation on the guest device.

(**2**) *Host analyzes device.* The host leverages the TCB to analyze the guest device. Our mechanism allows hosts to *remotely fetch memory pages* (and CPU register state) belonging to the guest device. The TCB computes a cryptographic checksum over the memory pages to ensure that they are not tampered with as they are transferred from the guest to the host.

The host uses raw memory pages from the device in two ways. First, it scans memory pages to ensure that the device is free of malicious software, *e.g.,* in the form of malicious apps or kernel modules. Second, it extracts configuration information from the device. This includes the kernel version, the list of peripherals supported by the device, memory addresses of various device drivers for peripherals on the device and the state of these peripherals (*e.g.,* whether a certain peripheral is enabled and its settings). The host can also checkpoint the state of these peripherals so that they can be restored at check-out.

(**3**) *Host modifies guest's configuration.* The host modifies the guest device's configuration to conform to its restricted usage policies. In the example shown in Figure 1, the host's policy is to disable the camera and the 3G/4G data plan on all devices. The host enforces this policy by creating a sequence of *remote memory writes* that directly modify the memory state of the device. For example, the host could prevent the use of the camera and 3G/4G data plan by unlinking the device drivers corresponding to the camera and the modem. The host uses the configuration information extracted in the previous step to determine the memory addresses that must be modified to unlink these drivers.

We assume that it is the host's responsibility to ensure that these configuration modifications are not easily bypassable. For example, these modifications may be undone if the user of the guest device can directly modify kernel memory, *e.g.,* by dynamically loading kernel modules or using `/dev/kmem` in the end-user's work environment. The host must use the inspection phase to identify device configurations that could lead to such attacks, and disallow the use of such devices in the restricted space.

(**4**) *Host obtains verification token from guest.* After the guest device has been configured, the TCB produces a *verification token* to be transmitted to the host. The verification token is an unforgeable value that encapsulates the set of configuration changes to the device. The TCB computes the token as a checksum over the memory locations that were modified. The token is unforgeable in that only the TCB can re-create its value as long as the device configuration has not been altered, and any malicious attempts to modify the token can be detected by the TCB and the host.

At any point when the device is in the restricted space, the host can request the TCB on the device to send it the verification token. The TCB computes this token afresh, and transmits it to the host,[1] which compares this freshly-computed token with the one obtained during check-in. It can use this comparison to ensure that the guest has not altered the device configurations from the previous step. The verification token is ephemeral, and can be computed afresh by the guest only within an expiration period. In our prototype, the TCB cannot recompute the verification token if the guest device is rebooted, thereby ensuring that end-users cannot undo the host's configuration changes by simply rebooting the device.

Check-out. Once checked-in, the guest device can freely avail of the facilities of the restricted space under the policies of the host. For example, in Figure 1, the smart glass can pair with the smart phone via Bluetooth, while the smart phone can connect to and use the host's WiFi access point. When the guest exits the restricted space, he checks-out the device, accomplishing two goals:

(**1**) *Host checks guest state.* The host checks guest device's configuration by requesting the verification token from the device's TCB to ensure that the configuration has not been altered. If it finds that the verification token does not match the value obtained from the device at check-in, it can detain the device for further inspection, *e.g.,* to determine whether any data from the restricted environment was exfiltrated.

Note that it is not usually possible to differentiate between mismatches that happen because of benign reasons, such as a device reboot, or malicious ones, such as when an end-user intentionally modified the peripheral configurations required by the host. This is because even malicious modifications can be masked by simply rebooting the device, and making the mismatch seem benign. Thus, the host's policy to deal with mismatches depends upon the sensitivity of the restricted environment. For example, in a federal setting, a detailed forensic examination of the device may be necessary, the possibility of which could deter a malicious guest from bypassing the host's policy enforcement. As previously discussed, hosts can request the verification token from the device at any time when it is in the restricted space. Hosts can use this feature to frequently check the verification token and narrow down the timeframe of the violation.

(**2**) *Restoring guest state.* To restore the state of the device, the end-user could simply reboot the device. The host only modifies the memory of the device, and not persistent storage. Rebooting therefore undoes all the memory modifications performed by the host and boots the device from an unmodified version of the kernel in persistent storage. Alternatively, the host can restore the state of the guest device's peripherals from a checkpoint created at check-in. The main challenge here is to ensure consistency between the state of a peripheral and the view of the peripheral from the perspective of user-level apps. For example, when the 3G interface is disabled, an app loses network connectivity. However, because we only modify memory and do not actually reset the peripheral, the 3G card may have accumulated packets, which the app may no longer be able to process when the kernel state is restored. Mechanisms such as shadow drivers [61] can enable such "hot swaps" of kernel state, enabling guest devices to continue without rebooting.

2.2 Malicious Hosts

Our discussion so far has assumed that hosts are benign. Authentication at check-in ensures that remote access to guest device memory is available only to hosts that the guest approves. However, it may be possible even for such hosts to misuse the facilities of our

[1] This assumes that the host's policy still allows a communication channel between the host and the guest. If all of the guest's peripherals are disabled, the host will need physical access to the guest to visually obtain the freshly-computed verification token.

mechanism to violate the security and privacy of the guest. For example, a malicious host could use remote memory reads to obtain the guest's personal data. It could also install a key logger or a backdoor to spy on the guest's activities. Even if the host is not overtly malicious, it is possible that the configuration changes that it makes will render the guest's device vulnerable to attacks. This is reminiscent of the 2006 incident when CD DRM software installed by Sony made the systems on which it was installed vulnerable to certain kinds of attacks [36].

To protect guest devices from malicious hosts, we provide a *trusted vetting service*. We assume that guests register their device(s) with the vetting service beforehand. When the host sends a remote read/write request, the guest device forwards the request to the service together with its current memory configuration. The vetting service analyzes the requests against the memory configuration and determines whether the request conforms to certain safety policies. Section 6 presents the details of our vetting service.

The vetting service could directly be implemented in the TCB executing on the guest device, but this has the undesirable effect of bloating the TCB on the device. We therefore implement vetting as a cloud service. Note that vetting is optional. If the guest trusts the host, it could carry out the host's requests without vetting.

2.3 Covert Use and Legacy Devices

It is certainly possible for a guest to bypass the host's policies by not declaring a device during check-in, and using it covertly within the restricted space. As long as the guest carefully configures the device to avoid accessing any of the host's resources in the restricted space, *e.g.,* its WiFi access points, and remain stealthy, the device cannot be detected by the host.

Our focus in this paper is to address policy enforcement for overt uses of smart devices. Covert uses, such as the above, are out of the scope of the mechanisms developed in this paper. Instead, we assume that traditional methods such as physical security checks are necessary to detect covertly-hidden devices.

Finally, what if the guest uses a "legacy" device, *i.e.,* one that is not equipped with trusted hardware, such as the ARM TrustZone? In Section 7, we present a number of design alternatives to enforce policies on such legacy devices. However, because they do not use secure hardware, these alternatives cannot offer the same security guarantees as our approach, or require larger TCBs on guest devices to offer similar guarantees. Our take on the issue of legacy device support is that while legacy devices are certainly important in today's settings, we are beginning to see an increasing deployment of devices equipped with trusted hardware (*e.g.,* see [11]). We hypothesize that moving forward, hosts will have to contend with fewer legacy guest devices than they do today.

2.4 Threat Model

Given the discussion in this section, we now summarize our threat model. Each guest device is assumed to be partitioned into two parts: (1) the end-user's work environment, and (2) the environment that runs the policy enforcement mechanism.

From the perspective of the host, the end-user's work environment is untrusted. The host must trust the policy enforcement mechanism, but because it executes on the guest device, the host leverages secure hardware, the ARM TrustZone in our case, to bootstrap this trust. Having established trust, the host then uses the policy enforcement mechanism to securely read and modify the memory state of the work environment. It is the host's responsibility to inspect the memory state of the work environment to determine whether it is malicious, contains known exploitable vulnerabilities, or allows guests to bypass the configuration changes that the host may make. Once the host determines that the guest's work environment is acceptable, it can induce changes to the guest's memory state. Guests are assumed to keep their devices powered on for the duration of their stay in the restricted space, failing which the verification tokens will no longer match. Mismatches may also happen if the guest maliciously modifies the host's changes.

