App Developer Centric Trusted Execution Environment

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Abstract—ARM TrustZone is the de-facto hardware TEE implementation on mobile devices like smartphones. As a vendor-centric TEE, TrustZone greatly overlooks the strong protection demands and requirements from the App developers. Several security solutions have been proposed to enable the TEE-assisted isolation in the Normal World of ARM, attempting to balance the security and usability. However, they are still not fully-featured in serving Apps’ needs. In this paper, we introduce LEAP, which is a lightweight App developer Centric TEE solution in the Normal World. LEAP offers the auto DevOps tool to help developers to prepare the codes running on it, enables isolated codes to execute in parallel and access peripheral (e.g., mobile GPUs) with ease, and dynamically manage system resources upon Apps’ requests. We implement the LEAP prototype on the off-the-shelf ARM platform without any hardware change. We perform the comprehensive analyses and experiments to demonstrate that LEAP is efficient in design, comprehensive in support, and convenient in adoption.

I. INTRODUCTION

The TrustZone technology was introduced in 2003 as the Trusted Execution Environment (TEE) design on the ARM architecture. It has been pervasively deployed on mobile devices and continuously upgraded with new features since then. Unfortunately, TrustZone, although providing stronger security guarantees than software-based security, is currently underutilized or even not popular among app developers due to the following reasons.

TrustZone is vendor-centric rather than developer-centric. Every code change in TrustZone must be approved ahead by vendors, and resources in TrustZone are extremely limited. Such inconvenient restriction significantly impedes the adoption of TrustZone in the App security. Moreover, adopting TrustZone requires substantial development efforts and TEE knowledge at the App side, especially for the existing Apps. Vulnerabilities could be otherwise created and lead to the TEE compromising [1]. Additionally, rapid App development has dramatically reshaped the mobile computing landscape since 2003. Emerging App security demands, e.g., the mobile GPU access during secure execution, are not recognized or supported through the evolution of TrustZone.

Research works have been recently carried out to build App-friendly security solutions on top of TrustZone (shown in Figure 1). These TEE-based solutions are carefully designed to isolate the execution of protected codes in the Normal World (NW) of ARM architecture, rather than in the Secure World (SW), to mitigate the resource problem. TrustICE [2] first attempts to move the APP ENV (containing protected codes) out of SW. It only allows one App ENV to run and meanwhile freezes the whole ROS, sacrificing the efficiency. PrivateZone [3] lifts the restriction of frozen ROS by introducing another layer of isolation in NW. OSP [4] further enables the parallel running of multiple APP ENVs. Unfortunately, this feature is achieved by introducing an extra TCB (Trusted Computing Base) hypervisor, which increases system overheads and security risks. Most recently, SANCTUARY [5] leverages the new TrustZone feature to get rid of the hypervisor need and keeps the ability of one-time APP ENV resource assignment like OSP. However, it does not support the parallel APP ENV. More details on related works are provided in Section II-C.

The NW-side TEE solutions above, although balancing the security and usability for TrustZone, are not fully developer-centric, according to the aforementioned problems TrustZone faces. First, their secure environments (APP ENVs) lacks comprehensive supports for the App code execution, specifically the parallel isolated environments, secured peripheral access, and dynamic resource management. Parallelism is an important strategy optimizing performance on the multicore system, which is widely used by smartphones; more and more codes that require protections contain operations of accessing peripherals, e.g., receiving a cloud-pushed patch inside the APP ENV or exclusively access the mobile GPU for deep learning; adapting resources upon online demands is necessary for parallel isolated environments to reduce resource wasting and meanwhile survive in bursty workloads. Second, the difficulty of solution adoption is not considered for developers of Apps, especially developers of existing Apps. Usually, it is required to manually modify App codes according to the targeted TEE-based solution and calculate the resource assignment beforehand. This inconvenience greatly de-motivates App developers to take any action on the solution adoption. Third, emerging developer demands are omitted. For example, many intelligent Apps have shown up, and they deploy their deep learning (DL) models, which are often intellectual properties, on devices to provide timely services. Existing NW-side TEE solutions cannot well protect executions of DL as there is no mobile GPU support inside the APP ENV.
Therefore, we propose LEAP, a developer-centric Trust-Zone solution securing critical operations of current and emerging Apps. LEAP is lightweight in design and addresses the deficiencies in existing NW-side TEE solutions on the ARM architecture. LEAP can balance the security strength and App usability for six developer-centric goals below:

**(S1) Secure Isolation.** The App sandbox (i.e., APP ENV in LEAP) must be isolated with hardware guarantee. TCB cannot be modified after deployment.

**(S2) Secure Peripherals.** The codes inside App sandbox can easily and securely access peripherals, such as the mobile GPU, NIC, and Bluetooth, without worrying about the snifing from ROS or codes in other App sandboxes.

**(S3) Secure Boot.** Each App sandbox can be properly measured for integrity and verified for genuineness before booting.

**(U1) Parallel Environment.** LEAP can enforce the isolation of multiple parallel-running App sandboxes.

**(U2) Flexible Resource.** LEAP can adjust the sandbox resources on demand in order to prevent resources from being wasted or underutilized.

**(U3) Easy Adoption.** The auto DevOps tool can be provided for App developers to conveniently adopt LEAP to protect critical executions in their Apps.

LEAP introduces four developer-centric designs. First, For an existing normal App, an DevOps tool App Adapter is introduced to automatically convert it into a LEAP-adapted App through static program analysis. After the conversion, the sensitive part of this App is extracted and executed in an isolated sandbox enforced by hardware. Second, multiple isolated sandboxes can run in parallel with performance almost as same as the bare-metal case, and each of the flights for the codes in it against threats with high privileges. LEAP's strongly-protected App execution is general enough to be deployable on the majority existing ARM devices. Third, unlike SW Apps, normal Apps often have various workloads at different time. LEAP’s resource management is able to ensure a peripheral already assigned to a sandbox cannot be accessed by any others all the time. Our exclusive peripheral feature has not been supported by previous work, and its granularity is finer than the TrustZone case, where there are only two groups/worlds.

Our LEAP might also have broader impacts and shed light on future TrustZone hardware evolution. First, LEAP may boot the development of emerging Apps that have security issues. For example, with LEAP protection, intelligent App developer do not have to worry about their locally-deployed large deep learning models. Moreover, LEAP achieves desired goals by utilizing a small set of existing ARM hardware features, which might indicate a minimalism design of TrustZone for the mobile scenario.

In summary, our work makes the following contributions:

1) We propose a lightweight NW-side TEE LEAP which can balance both security and usability specifically for mobile Apps. Compared to existing solutions, LEAP can support parallel isolated App execution environments featuring secure peripheral access and dynamic resource management.

2) We also close the gap for existing Apps and emerging Apps to easily enjoy LEAP's hardware-enforced protection. For existing Apps, we provide the auto DevOps tool to make an App LEAP-ready without source codes; for emerging Apps, we enable mobile GPU access and sharing inside isolated execution environments.

3) We implement the LEAP prototype on the off-the-shelf ARM platform without any hardware change. We perform comprehensive analyses and experiments to demonstrate that LEAP is efficient in design, comprehensive in support, and convenient in adoption.

II. BACKGROUND AND RELATED WORK

A. ARM TrustZone

ARM TrustZone [6] is a security extension of ARM processors. As shown in Figure 2, it divides the System-on-Chip (SoC) into two worlds, namely Normal World (NW) and Secure World (SW), to manage CPU, memory, and peripheral devices securely. A CPU can run in either NW or SW under the control of the *NS-bit* on AXI-Bus. Secure boot [7] is used...
to ensure the image integrity of the system during the boot procedure. By configuring TrustZone Peripheral Controller (TZPC) [8], we can isolate the peripheral, that is, preventing the device from being accessed from NW. Since ARMv8.4, the TrustZone architecture has evolved with the introduction of virtualization extensions, i.e., SEL2, in SW. With SEL2, SW can support multiple Trusted OS in parallel. The virtualization extension can solve TEE fragmentation to a certain extent. This mechanism allows a high-security Trust App to run in a standalone Trusted OS that is isolated not only from the NW but also from other software in SW.

B. Stage-2 Address Translation

In ARMv8 architecture, the CPU can execute in four different exception levels (EL0-EL3). Both worlds have the user space (EL0), the kernel space (EL1), and the virtualization extension (EL2). EL3 (monitor mode) is used to respond to world switching. Please note that there is typically no hypervisor running in EL2 on mobile devices due to performance overhead. So EL2 is usually disabled during the booting procedure [7].

There are two address translation stages when the virtualization extension is enabled. In the first stage, VM translates the virtual address (VA) to an intermediate physical address (IPA) based on its page table. The second stage is called stage-2 translation, in which the IPA will be translated to the physical address (PA). The base address of stage-2 page tables is stored in the VTTBR_EL2 register, which can only be accessed in EL2 or a higher exception level. The hypervisor controls VMs accessing PA through managing stage-2 page tables. What’s more, the second stage can not be bypassed even if the MMU is turned off by the VM. ARM offers SMMU [9] to translate IPA to PA for the devices, which have the Direct Memory Access (DMA) capability. The hypervisor can manage the page tables for SMMU and control the memory access space to prevent the DMA attack.

C. Previous Solutions

NW-Side TEE Solutions. The First kind of works devotes itself to create TrustZone-assisted isolation in NW to improve the TrustZone’s usability. Figure 1 illustrates some representative works of this type, i.e., TrustICE [2], PrivateZone [3], OSP [4], and SANCTUARY [5]. We will compare these works with our LEAP one by one. TrustICE designs an isolated computing environment in NW without using a hypervisor. However, when the isolation environment is running, ROS and other isolation environments will be frozen. In addition, TrustICE sandbox cannot adjust its resources on-demand flexibly. PrivateZone proposes an isolation environment in NW and enables security-critical code to run in the isolated environment instead of running in SW. PrivateZone can only maintain one isolation environment, so codes from different developers run in one sandbox. The lack of isolation among different developers’ codes can cause security concerns. In addition, PrivateZone also cannot flexibly adjust resources to balance the workload, nor can it guarantee the peripheral access’s security. OSP enables virtualization in NW to provide SGX-like enclaves. This work uses hypervisor to support the enclave’s isolation, and the hypervisor will bring overhead when the sensitive code is running [4]. In addition, OSP cannot support flexible resource adjustment and secure peripheral access. SANCTUARY aims to provide a NW isolation environment through TZASC [10], a hardware mechanism of TrustZone used to control memory access permission. Compared with LEAP, SANCTUARY does not support secure peripheral access, flexible resource, and parallel isolation. There is another work vTZ [11], which provides a TrustZone-enhanced virtual machine (VM) design for cloud computing scenario. The goal of vTZ is to provide each VM with a virtual TrustZone, which has several differences from the developer-centric design of LEAP. First, it cannot provide an isolated execution environment for Apps from different developers. Second, it enables secure peripheral access between the VM and its bounded virtual TrustZone; however, for different VMs using the same peripheral, it allows the hypervisor to share the device. Third, it does not provide flexible resource management for Apps, and there must be a hypervisor running in EL2 to manage VMs, which will bring non-negligible performance overhead to mobile devices [12]. Our LEAP can work without a hypervisor and is therefore more suitable for mobile scenarios.

SW-Side TEE Solutions. The second kind of works tries to improve the SW’s usability and security. Work [13] slices the security-critical part of an App’s through annotating the sensitive data in source code and ports the sliced part into SW. TrustShadow [14] explores how to run legacy Apps in SW. It introduces a runtime to help legacy App run in SW without any modification. secTEE [15] proposes an Enclave-like design in SW to isolate the security-critical services from other SW softwares. TEEv [16] and PrOS [17] introduce the virtualization technology to the SW through the software-based isolation. However, these works import the third-party
executable code into SW and enlarge the TCB. A larger TCB is inherently more vulnerable to compromise, and the code imported by a third-party developer may exacerbate the security issues. Our LEAP has a tamper-resistant TCB. After development, no executable code will be added to the SW.

III. LEAP DESIGN OVERVIEW

In this section, we first introduce all system components of LEAP, including their roles and functions. We then illustrate how these components interact with each other, a.k.a. the LEAP workflow, throughout the life-cycle of a LEAP sandbox. In the end, we briefly highlight the key designs, which are elaborated with more details in the following section.

A. Security Model

Before diving into LEAP design, we first explain our security model. We consider the scenario of protecting the execution of sensitive App codes on the ARM platform with hardware security enforcement. Sensitive codes (i.e., security-critical codes) have various activities, such as accessing peripherals and adjusting resources, and contain valuable App assets like closed-source deep learning models.

We assume the Rich OS in NW (ROS) could be malicious or compromised by the adversary. The goal of the adversary is to compromise the execution integrity or access the App assets under protection. We assume the driver used by developer for peripheral access is benign and bug free. We also assume some sensitive codes requiring our protection are curious about the execution of other sensitive codes. For example, they may try finding out what sensing data others collect.

We only trust the low-level features of the ARM architecture, including the secure boot, TrustZone, and stage-2 translation. Similar to previous works [11], we do not consider physical attacks like the cold boot [18] and the bus monitoring attacks [19], [20]. Deny-of-Service (DoS) attack, and cache side channel attacks [21]–[24] in this work.