The work environment may contain zero-day vulnerabilities, such as a newly-discovered buffer overflow in the kernel. The host may not be aware of this vulnerability, but a malicious guest may know of it and have an exploit to bypass the host's policies. Such threats are outside the scope of our work, but the host may protect itself by requiring the guest's work environment to run a fortified software stack (*e.g.,* Samsung Knox [11] or MOCFI [28]). The host can check this requirement during the inspection phase. A malicious work environment may also launch a denial-of-service attack, which will prevent the host from communicating with the TCB on the guest device. However, such attacks can readily be detected by the host, which can then prevent the device from entering the restricted space. We exclude such attacks from our threat model.

From the perspective of the guest, if the host is untrusted, it can rely on a trusted vetting service to determine if the host's read and write requests are safe.

3 GUEST DEVICE ANALYSIS AND CONTROL

The ability to remotely inspect and configure guest devices gives hosts the power to enforce a wide array of policies. In this section, we present a number of applications of such remote device analysis and control.

3.1 Kernel Analysis

The host can perform a variety of analyses on the guest device by remotely reading its memory contents.

Kernel-malware Detection. The host can analyze memory pages to identify malicious software in the end-user's work environment. Such *kernel-level rootkits* allow attackers to retain long-term control over infected devices, and are a realistic threat for mobile devices [16, 17]. It is well-accepted by the security community that rootkits cannot reliably be detected by user-space anti-malware tools on the infected device because these tools rely on the services provided by the operating system, which is itself infected. Rootkits can reliably be detected only using external methods, which inspect the infected kernel without relying on its services.

There are a number of ways to detect kernel-level malware by analyzing raw-memory pages. In the past, simple kernel-level rootkits operated by maliciously modifying code pages of the kernel. The host can easily detect such rootkits by checking that all executable code pages of the kernel belong to a whitelist of known-good pages. Modern rootkits work by injecting malicious code into the kernel, and modifying key kernel data structures to force their execution [49]. For example, a rootkit could inject a device driver, and modify function pointers within the kernel to invoke functions from this driver. More generally, a rootkit can modify an arbitrary kernel data structure to implement its malicious functionality. Such data structure modifications can be used to hide malicious user processes by modifying process lists, disable firewalls by modifying kernel hooks, and weaken cryptographic functions by modifying entropy pools [14].

Prior work [13, 20, 25, 49, 54] has developed a generic approach to detect malicious data modifications by analyzing raw memory pages. The main idea is for the host to externally reconstruct the kernel's data structures, and use this view to reason about the integrity of kernel data. We assume that the host has access to the type declarations of the data structures used by the kernel being analyzed, *e.g.,* the sizes, layouts, and fields of every data structure. The host starts the reconstruction process from some well-known

entrypoints into the system's memory, *e.g.,* the addresses of the entities in `System.map`, and recursively traversing kernel data structures. When the traversal process encounters a pointer, it must fetch the data member referenced by the pointer. The host therefore iteratively requests virtual pages from the guest device based upon the needs of this recursive traversal. Having reconstructed data structures, the host can then determine whether they have been maliciously modified. For example, it could check that function pointers in the kernel point to pre-determined addresses in the kernel's code space [49]. Similarly, the host can check that the kernel's data structures satisfy invariants that must typically hold in an uncompromised kernel [13].

Reverse-engineering Configurations. The host can use the memory pages obtained from the guest to identify the version of the kernel, and to determine if security patches have been applied. The host can also use it to check whether the configuration of the kernel disallows certain well-known attack surfaces (*e.g.,* that access to `/dev/kmem` and dynamic module loading are disabled). The recursive traversal method described above can also be used to reconstruct kernel configurations. For example, it can be used to identify addresses at which the functions of a peripheral's driver are loaded, where they are hooked into the kernel, and the addresses that store memory-mapped peripheral configurations. The host uses this information to create remote write requests that can uninstall peripherals from the device.

Check Running Processes and Apps. Once the host has ensured that the kernel is not infected by rootkits, it can use the clean kernel to bootstrap security at the user level. For example, it can require the end-user's work environment to execute an anti-malware app that relies on the clean kernel to detect sources of infection at user-space, *e.g.,* infected apps that reside on the file system. The host can ensure that this anti-malware app is executing on the guest device during check-in by traversing the kernel's list of running processes. At check-out, it can ensure that the same app is still executing by comparing its process identifier to the value obtained at check-in.

3.2 Control over Peripherals

The host can remotely configure peripherals on the guest device by writing to suitable memory locations. We consider various peripherals and describe scenarios where control over them would be useful.

Camera. The use of the camera is perhaps the most obvious way for guests to violate privacy and confidentiality (*e.g.,* [63, 64]). In the federal and enterprise settings, employees may photograph or videotape sensitive documents and meetings, while in social settings, the camera can be used to record conversations. In such settings, the camera can be disabled at check-in.

Microphone. Much like the camera, the microphone can also be used to violate privacy and confidentiality. However, disabling the microphone on devices such as smartphones may not be acceptable to guests because it also prevents them from having phone conversations. It may be possible for the host to configure the microphone's driver so that the microphone is activated only when a call is placed, and is de-activated otherwise. However, this facility can potentially be misused by malicious guests to record meetings by simply placing a call during the meeting. Therefore, it may be desirable to simply disable the microphone except when the guest places an outgoing call to an emergency number, and require guests to check-out if they wish to place other phone calls.

Networking. Enterprises (and federal institutions) today often disallow employees and visitors from connecting their personal devices to the corporate network. This is typically to avoid exfiltrating information outside the enterprise. With our approach, enterprises can allow employees to use the network after inspecting their devices to ensure that they are free from malicious software. To prevent exfiltration, the enterprise can disable the use of 3G/4G, and restrict the device to only WiFi. Because the enterprise controls the WiFi network, it can therefore regulate what data is accessible to the device and the external hosts to which the device can connect. In an examination setting, for example, the proctor/university can similarly restrict networking interfaces when students check-in their devices.

Detachable Storage. USB dongles and flash drives are extensively used to copy files across devices. However, they have also served as the vehicle for malware infections (*e.g.,* the Conficker worm [56]) and can be used by malicious guests to exfiltrate sensitive data from the host. Many enterprises only have informal guidelines discouraging their employees from using dongles and flash drives to copy files. With our approach, the host can simply disable the drivers for USB and flash drives at check-in, thereby preventing the use of detachable storage media within the restricted space.

Bluetooth. Smart glasses and smart watches rely on Bluetooth to pair with a more powerful hub, such as a smart phone, via which they connect to the external world. While it is generally possible to control their connection to the outside world by constraining the networking interfaces on the hub device, in some scenarios it may be necessary to prevent the device from pairing with the hub. For example, a student wearing a prescription smart glass may pair the device with his smart phone and use it to access class notes stored on the phone. Disabling Bluetooth prevents this channel, but allows the student to use the glass for vision correction.

4 POLICY ENFORCEMENT

We now present the design of our policy enforcement mechanism. Although the core of our mechanism that relies on remote memory operations is platform agnostic, we describe it in the context of the ARM TrustZone. We leverage the TrustZone's features to isolate the enforcement mechanism and to bootstrap its security features. We present alternative designs in Section 7.

4.1 Background on ARM TrustZone

The TrustZone is a set of security enhancements to chipsets based on the ARM architecture. These enhancements cover the processor, memory and peripherals. With TrustZone, the processor can execute instructions in one of two security modes at any given time, a *normal world* and a *secure world*. A third *monitor mode* facilitates switching between the normal and the secure worlds. The secure and normal worlds have their own address spaces and different privileges. The processor can switch from the normal world to the secure world via an instruction called the secure monitor call (`smc`). When an `smc` instruction is invoked from the normal world, the processor context switches to the secure world (via monitor mode) and freezes execution of the normal world.