B. System Components

Figure 3 illustrates the high-level design of LEAP. LEAP consists of four components, i.e., LEAPROS, LEAPSOS, LEAPSW, and LEAPATF. They are software-based and leverages existed ARM hardware features so that LEAP can be easily deployed on existed mobile devices. ROS is the legacy OS running in the NW, e.g., the Android. An App adapting LEAP is called pAPP, and its sensitive codes under LEAP protection is called sc-pAPP. The LEAP sandbox is a sensitive-code execution environment protecting the sc-pAPP and LEAPSOS running inside it. The sc-pAPP is allowed to exclusively access peripherals when needed. Multiple LEAP sandboxes can run in parallel beside ROS with minimal performance influence. LEAPROS is a ROS kernel module. It loads images, i.e., sc-pAPP and LEAPSOS, maintains metadata, and pre-allot resources for LEAP sandbox. A pAPP can create and interact with its LEAP sandbox via LEAPROS. Before LEAP sandbox switching peripherals or adjusting resources, LEAPROS prepares the hardware configuration information required by LEAPSW.

LEAPSOS is a tiny kernel we tailored from Linux. It is used to provide a minimal runtime inside the LEAP sandbox for a sc-pAPP, named sandbox OS (SOS). LEAPSW interacts with LEAPROS on behalf of sc-pAPP for resource management. LEAPSW also leverages the rich Linux driver ecosystem to serve various peripheral access needs from sc-pAPP.

LEAPSW is a kernel module in TOS installed by the device vendor. Note it is a part of TCB and tamper-resist. LEAPSW is responsible for key storage and checking the integrity of the LEAP sandbox image before launching it. LEAPATF is a patch to the vanilla ARM Trusted Firmware. It also belongs to our tamper-resist TCB. LEAPATF enforces LEAP sandbox isolation and exclusive peripheral access, manages resources that pre-allocated by LEAPROS, and launches LEAP sandbox.

Except for system components, LEAP also provides an automatic DevOps tool for App developers. This tool, which is called App Adapter, can make the App adaption of LEAP transparent to its developer, which require no source code access and extra development efforts. More details are in Section IV-A.

C. System Workflow

This part introduces the workflow of LEAP throughout the life-cycle of a sandbox. We describe how to create, initialize, and terminate a LEAP sandbox LEAPSOS, and how the LEAPSOS accesses peripherals exclusively and adjusts resources.

Creation. A LEAP-adapted App can be created directly from scratch by a developer or converted from an existed App with the assistance of our DevOps tool. In the converting case, our tool first transforms the App into two parts, the NW part pAPP, and the security-critical part sc-pAPP, with a clean and neat interface between them. Next, it packs the sc-pAPP and LEAPSOS OS together as an encrypted image and signs it on behalf of the developer. When installing the LEAP-adapted App, this signature is securely stored by LEAPSW for verification purpose in the initialization stage.

Initialization. The LEAPSOS initialization is triggered when the pAPP calls its sc-pAPP counterpart. Once LEAPROS takes upon the pAPP’s request, it pre-allot resources, such as CPU cores and memory, for this LEAPSOS. Next, LEAPROS...
loads the encrypted packed image, which is prepared in the creation stage, into the allocated memory and notifies LEAP ATTF to lock the resources. Then, LEAP ATTF asks LEAP SW to verify the integrity. If the verification is passed, LEAP SW will decrypt it as well. LEAP ATTF then securely launches its sc-pAPP will respond to pAPP’s request after booting. Attestation can also be performed during runtime in a similar way like previous works [3], [15].

**Peripheral Access.** ROS holds all peripheral resources by default. When a sc-pAPP is willing to access one peripheral, LEAP SOS makes a request to LEAP ROS. LEAP ROS checks the status of modules loaded in the kernel, if the peripheral is available, LEAP ROS informs LEAP ATTF to unmap it from ROS and map it to the corresponding LEAP SOS via the stage-2 page table. Next, LEAP SO loads the device driver, and the sc-pAPP in it can then use the peripheral. Note that this peripheral cannot be accessed by other LEAP SOS and ROS until it is released from currently-engaged LEAP SOS.

**Resource Adjustment.** LEAP SOS is able to request and release resources, e.g., CPU cores and memory, on demand for the sake of efficiency and elasticity. When LEAP SOS requests more resources, LEAP ROS will prepare the resources and notify LEAP ATTF to check whether these resources are secure to be used. Upon the check passes, LEAP ATTF will assign these resources to requested LEAP SOS and enforce the resource isolation. When releasing resources, LEAP SOS notifies LEAP ATTF to securely return resources to ROS.

**Termination.** When sc-pAPP completes its tasks, its LEAP SOS informs LEAP ROS of its termination and asks LEAP ATTF to shutdown it. LEAP ROS then asks LEAP ATTF to release all resources of the terminated LEAP SOS. Released resources are in the end returned back to ROS.

### D. Developer-Centric Designs

In this part, we present at a high level several key designs applied in LEAP and principles behind them. These designs are driven by the App developer’s needs. Additionally, they practice the minimalism design principle and could be an alternative to the current TrustZone hardware evolution, which is more and more complicated.

**Automatic App Adapter.** The tedious DevOps experience is one of the key reasons why TrustZone and TEE-based solutions are not popular among App developers. Furthermore, many developers may not be familiar with the system programming. Thus, we introduce an auto DevOps tool to transform an App, even without source codes, into a LEAP-ready App. Technical details are explained in the next section.

**Isolated Parallel Execution.** Unlike the vendor-centric workload, it is necessary to enable the multiple App sandboxes running in parallel. At the same time, we want to keep the codes in SW, which is part of our TCB, minimal and fixed without change. Therefore, the attack surface can be reduced. Additionally, we rely on the hardware security features to fight against high-privileged threats. Thus, the attack surface is reduced. Technical details are explained in the next section.

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**IV. APP DEVELOPER CENTRIC DESIGNS**

The App developer-centric design realized by LEAP primarily has four techniques, the automatic App adapter used offline for the App preparation, the isolated parallel execution used online after the App installation, the exclusive peripheral management used for secure I/O and flexible resources adjustment used for resource allocation during runtime. Our isolated parallel execution is achieved by only leveraging a small set of existed ARM hardware features - the stage-2 translation, ARM monitor mode, and SEL1 (EL1 in SW) - so that this design can be easily applicable to existed ARM devices, building a foundation of evolving TrustZone toward a developer-centric TEE.

#### A. Automatic App Adapter

This App adapter is designed to minimize the development efforts when applying the LEAP protection on an existed App. The automation it offers greatly eliminates the adaption cost concern of non-expert developers. It is intended to demonstrate why the DevOps should be considered in the developer-centric TEE, so it does not cover all DevOps demands. We plan to make it more complete in the future.