TrustZone can partition memory into two portions, with one portion being exclusively reserved for the secure world. It also allows individual peripherals to be assigned to the secure world. For these peripherals, hardware interrupts are directly routed to and handled by the secure world. While the normal world cannot access peripherals or memory assigned to the secure world, the secure world enjoys unrestricted access to all memory and peripherals on the device. It can therefore access the code and data of the normal world. The secure world can execute arbitrary software, ranging from simple applications to an entire operating system.

A device with ARM TrustZone boots up in the secure world. After the secure world has initialized, it switches to the normal world

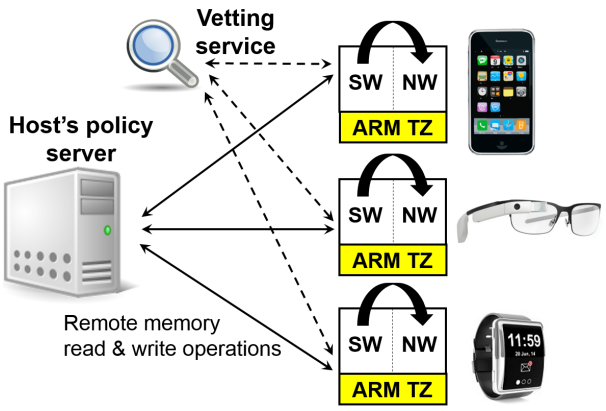


Figure 2: Overall setup showing communication between the host and guest devices. Guest devices are equipped with ARM TrustZone and execute components of the policy enforcement mechanism (see Figure 3). Abstractly, the goal is to establish a communication channel between the host's policy server and the enforcement mechanism running in the secure world (SW) of the guest devices. The host leverages the secure world to remotely inspect and modify normal world (NW) memory.

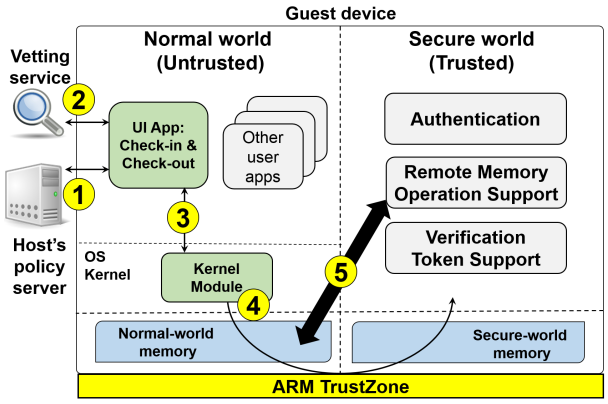


Figure 3: Guest device setup showing components of the policy enforcement mechanism. (1) The host communicates with the UI app on the guest and sends requests to perform remote memory operations. (2) The UI app uses the vetting service to determine the safety of the request. (3) If determined to be safe, the UI app forwards this request to the supporting kernel module. (4) The kernel module invokes the secure world by performing a world switch. (5) The secure world performs the requested memory operations on the normal world memory on behalf of the host. The components in the normal world, *i.e.,* the UI app and the kernel module are untrusted. The TCB consists of only the components that execute in the secure world.

and boots the operating system there. Most TrustZone-enabled devices are configured to execute a *secure boot* sequence that incorporates cryptographic checks into the secure world boot process [6]. For example, the device vendor could sign the code with its private key, and the vendor's code in the boot ROM would verify this signature using the vendor's public key. These checks ensure that the integrity of the boot-time code in the secure world has not been compromised, *e.g.,* by reflashing the image on persistent storage. Most vendors lock down the secure world via secure boot, thereby ensuring that it cannot be modified by end-users. This feature allows hosts to trust software executing in the secure world and treat it as part of the TCB. In the rest of this paper, we will assume that our guest devices use the secure boot process.

4.2 Overall Design

Figure 2 shows the overall setup of our framework. The host runs a policy server that communicates with guest devices in its restricted space. The normal world of each guest executes the end-user's work environment, and can run a full-fledged mobile operating system—in our prototype the normal world executes Android. Because this code is under the control of the end-user, the normal world is untrusted. The secure world of the guest runs a TCB that accepts and processes the operations remotely-initiated by the host to inspect the guest device and regulate the use of its peripherals.

For this setup to work, we need a communication channel that allows the host to securely relay its requests to the guest and obtain the guest's responses. In particular, the channel must not allow an attacker, such as the untrusted code executing in the normal world, to tamper with messages transmitted on it.

One way to set up such a channel is to configure the secure world to directly communicate with the host. In this case, the secure world would exclusively control a communications peripheral, say WiFi, and establish a connection with the host without involving the normal world. Thus, the code necessary to support this peripheral must also execute within the secure world and be part of the TCB. With WiFi, for instance, this would mean that several thousand lines from the networking stack would need to execute within the TCB.

In our work, we chose an alternative approach that minimizes the functionality implemented in the TCB. In this approach, the normal world mediates the communication channel between the secure world and the host, and is assigned all the peripherals on the device. Because the normal world is untrusted, the secure world and the host include cryptographic checksums with each message transmitted on the channel, and sanity-check the messages before processing them. The secure world itself executes a bare-minimum TCB that performs just three key operations: (1) mutual authentication (Section 4.3), (2) remote memory operations (Section 4.4), (3) verification tokens (Section 4.5).

Guest devices are therefore set up as shown in Figure 3. Within the normal world, the end-user interacts with the host as well as with the secure world via a user-level app (called the UI app). This app serves as the end-user's interface to the host, allowing him to perform operations such as check-in and check-out of the device. The app interacts with the components in the secure world via a kernel module. The host sends a request to perform remote memory operations on the guest device to the app. The app determines the safety of this request using the vetting service (Section 6), and forwards the request to the kernel module, which invokes `smc` to world switch into secure world. The components of the secure world then perform the request and communicate any return values to the host via the UI app.

We do not place any restrictions on how the host communicates with the guest. Thus, the host's policy server could be hosted on the cloud and communicate with the guest device over WiFi or 3G. Alternatively, the host could install physical scanners at a kiosk or on the entryway to the restricted space. The guest devices would use Bluetooth, NFC, or their USB interface to pair with the scanner and use it to communicate with the host.

One of the key features of our approach is that the core mechanisms that run on the TCB in the guest device are *platform-agnostic* and *policy-agnostic*. Rather, they present a narrow read/write interface that hosts can suitably use to enforce policy. All the complex tasks of device analysis and deciding policy are shifted to the host. Thus, in principle, we can use the same TCB mechanisms on guest devices that run Android, iOS and Windows. Hosts would have separate modules to analyze and control each kind of guest platform.

Let host's public/private keypair be PubH, PrvH.
Let guest's public/private keypair be PubG, PrvG.

1. **Guest → Host**: PubG, Cert(PubG)
2. **Host → Guest**: PubH, Cert(PubH)
3. Guest and host verify Cert(PubH) and Cert(PubG)
4. **Host → Guest**: M, $\mathsf{Enc}_{\mathsf{PrvH}}(M)$ (*i.e.,* host signs M), where M is $\mathsf{Enc}_{\mathsf{PubG}}(k_s$, timestamp)
5. Guest verifies host's digital signature, decrypts M to obtain k_s, and checks timestamp

Figure 4: Mutual authentication and establishment of k_s.

4.3 Authentication

Before accepting any remote memory requests, the guest and the host mutually authenticate each other. We assume that both the host and the guest device have public/private key pairs with digital certificates issued by a certifying authority. The guest device stores its private key PrvG in its secure world, thereby protecting it from the untrusted normal world.

Authentication is akin to TLS handshakes (Figure 4). The host and the guest exchange public keys and validate the certificates of these keys with the issuing authority. The host then computes a session key k_s, which is then transmitted to the client over an secure channel. Note that k_s is only used to protect the integrity of messages transmitted between the guest and the host and not its secrecy. The key k_s is stored in secure world memory, and is invisible to the normal world. If the guest is rebooted, k_s is erased from memory.