Figure 4 illustrates the processing pipeline of the App adapter. To converting an App, its developer only has to prepare a configuration file pointing out the entry points of the sensitive codes. For example, if a developer wants to protect...
the valuable deep learning model with corresponding inference code in her App, she just lists the APIs triggering the inference task in the configuration file for our App adapter. In such file, entry points are listed by line in the format of `<the class of the function definition: the function prototype>`. Then our App adapter primarily performs two tasks. The first task is to extract the indicated sensitive code, i.e., sc-pAPP, out from the targeted regular App, while the second task is to repack sc-pAPP for running in the LEAP sandbox.

More concretely, the AppSli module performs calls graph analysis and data flow analysis on the App and extracts the security-critical part, i.e., all code called by entry points. LibGen generates a dynamic linking library responsible for the communication between the normal part and the security-critical part according to entry points in the configuration file and the sliced codes. Next, the generated library and the App’s normal part are repacked as a pAPP to run on ROS. Therefore, all runtime communications between the normal and the security-critical parts will be forwarded through the generated dynamic linking library. As to the security-critical part, the App adapter compiles it into an executable java program, packs the Java program with a LEAP_pSOS, and encrypts it to produce an LEAP sandbox image. The encrypted image will be signed for the integrity verification during secure boot. The signature and the decryption key of the encrypted image will be stored in LEAP_SW as the whole App is installed onto the user device. The encrypted image will be stored on the disk. We provide more technical details about AppSli and LibGen as follows.

1) AppSli Module: . The AppSli module is built upon the Java optimization framework, Soot [25]. Soot is suited for performing various static analyses and instruments on Android Apps. We first decompile the App and locate all targeted entry points. We then build call graphs of the App and traverse all reachable codes from these entry points. We also perform the backward data-flow analysis to maintain the dependency of traversed codes. For example, if a developer-defined object type is used in the traversed code, we need to maintain a copy of the class definition in the traversed code. By iteratively performing backward data-flow analyses, all security-critical code can be found and ready for repackaging.

2) LibGen Module: . The LibGen module is used to produce a dynamic linking library, i.e., a communication proxy, which is integrated with the normal part of an App and connects with the corresponding security-critical part. In this library, one component is the code to create and initialize the LEAP sandbox. The sandbox creation functions first notify the LEAP_pROS to prepare one CPU-core and default 256M memory to launch the sandbox. Then LEAP_SW verifies the integrity of the prepared image containing the sc-pAPP before booting. The other component is to generate all new entry points for passing parameters between the pAPP and sc-pAPP, with the rely on LEAP_pROS. We present an example in Figure 4. For the entry point `<org.tensorflow.lite.Interpreter: public void run(Bytebuffer input, byte[] output)>` provided by the developer, LibGen generates a function `<public static native byte[] nativeRun(ByteBuffer input)>`. This generated function can pass the input data to sc-pAPP through the APIs provided by LEAP_pROS. When packing the pAPP, all calls to entry points of the original APP will be replaced with calls to generated ones.

B. Isolated Parallel Execution

It is not intuitive to design an isolated parallel environment, especially given efficiency and security. Figure 5 illustrates some current works who can (or can be extended to) support parallel isolation, but they have deficiencies in terms of efficiency and security. A virtualization-based design in NW requires a hypervisor that brings system overhead to the mobile device when sc-App is running [4], [11]. SANCTUARY [5] is a TZASC-based solution. It utilizes the hardware features of the latest TZASC, e.g., TZC-400 [26], to ensure the CPU and memory isolation. However, SANCTUARY cannot run sandboxes in parallel. Even if we improve SANCTUARY, the parallelism of this solution is also limited by the hardware. Because TZC-400 can only reserve a limited number of memory regions. Note that there are a number of differences between LEAP and these current works. We only discuss the differences in terms of parallel isolation here. The comprehensive comparison is presented in Section II-C.

Figure 5 shows the LEAP’s design of parallel isolated execution. LEAP provides a stage-2 page table based isolation for sandboxes. Each sandbox has exclusive resources, e.g., CPU cores and memory regions, which shares a similar idea with NoHype [27]. The exclusive resources can only be accessed by the software in the corresponding sandbox. Next, we will show how we design parallel isolation in terms of the differences between LEAP and existing works.

1) Low overhead.: LEAP applies the stage-2 translation to ensure the isolation. However, unlike the virtualization-based solutions, we do not introduce a hypervisor to virtualize any resources, i.e., CPU or memory. Enabling the virtualization may incur non-negligible performance overhead [12], which is prohibitive for the resources-limited mobile devices. LEAP enables and manages the stage-2 page table by LEAP_ATF in EL3, which is a patch of ATF shown in Figure 3. To enable the stage-2 translation without hypervisor, the LEAP_ATF lets the CPU go back to EL1 when it returns from EL3, instead of letting the CPU go back to EL1 via EL2. Before booting ROS, LEAP_ATF reserves a memory region to store the stage-2 page tables. And this region is reserved from ROS and sandbox OS. LEAP_ATF controls ROS, and any sandbox can only access its own resources through masking the corresponding stage-2 page table entries. Moreover, all resources and peripheral access are also controlled by these page tables, which will be introduced in Section IV-C.

2) Tamper-resisted TCB.: The SW-based virtualization solutions like TEEv need to install software to SW. The installation will increase TCB size, which inherently brings security risks, not to mention that the installed codes come from third parties. LEAP has a tamper-resisted TCB. That is LEAP does not need to load any executable code into
than the SW-based virtualization works. The small and tamper-resisted TCB makes our design safer constrained in LEAP sandbox through hardware-enhancement. All services provided by developers will be
verification for the image. Only when the verification passes, LEAP will start a sandbox once pAPP requests sc-pAPP’s services. The signature of the runtime code and sc-pAPP. The signature of the runtime image is produced in the
management into LEAP and put the services for secure boot into the LEAPSW, i.e., key storage, encryption/decryption, and hashing. All services provided by developers will be constrained in LEAP sandbox through hardware-enhancement. The small and tamper-resisted TCB makes our design safer than the SW-based virtualization works.

3) Enhanced Security.: Besides the tamper-resistant TCB, we further enhance the system security by proposing a cache protection mechanism. NW-based memory isolation solutions are vulnerable to the cache direct attack. For example, if an attacker accesses the memory region which is prepared for one sandbox, the memory content will be cached in the cache line. As L2 cache is usually shared by one cluster, the attacker can directly read the memory content from the cache line. SANCTUARY defends this attack by seeking for a hardware change, which is not available for current hardware, or simply disabling the L2 cache, which decreases system performance. LEAP solves this through proposing a cache sanitization technique. Since the cache is usually physically indexed on ARMv8 [28], LEAP prevents the attacker from successfully translate the virtual address to the physical address, which can be managed by unmapping stage-2 page table entries. However, the stage-2 translation entries may be cached in TLB. Therefore, before booting a sandbox or adjusting a memory region to LEAP sandbox, LEAPclears these TLB entries that map to the new prepared memory space, which has almost no impact on system performance in practical use.