4.4 Remote Memory Operations

Remote Reads. The host inspects and modifies the guest device's configuration via remote memory operations. During check-in the host typically requests the guest to send raw memory pages from the normal world for analysis. The UI app receives this request and performs a world switch to complete the request. The world switch suspends the UI app and transfers control to the secure world. Each request is a set of virtual memory addresses of pages that must be sent to the host. The host also includes a message-authentication code (a SHA1-based HMAC in our case) with the request. The HMAC is over the body of the request using the key k_s negotiated during the authentication phase.

The secure world checks the integrity of the request using the HMAC. This step is necessary to ensure that the request was not maliciously modified by the untrusted components in the normal world. The secure world then translates each virtual page address in the request to a physical page address by consulting the page table in the normal world kernel. In this case, the page table will correspond to the suspended context in the normal world, *i.e.,* that of the UI app, into which the running kernel is also mapped. It then creates a local copy of the contents of this physical page from the normal world, and computes an HMAC over the page (again using k_s). The page and its HMAC are then copied to a buffer in the normal world, from where they can be transmitted to the host by the UI app. The host checks the HMAC and uses the page for analysis. This process is iterative, with the host requesting more pages from the guest based upon the results of the analysis.

Note that in our case, both the host and the secure world are isolated from the normal world, which is untrusted. We only rely on the normal world kernel to facilitate communication between the host and the secure world. Moreover, both the host and the secure world use HMACs to protect the integrity of messages transmitted via the normal world. The normal world may drop messages and cause a denial-of-service attack; however, such attacks are outside our threat model (see Section 2.4). The host can therefore reliably obtain the memory pages of the normal world to enable the kinds of analyses described in Section 3.1. Communication between the host and the secure world is not confidential and is therefore not encrypted.[2] Thus, a malicious normal world kernel can potentially snoop on the requests from the host to fetch pages and attempt to remove the infection to avoid detection. However, this would have the desirable side-effect of cleaning the guest device at check-in.

Remote Writes. The host reconfigures the guest by modifying the running state of the normal world kernel via remote write requests. Each write request is a set of triples $\langle vaddr_i, val_i, old\text{-}val_i \rangle$ together with an HMAC of this request. The normal world conveys this request to the secure world, which verifies the integrity of the message using its HMAC. For each virtual address $vaddr_i$ (which refers to a memory location in the virtual address space of the UI app) in the request, the secure world ensures that the current value at the address matches $old\text{-}val_i$. If all the values match, then the secure world replaces their values with val_i.

Note that because the normal world is frozen during the course of this operation, the entire update is atomic with respect to the normal world. When a remote write operation succeeds, the secure world computes and returns a verification token to the host. If not, it returns an error code denoting a failure.

A remote write request can fail if the value stored at the virtual address $vaddr_i$ does not match the value $old\text{-}val_i$. This problem arises in our design because the host's remote read and write operations do not happen as an atomic unit. The host remotely reads pages copied from the normal world's memory, analyzes them and creates remote write request using this analysis. During this time, the normal world kernel continues to execute, and may have updated the value at the address $vaddr_i$.

If a remote write operation fails, the host repeats the operation until it succeeds. That is, it refetches pages from the guest, analyzes them, and creates a fresh write request. In theory, it is possible that the host's write requests will fail *ad infinitum*. However, for the setting that we consider, write operation failures are rare in practice. This is because our write operations modify the addresses of peripheral device driver hooks. Operating systems typically do not change the values of device driver hooks after they have been initialized at system boot.

In theory, a remote write request can also fail if the virtual address $vaddr_i$ referenced in the request is not mapped to a physical page in memory, *i.e.,* if the corresponding page has been swapped out to persistent storage. In practice, however, we restrict remote writes to kernel data pages that are resident in physical memory, as is the case with device drivers and pages that store data structures of peripherals. Therefore, we do not observe failures due to a failure to resolve $vaddr_i$s.

It is possible to completely avoid such problems by design if we complete both the read and write operations in a single world switch. During this time, the normal world remains frozen and cannot change the view of memory exported to the host. The read and write operations will therefore happen as an atomic unit from the normal world's perspective. However, in this case, the secure world must have the ability to directly communicate with the host. As already discussed in Section 4.2, we decided against this design because it has the unfortunate consequence of bloating the size of the TCB. Thus, we make the practical design tradeoff of minimizing the functionality of the TCB while allowing the rare remote write failure to happen.

[2] The host and guest could communicate over TLS, but the TLS channel on the guest ends at the UI app, which runs in the normal world.

Component Name	LOC
Secure World (TCB)	
(1) Memory manager	1,381
(2) Authentication	1,285
(3) Memory ops	305
(4) SHA1+HMAC	861
(5) X509	877
(6) RSA	2,307
Normal World	
(1) Kernel module	93
(2) UI app	72

Figure 5: Sizes of components executing on the guest.

4.5 Verification Tokens

The host receives a verification token from the secure world upon successful completion of a remote write operation. A verification token $\mathsf{VTok}[r]$ is the value $r \| MemState \| \mathsf{HMAC}_{k_s}[r \| MemState]$ where $MemState$ is $\langle vaddr_1,\ val_1 \rangle \| \ldots \| \langle vaddr_n,\ val_n \rangle$, the set of $vaddr_i$ modified by the remote write, and the new values val_i at these locations. The token $\mathsf{VTok}[r]$ is parameterized by a random nonce r. This nonce can either be provided by the host together with the remote write request, or can be generated by the secure world.

Verification tokens allow the host to determine whether the guest attempted to revert the configuration changes made by the remote write, either maliciously or by turning off the guest device. To do so, the host obtains a verification token $\mathsf{VTok}[r_{checkin}]$ upon completion of checkin, and stores this token for validation. During checkout, the host requests a validation token $\mathsf{VTok}[r_{checkout}]$ from the guest over the same virtual memory addresses. The secure world accesses each of these memory addresses and computes the verification token with $r_{checkout}$ as the nonce. The host can compare the verification tokens $\mathsf{VTok}[r_{checkin}]$ and $\mathsf{VTok}[r_{checkout}]$ to determine whether there were any changes to the values stored at these memory addresses.

The nonces $r_{checkin}$ and $r_{checkout}$ ensure the freshness of the tokens $\mathsf{VTok}[r_{checkin}]$ and $\mathsf{VTok}[r_{checkout}]$. The use of k_s to compute the HMAC in the verification token ensures that the token is only valid for a specific device and for the duration of the session, *i.e.,* until check-out or until the device is powered off, whichever comes earlier. Because k_s is only stored in secure world memory, it is ephemeral and unreadable to the normal world. This ensures that any attempts to undo the configuration changes performed at checkin will be detected by the host.

5 IMPLEMENTATION AND EVALUATION

We implemented our policy enforcement mechanism atop a Freescale i.MX53 Quick Start Board as our guest device. This TrustZone-enabled board has a 1GHz ARM Cortex A8 processor with 1GB DDR3 RAM. We chose this board as the guest device because it offers open, programmable access to the secure world. In contrast, the vendors of most commercially-available TrustZone-enabled devices today lock down the secure world and prevent any modifications to it. A small part of main memory is reserved for exclusive use by the secure world. On our i.MX53 board, we assigned the secure world 256MB of memory, although it may be possible to reduce this with future optimizations. The normal world runs Android 2.3.4 atop Linux kernel version 2.6.35.3.

We built a bare-metal runtime environment for the secure world, just enough to support the components shown in Figure 3. This environment has a memory manager, and a handler to parse and process commands received from the host via the normal world. To implement cryptographic operations, we used components from an off-the-shelf library called PolarSSL (v1.3.9) [4]. Excluding the cryptography library, our TCB in the secure world consists of about 3,000 lines of C code, including about 250 lines of inline assembly.

Figure 5 shows the sizes of various components. We used PolarSSL's implementation of SHA1 and HMACs, RSA and X509 certificates. As shown in Figure 5, the files implementing these components alone comprise only about 4,000 lines of code. In addition to these TCB components, we built the kernel module and the UI app (written as a native daemon) for the normal world, comprising 165 lines of code. We implemented a host policy server that authenticates guest devices, and performs remote memory operations. We conducted experiments to showcase the utility of remote reads and writes to enforce the host's policies on the guest. The guest and the host communicate over WiFi.