4) Secure Boot.: We design an integrity verification mechanism to ensure the secure boot of LEAP sandboxes (S3). LEAP will start a sandbox once pAPP requests sc-pAPP’s services. Before launching the sandbox, LEAP will verify the integrity of the encrypted runtime image, which contains LEAPSOS code and sc-pAPP. The signature of the runtime image is produced in the creation stage and securely stored by LEAPSW. LEAPSW is responsible for performing the integrity verification for the image. Only when the verification passes, the LEAPATF will boot the LEAP sandbox.

C. Exclusive Peripheral Management

1) Design Challenges: It is non-trivial to design a peripheral management mechanism when considering IO security and usability, e.g., develop effort and efficiency. We show design challenges by proposing two straw-man solutions (Figure 6) and explain why they fail to meet the peripheral management requirements.

Straw-man Solution 1. The first possible design is to redirect all peripheral IO to the Secure World and leverage the hardware-assisted Secure IO. As shown in Figure 6a, all devices are mapped into the Secure World, and all device management modules, e.g., device drivers, are installed into the Trusted OS. This seemingly simple solution has two serious design flaws.

Usability. All peripheral drivers needed by App developers should be installed into Secure World in this design. It is at least a hard task, if not an impossible task. Porting or implementing a driver for special Trusted OSs like OP-TEE [29] is difficult and time-consuming even if the corresponding driver for ROSs like Android is open-source. In reality, peripheral drivers are often very complicated and closed-source, rendering the Secure-World driver porting or developing impossible. Additionally, the system programming effort for arbitrary IO redirecting is heavy as well, given there are so many types of peripheral driver implementations. Therefore, this possible design puts too much burden on the shoulder of application developers. Security. Another important reason is that adding such drivers to the TOS will enlarge the TCB.

Straw-man Solution 2. The second possible design is to introduce a driver monitor module, shown in Figure 6b, to ensure there is only one Normal-World driver enabled for a device at a time. When a driver wants to use a device, it should make a request to the driver monitor. After being allowed, it will be enabled and access the requested devices. The driver monitor keeps scanning the normal world to detect if any driver works illicitly.

This design also has two problems. Usability. It is very costly to scan the kernel memory to detect if any driver works. As reported in DeepMem [30], recognizing a kernel object takes about 13 seconds even in a PC environment,
whose computation ability is more powerful than the mobile devices. The overhead of such a design is not acceptable. Security. The Normal World OS, e.g., ROS and LEAPSOS might access the peripheral through directly reading/writing a specific IO address without using driver. That is, any device access without drivers will bypass the driver monitor and fail this method.

2) Our Design: Our design follows three principles. (1) Developers should be able to directly reuse all off-the-shelf drivers of the Linux ecosystem in LEAP sandbox, as in the Normal World. That is, sc-pAPP can access any peripheral from the sandbox. (2) The peripheral access should be lightweight and efficient. The overhead of peripheral access from the sandbox should not be greater than that from ROS. (3) Only one Normal-World execution, i.e., ROS or a sandbox can access a peripheral at a time. If one device can be accessed from different executions at the same time, the IO security will be compromised.

Figure 6c illustrates our peripheral management mechanism. Our design abides all above three principles through manipulating the stage-2 tables. The stage-2 page tables are normally used to enforce memory isolation. However, the key observation of our design is that ARM adopts Memory Mapped IO (MMIO), which provides us with the opportunity to control IO access through managing stage-2 page tables. Recall there may be multiple sandboxes and ROS parallelly run in LEAP on different cores, LEAPATF sets different stage-2 page tables for each of them. When in use, the LEAP sandbox can request LEAPATF to use some device. LEAPATF will assign the device to the requester by modifying its stage-2 page tables on the fly. If the requested peripheral has been occupied by execution, the requester has to wait until the device is available before it can gain access permission to it. When a sandbox uses a device, all other sandboxes’ and ROS’s page table entries of this device will be marked as invalid to ensure exclusive access.

The stage-2 page tables to control the peripheral access are stored in a block of physical memory reserved by LEAPATF. This memory region is never mapped to ROS or LEAPSOS to prevent them from accessing it. The stage-2 page table takes 2MB and 4KB mapping for memory space and IO space respectively. The page tables of each execution only use less than a 2MB memory region to address and use peripherals. In our prototype system, there are 8 CPU cores. So the reserved memory region is only 16M, which can support ROS and at most 7 sandboxes to run in parallel.

D. Flexible Resources Adjustment

Dynamic CPU cores and memory adjustment can effectively balance the system workload and improve the system resources’ utilization. We detail the resources management in two parts, i.e., the dynamic memory adjustment and CPU cores adjustment.

1) Dynamic Memory Allocation: LEAP proposes two mechanisms, i.e., zero consumption policy and memory pool sharing, to allocate LEAP memory. The zero consumption policy is responsible for the preparation and adjustment of LEAPSOS memory on the fly. The memory pool sharing is used to manage the share memory between ROS and LEAP sandboxes. ROS communicates with LEAP sandbox through the share memory. Figure 7 illustrates these memory management schemes.

When booting a new sandbox, ROS will pre-allocate a memory region with the default size. Then the LEAPATF will sanitize the pre-allocated memory, assign the memory to the corresponding sandbox. When the LEAP sandbox needs to increase/decrease its memory size, the LEAPATF will perform the adjustment following the zero consumption policy. The zero consumption policy ensures that the sandbox’s memory
region is always physically continuous, no matter how many adjustments are performed. Ensuring the physical continuity of the memory region can reduce system maintenance costs and the complexity of TCB. A trivial method to ensure continuous memory is to reserve a large block of memory for the sandbox. But the reserved memory cannot be used by ROS, which wastes system resources when there is no sandbox running. We apply the Linux Contiguous Memory Allocator [31] (CMA) technology to manage the memory for LEAP sandbox. It can allocate the memory sections physically adjacent to the sandbox, which is used by ROS by default, into the sandbox.

The memory pool sharing maintains all communication channels, which is implemented through share memory, between ROS and LEAP sandboxes located in the same continuous memory region. LEAPROS continuously allocates a new share memory region from this pool when booting a new LEAP sandbox. Each sandbox has an exclusive communication channel. To prevent the LEAP sandbox from accessing others’ communication channels, LEAPATF will not map others’ communication channels to this sandbox with the access control guaranteed by the stage-2 page table.

2) Dynamic CPU Allocation: A LEAP sandbox is assigned with a CPU core by default at startup. However, LEAP sandbox is allowed to request more cores from ROS on-demand during running. This dynamic CPU allocation design can achieve a good system workload balance. When adjusting the CPU cores, the sc-pAPP can request a big core or little core according to its need to optimize the overall execution and energy consumption.

The adjustment procedure is as follows. The sc-pAPP issues a request to adjust its CPU core. LEAPROS checks whether there is an available core. If any core is available, LEAPROS notifies LEAPATF to remove the core from ROS through Linux CPU hot-plug [32] technology. LEAPATF clears the core’s cache to prevent data leakage and securely shutdown the core. In the end, LEAPSOS requests LEAPATF for the core and LEAPATF initialize the core with the correct context and boots the core for LEAPSOS.

The sc-LEAP can give up the surplus cores occupied by it through a similar procedure. Also, ROS can request LEAPSOS for core adjustment. If LEAPSOS finds there is free core, it can return the core back to ROS. LEAPSOS always holds at least one core so that sc-LEAP can execute, and LEAPATF ensures data security when switching cores between ROS and sandbox.

V. Security Analysis

In this section, we discuss how LEAP defends against possible attacks under our security model (See Section III-A). Since LEAP provides hardware-assisted isolation for applications, the malicious application codes, no matter they are in the ROS user space or in a LEAP sandbox, cannot access data or compromise executions in another LEAP sandbox. Therefore, our security analysis mainly focuses on a compromised ROS.

Malicious LEAPROS Manipulation. A compromised ROS can manipulate the LEAPROS installed by LEAP. The LEAPROS is responsible for preparing the sandbox image and pre-allocating the resources. So malicious manipulations lie in the sandbox creation and resources management. When creating a new sandbox, the compromised LEAPROS may prepare malicious LEAPSOS and sc-pAPP images to compromise secure services. LEAP copes with this attack with a Secure Boot mechanism (See Section III), which can ensure the LEAP sandbox images’ integrity before launching the image. The malicious ROS can also misconfigure resources at resources adjustment. To be specific, when a sandbox increases its memory, ROS can maliciously prepare a memory region for the requester that has already been used by another sandbox. LEAP solves this kind of attack by checking the configurations’ legitimacy through LEAPATF (See Section IV-D). Similarly, LEAPATF also ensures that a compromised ROS cannot allocate a CPU core that has already been used by a sandbox to another one through verification when creating sandboxes or adjusting CPU cores.

Peripheral IO Eavesdropping. The compromised ROS cannot successfully access the IO addresses of a peripheral occupied by a LEAP sandbox. It is because these addresses are blocked in the stage-2 address translation, which is controlled by the LEAPATF. At the same time, the IO address translation for this device is also blocked for other LEAP sandboxes. Thus, one LEAP sandbox cannot successfully perform IO Eavesdropping to other sandboxes, either. As to some devices capable of DMA, LEAP, except using the same method to block peripheral DMA, replies on the ARM’s SMMU [9] to prevent the bypassing of the main memory access. Thus, a compromised ROS cannot eavesdrop on the data in a peripheral occupied by a LEAP sandbox.

Cache Direct Attack. A compromised ROS may access the memory region to be allocated to the sandbox to cache it in L2 cache. After the memory adjustment, the compromised ROS tries to access the sandbox’s memory space through L2 cache. LEAP proposes a cache sanitization technique (See Section IV-B) to defend this kind of attack by clearing the CPU cores’ TLB entries related to the newly-allocated memory. For different LEAP sandboxes, the memory space that belongs to one sandbox is never mapped to other sandboxes. So one sandbox cannot directly access the address space of another sandbox, nor can it read the memory space of another sandbox through the cache, because it can never successfully translate the address space belongs to others to a valid physical address which is required by L2 cache indexing.

VI. Evaluation

In this section, we describe the experimental setup, followed by a comprehensive evaluation of LEAP by answering the following three questions:

1) How much performance improvement will be brought by the parallel isolation design?
2) How does the flexible resources design help the sandbox to balance the workload?
3) How does our exclusive peripheral design perform when accessing peripherals?
Last, the case study of a real-world GPU-accelerated machine learning application demonstrates how easily and efficiently an application can run in LEAP.

A. Experimental Setup

Hardware. We implemented a prototype of LEAP on Hikey960, which is a widely-used development board with the same SoC as many COTS smartphones such as Huawei P10. The board equips with eight cores (4 Cortex-A53 + 4 Cortex-A73) with big.LITTLE architecture, a 4GB physical memory of which 3.5 to 4GB address space is used for peripheral I/O address space, a Mali-G71 GPU, a Bluetooth 4.1, and a WiFi module.

Software. Android 9.0.0_r31 (kernel version 4.14) and a popular open-source Trusted OS OP-TEE (v3.4.0) [29] were chosen as the LEAP’s ROS and TOS, respectively. We used the standard ARM Trusted Firmware patched with LEAP ATF in EL3. The whole LEAP system has 4,689 lines of code (LOC), including LEAP_ATF (539 LOC), LEAP_SW (651 LOC), LEAP_ROS (1,327 LOC), LEAP_SOS (972 LOC), and DevOps (1,200). LEAP_SOS, the LEAP sandbox’s OS, utilized a customized Linux kernel (v3.13) whose size is only about 12MB. In order to further reduce the booting time of LEAP_SOS, we put extra engineering effort. First, the initialization code of GIC was removed since there is no need for a sandbox to initialize GIC, which has already been done by the ROS. Second, the code of setting system clocks was removed to prevent the sandbox from resetting the system clocks when switching devices. Last, the in-memory file system ramfs was used in LEAP_SOS. The sandbox’s file operations are assisted by LEAP_ROS.

Methodology. We compared our LEAP to a basic TrustZone-based TEE and a SANCTUARY [5] prototype. Because the former is a native implementation on existing devices, and the latter is the current state-of-the-art work. The software environment, i.e., ROS, TOS, and ATF, of the three prototypes are exactly the same. Since SANCTUARY is not open-sourced, we reproduced it following the paper [5] with one modification for a fair comparison. SANCTUARY uses a micro-kernel OS in its sandbox, while the reproduced SANCTUARY prototype uses the same sandbox OS as our LEAP. Note that this modification will not hurt its design idea. All three prototypes used the same hardware settings. Since Android automatically adjusts the CPU frequency according to the system workload and CPU temperature, which makes the CPU performance varies. We set the CPU frequency to a fixed maximum frequency, and we let the CPU cool down between every experiment.