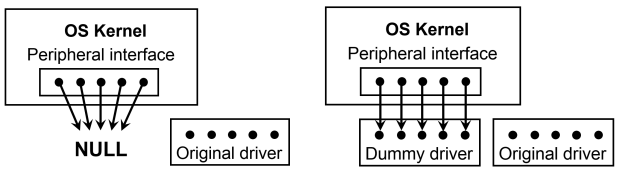
Guest Device Analysis. To illustrate the power of remote memory read operations to perform device analysis, we wrote a simple rootkit that infects the guest's normal world kernel by hooking its system call table. In particular, it replaces the entry for the `close` system call to instead point to a malicious function injected into the kernel. The malicious functionality ensures that if the process invoking `close` calls it with a magic number, then the process is elevated to `root`. Although simple in its operation, Petroni and Hicks [49] show that over 95% of all rootkits that modify kernel data operate this way.

We were able to detect this rootkit on the host by remotely reading and analyzing the guest's memory pages. We remotely read pages containing the `init`, `text` and `data` sections of kernel memory. Our analyzer, a 48 line Python script, reads the addresses in the system call table from memory, and compares these entries with addresses in `System.map`. If the address is not included, *e.g.,* as happens if the entry for the `close` system call is modified, it raises an error. Prior work (*e.g.,* [13, 20, 49]) has developed tools to recursively traverse kernel data structures from memory dumps. Such tools can also be used with the memory pages obtained by the host to detect more sophisticated rootkits.

For the above experiment, it took the secure world 54 seconds to create an HMAC over the memory pages that were sent to the host (9.2MB in total). It takes under a second to copy data from the normal world to the secure world and vice versa. It may be possible to accelerate the performance of the HMAC implementation using floating point registers and hardware acceleration, but we have not done so in our prototype.

Guest Device Control. We evaluated the host's ability to dynamically reconfigure a guest device via remote memory write operations. For this experiment, we attempted to disable a number of peripherals from the guest device. However, the i.MX53 board only supports a bare-minimum number of peripherals. As proof-of-concept, we therefore tested the effectiveness of remote writes on a Samsung Galaxy Nexus smart phone with a Texas Instruments OMAP 4460 chipset. This chipset has a 1.2GHz dual-core ARM Cortex-A9 processor with 1GB of RAM, and runs Android 4.3 atop Linux kernel version 3.0.72. This device has a rich set of peripherals, but its chipset comes with TrustZone locked down, *i.e.,* the secure world is not accessible to third-party programmers. We therefore performed remote writes by modifying memory using a kernel module in its (normal world) operating system. Thus, while remote writes to this device do not enjoy the security properties described in Section 4, they allow us to evaluate the ability to uninstall a variety of peripherals from a running guest device.

We adopted two broad strategies to uninstall peripherals. On modern operating systems, each peripheral has an interface within the kernel. This interface consists of a set of function pointers that are normally set to point to the corresponding functions within the peripheral's device driver, which communicates with the peripheral.



(a) NULLifying the interface **(b) Installing a dummy driver**

Figure 6: Uninstalling a peripheral by writing to kernel memory. Each device driver exposes an interface and is linked to the kernel via function pointers. Part (a) shows how to uninstall the peripheral by making the kernel's device interface point to NULL bytes. Part (b) shows how to uninstall the peripheral by unlinking the original driver and instead linking a dummy driver.

Peripheral	Method Used	Size (bytes)	Device
USB (webcam)	NULLify interface	104	i.MX53
USB (webcam)	Dummy driver	302	i.MX53
Camera	NULLify interface	140	Nexus
Camera	Dummy driver	212	Nexus
WiFi	Dummy driver	338	Nexus
3G (Data)	Dummy driver	252	Nexus
3G (Voice)	Dummy driver	224	Nexus
Microphone	Dummy driver	184	Nexus
Bluetooth	Dummy driver	132	Nexus

Figure 7: Peripherals uninstalled using remote write operations to a guest device. Also shown are the method used to uninstall the peripheral (see Figure 6), the number of bytes modified or added by the remote write, and the guest device used.

Our first strategy to uninstall the peripheral was to simply set the function pointers in the peripheral's interface to NULL, as shown in Figure 6(a). If the kernel checks these pointers prior to invoking the functions, it will simply return an error code to the application saying that the device is not installed. This approach has the advantage of only involving simple writes to the kernel (NULL bytes to certain addresses), which can easily be validated as safe if the guest so wishes. However, we found that this approach generally makes the guest unstable. For example, except in two cases, NULLifying the peripheral interface resulted in a system crash (Figure 7).

We therefore adopted the approach shown in Figure 6(b), which should work with any peripheral. In this approach, we write a dummy driver for the peripheral, *e.g.,* one that simply returns a suitable error code rather than communicating with the peripheral, and link it with the kernel in place of the original driver. With this approach we were successfully able to uninstall all the peripherals that we tried. Note that the host must introduce new code (*i.e.,* the dummy driver) into the guest, so the guests must check the remote write operations for safety. Section 6 discusses our prototype vetting service.

Figure 7 shows the set of peripherals that we uninstalled, the method used to uninstall the peripheral, the size of the write operation (the number of bytes that we had to modify/introduce in the kernel), and whether the operation was performed on the i.MX53 or the Nexus. We were able to uninstall the USB on the i.MX53 and the camera on the phone by NULLifying the peripheral interface. For the other peripherals, we introduced dummy drivers. We also used dummy drivers for the USB and the camera to compare the size of the write operations. In this case, the size of the write includes both the bytes modified in the peripheral interface and the dummy driver functions. For the 3G interface, we considered two cases: that of disabling only data transmission and that of only disabling calls. Our experiment shows it is possible to uninstall peripherals without crashing the operating system by just modifying a few hundred bytes of memory on the running device.

Installing a dummy driver disables the peripheral, but how does it affect the user app that is using the peripheral? To answer this question, we conducted two sets of experiments involving a number of client user apps that leverage the periperhals shown in Figure 7.

In the first set of experiments, which we call the *passive setting*, we start with a configuration where the client app is not executing, replace the device driver of the peripheral with a dummy, and then start the app. In the second set of experiments, called the *active setting*, we replace the periperhal's device driver with the dummy as the client app that uses the peripheral is executing.

Figure 8 shows the results of our experiments. For both the passive and active settings, we observe that in most cases, the user app displays a suitable error message or changes its behavior by displaying a blank screen or creating an empty audio file. In some cases, particularly in the passive setting, the app fails to start when the driver is replaced, and the Android runtime displays an error that it is unable to start the app.

6 VETTING HOST REQUESTS

We implemented a cloud-based trusted vetting service to allow guests to determine the safety of a host's requests. The guest device forwards the host's requests together with a copy of its memory image to the vetting service (via the UI app). We assume that the device and the vetting service have authenticated each other as in Figure 4, thus establishing an integrity-protected channel between the vetting server and the guest device TCB.

The UI app obtains an HMAC'ed memory image from the secure world as in Section 4.4 and transmits it to the vetting server. The vetting server checks the requests against its safety policies and returns a SAFE or UNSAFE response to the device. The response is bound with a random nonce and an HMAC to the original request in the standard way to prevent replay attacks. The secure world performs the operations only if the response is SAFE.

Vetting servers can determine safety using arbitrary, domain-specific policies. Our prototype vetting service, which we built as a plugin to the Hex-Rays IDA toolkit [1], analyzes memory images and checks for the following safety policies. Although simple and conservative, these policies worked well during our experiments, proving safety without raising false positives.

Read Requests. For each request to read from address $vaddr_i$, we return SAFE only if $vaddr_i$ falls in a pre-determined range of addresses. The vetting server pre-computes this range of addresses by analyzing the memory image of the device. In our prototype, acceptable address ranges only include pages that contain kernel code and data structures. In particular, the vetting server returns UNSAFE if the read request attempts to fetch any addresses from kernel buffers that store user app data, or virtual address ranges for user app code and data.