B. Parallel Execution Performance

We implemented a decryption App based on the mbedtls [33] to measure the performance of the parallel execution of LEAP sandboxes. The App takes an encrypted data stream as input and decrypts the data securely using its secret key. The encryption spec was set to AES-256-CBC with a 64KB block size. We measured the total time cost when the decryption App was requested by 3 other Apps for data decryption. In TrustZone and SANCTUARY, there is no parallel environment, so the decryption has to be performed in turn without parallel. In LEAP, we instanced one, two, and three sandboxes respectively to test such an operation.

The aforementioned experiment was performed with different data size, and the results are shown in Figure 8. Due to the parallel design, LEAP performs better than TrustZone from 7.52 × to 7.54 × and better than SANCTUARY from 2.95 × to 3.71 × when there are 3 sandbox instances (LEAP-3Ins.). Also, LEAP-3Ins. performs about 1.72 × to 2.24 × better than LEAP-2Ins. When only one sandbox is instanced, i.e., LEAP-1Ins, it gets a similar performance with SANCTUARY since the tasks are also executed in turn. This indicates that our stage-2 translation based isolation incurs negligible overhead.

We also notice that TrustZone performs much worse than LEAP and SANCTUARY as the file size increases. This is mainly because OP-TEE does not have its own scheduler, and it is scheduled by ROS instead, leading to the result that the longer time one TA runs, the more CPU context switches are performed between two worlds.

C. Flexible Resources Performance

To demonstrate the benefits of flexible resources, we implemented the following two Apps and evaluated their performance with different workloads. The results conclude that
Data signing App. We implemented a data signing App, which accepts a 4KB data stream and performs the SHA-256 digest algorithm for the data, and finally signs the digest with an RSA-2048 private key. The data signing App runs two threads that share a ring queue to handle requests. One thread is responsible for enqueuing the requests, the other thread is responsible for processing the requests in the queue, and it dequeues a request when one signing task is completed.

We deployed data signing App to three prototypes. In TrustZone, because OP-TEE does not provide multi-threading to TA, we had to implement the request queue in NW. In LEAP, we added one modification, that is, when the queue length exceeds 5, the processing thread will request to temporarily increase the CPU core to help process the request and returns the CPU core back to ROS when the queue length is 0. This modification is beneficial from the LEAP flexible resource adjustment design.

We evaluated the processing efficiency of the data signing App in two ways. First, we set the request frequency to 8 requests/s and observed the queue length at every second. Second, we changed the request frequency, ranging from 6 requests/s to 10 requests/s, and observed the queue length at the fifth second for each frequency.

The experimental results are shown in Figure 9 and Figure 10. It is seen that LEAP always has a good performance under different workloads. In figure 9, when the request frequency is set to 8 requests/s, the processing speed of TrustZone and SANCTUARY cannot meet the request speed, so the queue length grows every second. For LEAP, the queue length also increases in the first two seconds, but the queue length starts to decrease from the third second. This is because it dynamically requests one CPU core from ROS to help process the request. In Figure 10, when the request frequency is low (6 requests/s), each new request can be processed in time by SANCTUARY and LEAP, so the queue length is 0 at the fifth second. However, TrustZone cannot fully catch up with the request speed and the queue length is 8. This is also because of the context switch overhead. As the request frequency increasing, the processing speed of SANCTUARY also begins to fail to keep up with the request speed, and the length of both TrustZone and SANCTUARY increases quickly. However, LEAP always keeps a low and stable queue length even in the face of high request frequency. The result indicates that LEAP enables sc-pAPP to adjust its computing resources in time under different workloads.

Encrypted data query App. The second security App we tested is a ciphertext query App that accepts the key provided by a user as a query keyword, performs the query in the encrypted file with key-value data, and returns the results to the user. To speed up the query procedure, the query App caches the decrypted data in the memory. Only when the key is not found in the memory, it loads the encrypted file from the disk and caches it in the memory. The encryption method we chose is the same as the secure storage encryption method provided by OP-TEE, which uses AES-128-CBC to encrypt files, and the size of each encrypted block is 256 bytes.

We generated 10 encrypted files contains different key-value pairs with different sizes, ranging from 10MB to 100MB, and we also randomly generate 10 query sequences for each file. We measured the time to complete 10 queries for each file and record the total time cost to complete all queries for 10 files. In OP-TEE, the query App was based on its secure storage TA, and we used 10MB memory size as the file cache space, as the total available memory space for TAs does not exceed 16 MB. In both SANCTUARY and LEAP, we set memory size to 10MB. However, the query App on LEAP can dynamically adjust its memory size, which is set at a 16MB granularity to handle files with different sizes.

It took about 19.24 seconds to finish all queries for LEAP and the time for TrustZone and SANCTUARY was 686.24 seconds and 61.64 seconds respectively. LEAP performs about 35.67 and 3.20 faster than TrustZone and SANCTUARY respectively. TrustZone is much slower because it relies on the ROS driver to load files, which incurs frequent context switches when loading large files. LEAP is faster than SANCTUARY since the query App can dynamically change its memory size when handling files with different sizes.

Although it is possible to make SANCTUARY allocate a large memory size in advance to improve efficiency, however, this will greatly waste resources because most of these memory are not used most of the time. We measured the

TABLE 1: The execution time and resource utilization rate with different memory allocation strategies. The resource utilization rate is calculated based on the actual used resources accounted for the allocated resources during the query App execution.

| Memory Size (MB) | Time(s) | Resource utilization |
|------------------|---------|----------------------|
| 30               | 35.50   | 98.98%               |
| 50               | 34.43   | 96.37%               |
| 60               | 27.76   | 93.43%               |
| 80               | 22.58   | 85.52%               |
| 100              | 17.63   | 70.39%               |

Fig. 10: Data signing App performance with different request frequency. The request queue length at the fifth second is presented and smaller is better.
SANCTUARY performance with different memory allocation size and compared its efficiency and resource utilization with LEAP. The result is shown in Table I.

As Table I shows, when SANCTUARY increases the pre-allocated memory size, it indeed improves efficiency. However, the resource utilization also decreases. The resource utilization rate of LEAP is 92.13%. Compared with SANCTUARY, LEAP is faster than SANCTUARY by 1.44 $\times$ in the case of similar resource utilization rate (93.43%). When SANCTUARY and LEAP have similar performance, SANCTUARY’s resource utilization rate is lower than LEAP by 21.74%. More importantly, when security-critical Apps need to handle a variety of workloads, it is difficult to choose an appropriate resource allocation strategy in advance to balance resource usage and application performance well.

To clearly know our flexible resource overhead, we further profile the resource adjustment cost, and it proves that resource adjustment can be performed efficiently. Specifically, it takes about 199ms and 137ms to add a big or little core, and the time to remove a big or little core is 92ms and 72ms, respectively. And it only takes 54ms for sc-pAPP to add a block of memory, and the operation to release a block of memory can be completed in 56 ms. The ability to adjust resources at such a small cost demonstrates the flexibility and efficiency of LEAP in terms of flexible resources adjustment.

D. Peripheral Access Performance

We used the WiFi module to evaluate the LEAP’s performance of accessing peripherals. Although the WiFi module can be configured as secure through TZPC so as to be used in TrustZone directly, however, OP-TEE typically lacks the device drivers, so we cannot measure the performance of these devices in TrustZone. Since SANCTUARY relies on TrustZone to securely access peripheral, we can neither measure its performance. Hence, we compare LEAP with native ROS to show our peripheral accessing efficiency.

We run iPerf [34] to benchmark the network throughput for LEAP, ROS when they utilize the WiFi module respectively. Although OP-TEE does not have a WiFi driver, it is possible to send its network data through ROS. iPerfTZ [35] is an open source tool that measures the OP-TEE network throughput through forwarding network data to a client process running in NW, so we run iPerfTZ to benchmark the network throughput of OP-TEE. As SANCTUARY relies on TOS to securely access peripheral, this also represents the performance of SANCTUARY. Note that it is not a secure way but we have to measure OP-TEE in this way because it lacks WiFi driver. The benchmarks were run in the same settings. We set the socket buffer size to 128KB and tested the network throughput with different TCP windows sizes. Results are presented in Figure 11. The performance of accessing the network in LEAP is comparable to that of accessing the network in ROS. However, for OP-TEE the network throughput of this naive solution is only about 12.5% of that of LEAP. The poor network throughput is due to the frequency context switch between ROS and TrustZone to transfer the network data.

E. Case Study

We perform case studies that how a representative application, a deep-learning inference using the mobile GPU acceleration, adopts the LEAP for secure model execution. According to the study [36], [37], currently, it is feasible to steal such valuable in-device models from intelligent APPs. By applying LEAP, the model of the demo application can easily avoid being stolen and defense against other security attacks. We have selected three examples. The first one is an MNN-based [38] intelligent App that is deployed on LEAP platform through our LEAP adapter automatically; the other two intelligent Apps are developed from scratch with NCNN [39] and DarkNet [40] framework. Below we will first study the results of automatic adaptation, and then evaluate the system performance on these three examples.

Deploy with LEAP Adaptor. Please recall that our LEAP Adaptor works on the existing Apps, and all operations are done on the intermediate code. This demo application (21w lines of intermediate code) is a deep-learning inference of image classification with the Mali mobile GPU acceleration, representing a popular emerging application category. The sensitive part to protect contains the deep-learning model and its inference framework MNN. We adapt this intelligent App to our LEAP through the LEAP Adaptor, described in Section III-C. Our LEAP Adaptor takes 11s to complete the adaptation, occupies 1G of memory, and uses two CPU cores. The Adaptor adds only 80 lines of code to the original App. The generated sc-pAPP has a total of 856 lines of code.

Develop from scratch. We also adapt two example Apps manually to show how to develop a LEAP-enabled App from scratch. The split is completed in the following steps. First, we add an integrated LEAP$_{ROS}$ API lib into the App project. Second, we add the function of booting the LEAP sandbox in JNI code, and the code will be called when the App starts. Third, we modify part of the JNI code that switches the local DL framework, i.e., NCNN and Darknet, call to the “remote” DL framework call of the sandbox. Therefore, when there is an inferring request, it will be forwarded to LEAP sandbox, the inferring procedure will be performed in LEAP sandbox, and the inferring result will be sent back.
The application with the modified JNI code is called pAPP. Finally, we package the sensitive codes as sc-pAPP into the ramfs of a pre-distributed LEAP sandbox image. In order to access the Mali GPU securely, we just need to directly put the Mali Linux kernel driver into the sandbox image.

We evaluate the LEAP’s performance with these end-to-end demo Apps. We develop several applications with different models and DL frameworks and run the applications with both CPU and GPU of the prototype. In addition to conducting the measurement on LEAP, We train four models, i.e., SqueezeNet [41], MobileNetV2 [42], DenseNet201 [43], and ResNet50 [44], for each framework.

Figure 12 shows the performance of running the demo applications in both LEAP. The CPU version means running the demo application with the big or little cores on Hikey960. And more than one cores represent the situation that it dynamically request CPU cores from ROS for inference. When the demo applications deployed in LEAP uses the CPU to perform the inference, the inference speed for the big core is $2.9 \times 3.4 \times$ faster than little core for DarkNet, and $2.5 \times 4.4 \times$ for NCNN, and $2.3 \times 3.1 \times$ for MNN, respectively. Moreover, LEAP’s flexible resource adjustment enables the inference speed on the big core to improve $1.2 \times 1.8 \times$ for DarkNet, $1.6 \times 1.8 \times$ for NCNN, and $1.4 \times 1.6 \times$ for MNN.

Without loss of generality, we compare the inference speed of CPU and GPU based on MNN. As shown in Figure 12d, when the demo applications run with little core to perform inference with GPU, it is $1.2 \times 3.5 \times$ faster than two big cores. And it is $1.5 \times 4.9 \times$ faster than two big cores when the demo applications perform inference with a big core and GPU. We also evaluate the performance of running the demo application in TrustZone directly. When the demo application runs in LEAP, the inference speed is $1.4 \times$ faster than that of running in the vanilla TrustZone.

VII. DISCUSSION

Malicious Driver. In this work, we assume that the driver used by the developer is benign and bug free. Although a malicious or buggy driver can not affect other sandboxes, it may compromise the sandbox it resides in. To prevent this, we can refer to some driver isolation works to prevent malicious drivers from compromising the sandbox.

Parallel Peripheral Access. LEAP supports parallel execution of multiple sc-pAPP, but currently its exclusive IO design does not allow multiple sandboxes to access the same device at the same time. We think this is acceptable since many sensors in Android, such as cameras, can only be used by one application at the same time. Further research can also be conducted to seek a solution that enables devices to be securely shared among multiple distrusted parties.

Maximum Sandbox Number. At present, our design is based on an exclusive CPU and memory design. Therefore, the maximum number of sandboxes is limited by the number of CPU cores on the device. We plan to increase the sandbox density in future work to support more parallel environments.

VIII. CONCLUSION

In this paper, we challenge the TrustZone’s evolution strategies and argue the future TrustZone should be a developer-centric TEE to fulfill the App developers’ growing security demand. We comprehensively analyze the design requirements of App developers and present LEAP, a lightweight developer-centric TEE for mobile Apps, to respond to developers’ needs. We implement the LEAP prototype on Hikey960 and conduct comprehensive analyses to show that LEAP can balance security and usability in mobile scenarios. We believe LEAP can provide new ideas for future TrustZone.

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