Write Requests. Our prototype currently only allows write requests to NULLify peripheral interfaces or install dummy drivers. Dummy drivers are determined to be SAFE using the following policy. For each function f implemented in the dummy driver, consider its counterpart f_{orig} from the original driver, which the vetting service obtains from the device's memory image. We return SAFE only if (1) the function f is identical to f_{orig}, or (2) f's body consists of a single `return` statement that returns a *valid* error code (*e.g.,* -ENOMEM). We define an error code as being valid for f if and only if the same error code is returned along at least one path in f_{orig}. The intuition behind this safety check is that f does not modify the memory state of the device or introduce new and possibly buggy code, but returns an error code that is acceptable to the kernel and client user apps.

USB	*MobileWebCam*	*Camera ZOOM FX*	*Retrica*	*Candy Camera*	*HD Camera Ultra*
Passive	AppErrMsg	AppErrMsg	AndroidErrMsg	AppErrMsg	AndroidErrMsg
Active	AppErrMsg	AppErrMsg	AppErrMsg	AppErrMsg	AppErrMsg
Camera	***Camera for Android***	***Camera MX***	***Camera ZOOM FX***	***HD Camera for Android***	***HD Camera Ultra***
Passive	AndroidErrMsg	AppErrMsg	AppErrMsg	AndroidErrMsg	AndroidErrMsg
Active	BlankScreen	AppErrMsg	AndroidErrMsg	BlankScreen	BlankScreen
WiFi	***Spotify***	***Play Store***	***YouTube***	***Chrome Browser***	***Facebook***
Passive	LostConn	LostConn	LostConn	LostConn	LostConn
Active	LostConn	LostConn	LostConn	LostConn	LostConn
3G (Data)	***Spotify***	***Play Store***	***YouTube***	***Chrome Browser***	***Facebook***
Passive	LostConn	LostConn	LostConn	LostConn	LostConn
Active	LostConn	LostConn	LostConn	LostConn	LostConn
3G (Voice)	***Default call application***				
Passive	AppErrMsg: Unable to place a call				
Active	AppErrMsg: Unable to place a call				
Microphone	***Audio Recorder***	***Easy Voice Recorder***	***Smart Voice Recorder***	***Sound and Voice Recorder***	***Voice Recorder***
Passive	AppErrMsg	AppErrMsg	AppErrMsg	AppErrMsg	AppErrMsg
Active	EmptyFile	EmptyFile	EmptyFile	EmptyFile	EmptyFile

Figure 8: Results of robustness experiments for both the passive and active settings. We use *Passive* to denote experiments in which the user app was not running when the peripheral's driver was replaced with a dummy, and the app was started after this replacement. We use *Active* to denote experiments in which the periperhal's driver was replaced with a dummy even as the client app was executing. (1) AppErrMsg denotes the situation where the user app starts normally, but an error message box is displayed within the app after it starts up; (2) BlankScreen denotes a situation where the user app displayed a blank screen; (3) LostConn denotes a situation where the user app loses network connection; (4) EmptyFile denotes a sitution where no error message is displayed, but the sound file that is created is empty; (5) AndroidErrMsg denotes the situation where the user app fails to start (in the passive setting) or a running app crashes (in the active setting), and the Android runtime system displays an error.

7 DESIGN ALTERNATIVES

The design of our enforcement mechanism relies on the ARM TrustZone to isolate the TCB and to provide a root of trust on the guest device. While devices featuring the ARM TrustZone hardware are becoming increasingly available (millions of deployed devices, according to the Samsung Knox team [11]), we consider alternatives that can be used by hosts to regulate guest devices.

Virtualization. On x86 machines, virtualization is the most popular technique to perform introspection [21, 33]. There have been recent efforts to build virtualization infrastructure for smart phones [7, 9, 24] and other ARM devices [26].

It is possible to regulate the use of peripherals on virtualized smart devices using virtual machines (VMs) to implement various persona. For example, for an employee to use his personal device at work, he may be required to download a work VM from enterprise. The virtual peripherals in this work VM can be pre-configured to reflect the enterprise policy. Thus, if the enterprise disallows the use of the camera, the work VM is simply configured to not export a virtual camera peripheral to apps executing within the VM. Virtualized platforms also support remote memory operations—the hypervisor simply reads/modifies the pages belonging to a VM to perform the operations. Thus, the enterprise can even dynamically reconfigure its work VM via such operations.

However, in virtualized solutions, the TCB typically includes the hypervisor. Although prior research has developed small hypervisors [58], modern production hypervisors are large and complex because they must support different virtualization modes, guest quirks, and hardware features; this bloats the TCB. Moreover, without a hardware root of trust, it is hard to establish whether the guest has maliciously bypassed the host's enforcement. In the above example, the employee could suspend the work VM, and switch to a different VM that allows the use of the camera. The hypervisor must include additional functionality to prevent the employee from suspending the work VM, thus bloating TCB size.

We also feel that virtualization may not be applicable to large majority of personal computing devices. Many classes of smart devices are personal, single-user devices and specialized in their function. Judging by their typical use-cases, virtualization may be an overkill for most of these devices except those at the highest end of the form factor (*e.g.,* enterprise-class smart devices). This reduces the motivation to virtualize these devices.

Hardware Interfaces. It may be possible to use hardware interfaces to perform remote memory operations on a guest system. Such interfaces were investigated for the server world to perform remote DMA as a means to bypass the performance overheads of the TCP/IP stack [2, 3]. This work has since been repurposed to perform kernel malware detection [50] and remote repair [18]. These systems use a PCI-based co-processor on the guest system via which the host can remotely transfer and modify memory pages on the guest.

On personal devices, the closest equivalent to such a hardware interface is the IEEE 1394, popularly called the Firewire. The host can leverage the Firewire interface on a guest device to directly read and modify its memory pages. However, a large majority of small form-factor mobile devices available today are not equipped with the Firewire interface. For instance, to our knowledge, except for some laptop computers, most other mobile devices do not have a Firewire port. Another possibility is to use the JTAG interface, defined by the Joint Test Action Group (IEEE 1149.1). Via a few dedicated pins on the chip, the JTAG allows testing functions such as reading and writing to the memory and registers of the chip. However, the JTAG is primarily used for debugging and is not easily accessible on consumer devices.

The main drawback of hardware interfaces is that they typically cannot authenticate the credentials of the host that initiates the memory operation. This shortcoming can be exploited by a malicious host to compromise guest security. Moreover, to configure guest devices via these hardware interfaces, the host must physically plug into the network interfaces of these devices. Thus, these interfaces are best used when the guest can physically authenticate the host and trust it to be benign.

OS-based Mechanisms. Operating systems can be modified to dump the contents of their memory. For example, on Android, LiME [37] and similar tools [35, 59, 62] can be used to acquire memory from a running system. However, without trusted hardware, the host has no way to check the integrity of memory dumps.

Finally, it is possible to regulate the use of guest devices by requiring the user's work environment to run a security-enhanced operating system. For instance, ASM [38] introduces a set of security hooks in Android, which consult a security policy (installed as an app) to enforce fine-grained control over the device. ASM policies can be used to create persona that can determine the set of apps, files, and peripherals that are visible to the end-user. This approach has the benefit of offering greater visibility and control than remote memory operations into app-level context and behavior. With this visibility, it may be possible to enforce much finer-grained policies than our work. For example, prior work [52] has leveraged the visibility from within the operating system (using the recognizer abstraction [39]) to selectively block sensitive audio, blur faces and block RGB events to the corresponding apps. Without suitable techniques to bridge the semantic gap between raw memory and application state, this level of visibility is difficult to achieve at the granularity of raw memory reads and writes.

But as with virtualization, the approach presents a large TCB because the security mechanism is closely integrated with the operating system. In contrast, in approaches that use remote memory operations, the mechanism is agnostic to the operating system executing on the guest device. The burden of analyzing memory and determining which locations to modify is left to the host, while the guest runs a minimal, platform-agnostic TCB.

8 RELATED WORK

TrustZone-based Frameworks. Since the introduction of TrustZone, a number of projects have used it to build novel security applications. TrustDump [60] is a TrustZone-based mechanism to reliably acquire memory pages from the normal world of a device. While similar in spirit to remote reads, TrustDump's focus is to be an alternative to virtualized memory introspection solutions for malware detection. Unlike our work, TrustDump is not concerned with restricted spaces, authenticating the host, or remotely configuring guest devices.

Samsung Knox [11] and SPROBES [34] leverage TrustZone to protect the normal world in real-time from kernel-level rootkits. These projects harden the normal world kernel by making it perform a world switch when it attempts to perform certain sensitive operations to kernel data. A reference monitor in the secure world checks these operations, thereby preventing rootkits. In our work, remote reads allow the host to detect infected devices, but we do not attempt to provide real-time protection from malware. As discussed in Section 2.4, our work can be used in conjunction with Knox to improve the security of the normal world.

TrustZone has also been used to improve the security of user applications. Microsoft's TLR [53] and Nokia's ObC [41] leverage TrustZone to provide a secure execution environment for user applications, even in the presence of a compromised kernel. Other applications include ensuring trustworthy sensor readings from peripherals [43] and securing mobile payments [5].

Enterprise Security. With the growing emphasis on BYOD, a number of projects have developed enterprise security solutions for smart devices. Many of these projects have focused on enabling multiple persona (*e.g.,* [9, 19, 38]) or enforcing mandatory access control policies on smart devices (*e.g.,* [19, 38, 57, 65]). Prior work has also explored fine-grained access control for devices based on the context or location of their use, and has developed techniques for real-world objects owned by the host to push access control policies onto guest devices [12, 22, 23, 27, 45, 47, 48, 51, 52].

There are three differences between these projects and ours. First, they typically exercise their policies at the level of user apps and not peripherals. Our work can synergistically complements the app-level control that they provide. Second, most of these techniques are typically implemented by enhancing the runtime platform on the guest device. In our work, the policy enforcement mechanism is agnostic to the guest platform because it works at the level of memory reads and writes. The platform-specific portions (*i.e.,* analyzing memory images and designing the write operations) are performed at the host. This approach keeps the TCB that executes on the guest minimal in functionality. Again, our work can potentially complement these efforts. For example, the concept of remote memory reads and verification tokens can be used to check the guest's configuration, and ensure that the device runs the enhanced runtime platform that enforces the host's policies on apps.

The third and most significant difference is that these prior projects have generally assumed compliant guest devices. That is, they enhance the runtime platform (*e.g.,* the OS) on guest devices with policy-enforcement mechanisms, which is part of the TCB, and assume that the runtime platform is not malicious. In contrast, our work builds upon trusted hardware on guest devices, thereby allowing hosts to enforce policies and check policy compliance on both benign and malicious guest devices.

App Security. It is now well-known that many popular apps exfiltrate sensitive user data from smart devices [29]. Moreover, a significant fraction of apps (on Android) are over-privileged [10, 30] and end-users are poor at understanding the meaning of app permissions [32, 42]. Such apps can leverage the increasing array of sensors on modern smart devices in novel and dangerous ways [55, 64]. These threats will amplify in the future as we see an increasing number of augmented reality apps that continuously monitor sensor feeds and extract data from the device's environment.

Some projects have attempted to rectify the situation by offering improved app permission models [31] or modifying the execution environment on the device to return "fake" sensor data to apps [15]. However, such techniques are usually ineffective when the device itself is compromised (*e.g.,* via kernel rootkits), or if the user unintentionally installs a malicious app. Researchers have also investigated defenses tailored toward improving privacy in the presence of augmented reality apps [39, 40]. Our work can complement these efforts by allowing hosts to control peripherals below the app layer.

9 CONCLUDING REMARKS

The increasing ubiquity and capability of smart devices has driven society to create restricted spaces. We presented a mechanism for hosts to remotely inspect and control devices within restricted spaces. Our mechanism achieves this goal via a narrow interface that permits remote memory operations. Our prototype implements the mechanism for TrustZone-enabled devices.

While technically feasible, our approach must overcome certain hurdles before it can be practically adopted. The foremost among these is end-user willingness to subject their devices to regulation in restricted spaces. It is possible that many users would simply choose not to use their devices within the restricted space rather than give the host control over their devices (assuming they do not resort to using the devices covertly). However, given our increasing reliance on smart devices and the ways in which they are becoming integral parts of our daily lives, it is unclear going forward whether such simple "opt-out" solutions would even be a possibility. For example, opting-out would not be a practical solution for smart devices integrated with health monitoring and assistive functionality. Even if end-users were willing to subject their devices to regula-

tion, it is unclear to what extent they will trust the host's control over their device. Solutions such as our vetting service could ameliorate these concerns. We plan to explore these user-interaction and user-perception issues in future work.

REFERENCES

[1] Hex-rays software: About IDA. https://www.hex-rays.com/products/ida/index.shtml.

[2] The Infiniband trade association. http://www.infinibandta.org.

[3] Mellanox technologies Inc. http://www.mellanox.com.

[4] PolarSSL: Straightforward, secure communication. https://polarssl.org.

[5] Proxama. http://www.proxama.com/products-and-services/trustzone.

[6] ARM security technology – Building a secure system using TrustZone technology, 2009. ARM Technical Whitepaper. http://infocenter.arm.com/help/topic/com.arm.doc.prd29-genc-009492c/PRD29-GENC-009492C_trustzone_security_whitepaper.pdf.

[7] VMware news release — Verizon Wireless and VMware securely mix the professional and personal mobile experience with dual persona Android devices, October 2011. http://goo.gl/D3uJJr.

[8] N. Anderson and V. Strauss. Cheating concerns force delay in SAT scores for South Koreans and Chinese. In *Washington Post*, October 2014. http://goo.gl/6n45Gx.

[9] J. Andrus, C. Dall, A. V. Hof, O. Laadan, and J. Nieh. Cells: A virtual mobile smartphone architecture. In *ACM SOSP*, 2011.

[10] K. Au, B. Zhou, J. Huang, and D. Lie. PScout: Analyzing the Android permission specification. In *ACM CCS*, 2012.

[11] A. Azab, P. Ning, J. Shah, Q. Chen, R. Bhutkar, G. Ganesh, J. Ma, and W. Shen. Hypervision across Worlds: Real-time kernel protection from the ARM TrustZone secure world. In *ACM CCS*, 2014.

[12] G. Bai, L. Gu, T. Feng, Y. Guo, and X. Chen. Context-aware usage control for Android. In *SecureComm*, 2010.

[13] A. Baliga, V. Ganapathy, and L. Iftode. Detecting kernel-level rootkits using data structure invariants. *IEEE TDSC*, 8(5), 2011.

[14] A. Baliga, P. Kamat, and L. Iftode. Lurking in the shadows: Identifying systemic threats to kernel data. In *IEEE Symp. on Security and Privacy*, 2007.

[15] A. Beresford, A. Rice, N. Skehin, and R. Sohan. MockDroid: Trading privacy for application functionality on smartphones. In *HotMobile*, 2010.

[16] J. Bickford, H. A. Lagar-Cavilla, A. Varshavsky, V. Ganapathy, and L. Iftode. Security versus energy tradeoffs in host-based detection of mobile malware. In *ACM MobiSys*, 2011.

[17] J. Bickford, R. O'Hare, A. Baliga, V. Ganapathy, and L. Iftode. Rootkits on smart phones: Attacks, implications and opportunities. In *HotMobile*, 2010.

[18] A. Bohra, I. Neamtiu, P. Gallard, F. Sultan, and L. Iftode. Remote repair of operating system state using backdoors. In *Intl. Conf. on Autonomic Computing*, 2004.

[19] S. Bugiel, S. Hauser, and A.-R. Sadeghi. Flexible and fine-grained mandatory access control on Android for diverse security and privacy policies. In *USENIX Security*, 2013.

[20] M. Carbone, W. Cui, L. Lu, W. Lee, M. Peinado, and X. Jiang. Mapping kernel objects to enable systematic integrity checking. In *ACM CCS*, 2009.

[21] P. M. Chen and B. Noble. When virtual is better than real. In *USENIX HotOS*, 2001.

[22] M. Conti, V. T. N. Nguyen, and B. Crispo. CRePE: Context-related policy enforcement for Android. In *ISC*, 2010.

[23] M.J. Covington, P. Fogla, Z. Zhan, and M. Ahamad. A context-aware security architecture for emerging applications. In *ACSAC*, 2002.

[24] L. P. Cox and P. M. Chen. Pocket hypervisors: Opportunities and challenges. In *HotMobile*, 2007.

[25] W. Cui, M. Peinado, Z. Xu, and E. Chan. Tracking rootkit footprings with a practical memory analysis system. In *USENIX Security*, 2012.

[26] C. Dall and J. Nieh. KVM/ARM: The design and implementation of the Linux ARM hypervisor. In *ASPLOS*, 2014.

[27] M. Damiani, E. Bertino, B. Catania, and P. Perlasca. GEO-RBAC: A spatially aware RBAC. *ACM TISSEC*, 10(1), 2007.

[28] L. Davi, A. Dmitrienko, M. Egele, T. Fischer, T. Holz, R. Hund, S. Nurnberger, and A-R. Sadeghi. MoCFI: A framework to mitigate control-flow attacks on smartphones. In *NDSS*, 2012.

[29] W. Enck, P. Gilbert, B-G. Chun, L. P. Cox, J. Jung, P. McDaniel, and A. N. Sheth. TaintDroid: An information-flow tracking system for realtime privacy monitoring on smartphones. In *USENIX OSDI*, 2010.

[30] A. Felt, E. Chin, K. Greenwood, and D. Wagner. Android permissions demystified. In *ACM CCS*, 2011.

[31] A. Felt, S. Egelman, M. Finifter, D. Akhawe, and D. Wagner. How to ask for permission. In *USENIX HotSec*, 2012.

[32] A. Felt, E. Ha, S. Egelman, A. Haney, E. Chin, and D. Wagner. Android permissions: User attention, comprehension, and behavior. In *ACM SOUPS*, 2012.

[33] T. Garfinkel and M. Rosenblum. A virtual machine introspection based architecture for intrusion detection. In *NDSS*, 2003.

[34] X. Ge, H. Vijayakumar, and T. Jaeger. SPROBES: Enforcing kernel code integrity on the TrustZone architecture. In *IEEE Mobile Security Technologies Workshop*, 2014.

[35] Google. Using DDMS for debugging. http://developer.android.com/tools/debugging/ddms.html.

[36] J. A. Halderman and E. W. Felten. Lessons from the Sony CD DRM episode. In *USENIX Security*, 2006.

[37] A. P. Heriyanto. Procedures and tools for acquisition and analysis of volatile memory on Android smartphones. In *11th Australian Digital Forensics Conf.*, 2013.

[38] S. Heuser, A. Nadkarni, W. Enck, and A. R. Sadeghi. ASM: A programmable interface for extending Android security. In *USENIX Security*, 2014.

[39] S. Jana, D. Molnar, A. Moshchuk, A. Dunn, B. Livshits, H. J. Wang, and E. Ofek. Enabling fine-grained permissions for augmented reality applications with recognizers. In *USENIX Security*, 2013.

[40] S. Jana, A. Narayanan, and V. Shmatikov. A scanner darkly: Protecting user privacy from perceptual applications. In *IEEE Symp. on Security and Privacy*, 2013.

[41] K. Kostiainen, J. Ekberg, N. Asokan, and A. Rantala. On-board credentials with open provisioning. In *ASIACCS*, 2009.

[42] J. Lin, S. Amini, J. Hong, N. Sadeh, J. Lindqvist, and J. Zhang. Expectation and purpose: Understanding users' mental models of mobile app privacy through crowdsourcing. In *ACM UbiComp*, 2012.

[43] H. Liu, S. Saroiu, A. Wolman, and H. Raj. Software abstractions for trusted sensors. In *ACM MobiSys*, 2012.

[44] M. McGee. Glass alamanac – New website tracks "Glasshole-Free Zones" – businesses that have banned Google Glass, March 2014. http://goo.gl/h9uew4.

[45] M. Miettinen, S. Heuser, W. Kronz, A.-R. Sadeghi, and N. Asokan. ConXsense – Context profiling and classification for context-aware access control. In *ASIACCS*, 2014.

[46] A. Migicovsky, Z. Durumeric, J. Ringenberg, and J. Alex Halderman. Outsmarting proctors with smartwatches: A case study on wearable computing security. In *Intl. Conf. on Financial Cryptography and Data Security*, 2014.

[47] M. Ongtang, S. McLaughlin, W. Enck, and P. McDaniel. Semantically-rich application-centric security in Android. In *ACSAC*, 2009.

[48] S. Patel, J. Summet, and K. Truong. Blindspot: Creating capture-resistant spaces. In *Protecting Privacy in Video Surveillance*, 2009.

[49] N. Petroni and M. Hicks. Automated detection of persistent kernel control-flow attacks. In *ACM CCS*, 2007.

[50] N. L. Petroni, T. Fraser, J. Molina, and W. A. Arbaugh. Copilot: A coprocessor-based kernel runtime integrity monitor. In *USENIX Security*, 2004.

[51] N. Raval, A. Srivastava, K. Lebeck, L. P. Cox, and A. Machanavajjhala. MarkIt: Privacy markers for protecting visual secrets. In *ACM UbiComp UPSIDE Workshop*, 2014.

[52] F. Roesner, D. Molnar, A. Moshchuk, T. Kohno, and H. J. Wang. World-driven access control for continuous sensing. In *ACM CCS*, 2014.

[53] N. Santos, H. Raj, S. Saroiu, and A. Wolman. Using ARM TrustZone to build a trusted language runtime for mobile applications. In *ASPLOS*, 2014.

[54] K. Saur, M. Hicks, and J. S. Foster. C-Strider: Type-aware heap traversal for C, May 2014. University of Maryland Technical Report.

[55] R. Schlegel, K. Zhang, X. Zhou, M. Intwala, A. Kapadia, and X. Wang. Soundcomber: A stealthy and context-aware sound trojan for smartphones. In *NDSS*, 2011.
[56] S. Shin, G. Gu, N. Reddy, and C. Lee. A large-scale empirical study of Conficker. *IEEE TIFS*, 7(2):676–690, 2012.
[57] S. Smalley and R. Craig. Security enhanced Android: Bringing flexible MAC to Android. In *NDSS*, 2013.
[58] U. Steinberg and B. Kauer. NOVA: A microhypervisor-based secure virtualization architecture. In *ACM EuroSys*, 2010.
[59] A. Stevenson. Boot into recovery mode for rooted and un-rooted Android devices. http://androidflagship.com/605-enter-recovery-mode-rooted-un-rooted-android.
[60] H. Sun, K. Sun, Y. Wang, J. Jing, and S. Jajodia. TrustDump: Reliable memory acquisition on smartphones. In *ESORICS*, 2014.
[61] M. M. Swift, M. Annamalai, B. N. Bershad, and H. N. Levy. Recovering device drivers. *ACM TOCS*, 24(4), 2006.
[62] J. Sylve, A. Case, L. Marziale, and G. G. Richard. Acquisition and analysis of volatile memory from Android smartphones. *Digital Investigation*, 8(3-4), 2012.
[63] R. Templeman, M. Korayem, D. Crandall, and A. Kapadia. PlaceAvoider: Steering first-person cameras away from sensitive spaces. In *NDSS*, 2014.
[64] R. Templeman, Z. Rahman, D. Crandall, and A. Kapadia. PlaceRaider: Virtual theft in physical spaces with smartphones. In *NDSS*, 2013.
[65] X. Wang, K. Sun, Y. Wang, and J. Jing. DeepDroid: Dyanmically enforcing enterprise policy on Android device. In *NDSS*, 2015.

Last access date for URLs in references was July 20, 2015.