Sovereign Smartphone:
To Enjoy Freedom We Have to Control Our Phones

Friederike Groschupp  Moritz Schneider  Ivan Puddu  Shweta Shinde  Srdjan Capkun

ETH Zurich

Abstract
The majority of smartphones either run iOS or Android operating systems. This has created two distinct ecosystems largely controlled by Apple and Google—they dictate which applications can run, how they run, and what kind of phone resources they can access. Barring some exceptions in Android where different phone manufacturers may have influence, users, developers, and governments are left with little to no choice. Specifically, users need to entrust their security and privacy to OS vendors and accept the functionality constraints they impose. Given the wide use of Android and iOS, immediately leaving these ecosystems is not practical, except in niche application areas. In this work, we draw attention to the magnitude of this problem and why it is an undesirable situation. As an alternative, we advocate the development of a new smartphone architecture that securely transfers the control back to the users while maintaining compatibility with the rich existing smartphone ecosystems. We propose and analyze one such design based on advances in trusted execution environments for ARM and RISC-V.

1 Introduction
Smartphones are the centerpiece of most people’s digital life. However, they do not offer the same flexibility as PCs, where users can install and run arbitrary software. Smartphone manufacturers and vendors of major operating systems such as iOS and Android restrict which apps can be run on smartphones, type of peripheral access, and data access. While Android allows side-loading, users are still limited in the way they can run apps and the kind of access they have. There are several examples where, in order to protect the users from developers, Apple and Google limit apps’ access to peripherals and data even if the users would allow such access [27, 38].

Smartphone manufacturers and OS vendors can use such control to optimize performance, provide a good user experience, and protect users from malicious apps. At the same time, these companies become arbiters and gatekeepers. Recent examples show that this is not a minor issue. In the case of contact tracing apps, Apple (and to some extent Google) restricted access that government apps can have to Bluetooth beacons, citing privacy and performance concerns. This restricted the design space and performance of contact tracing apps in several countries [38, 44, 45]. After recent developments in the US, the Parler app has been removed from Apple and Google app stores [22] and Google banned the app of a traditional Danish children’s program after the company deemed its content unsuitable [37]. Apple and Google policies required in-app purchases to use in-store payments, resulting in these companies being accused of gatekeeping in several jurisdictions [46]. Users, developers, and governments have therefore faced restrictions under the current model. Most notably, users are unable to freely use their smartphones—they are subject to several limitations that they do not face on their PCs.

This is clearly an undesirable situation. Even if the current OSs offer some leeway, like side-loading, they can and have taken it away from users and developers [49]. Few companies should not be in a position to have such control. As much as possible, control over the devices should be handed back to the users who own the phones and whose data the phones primarily hold.

This is a complex technical, legal, and societal issue that cannot be resolved by technical means alone [19, 21]. However, new smartphone designs can be a part of the solution to this problem. Ideally, a sovereign smartphone will give the user full control of the software, hardware (e.g., peripherals), and data on the phone. One obvious solution is to replicate the PC model for smartphones. Projects that allow this already exist [35, 36]. However,
they require the users to switch to other app stores. More importantly, they cannot easily replicate the functionality and protections that existing OSs offer. Virtualization-based solutions [2, 11] would hand the control to the hypervisors. However, such privileged software can inspect and modify the OS and app memory, therefore, removing control from the users and preventing OS vendor from protecting their ecosystems. Furthermore, removing control from the OS vendor only to hand it to the smartphone manufacturers, which would typically control such hypervisors, would not solve the underlying issues.

We propose a new design that demonstrates the feasibility of building a sovereign smartphone. We give control back to the users, without taking away the functionality and security from the existing operating system vendors and smartphone manufacturers. Such design allows companies to offer comprehensive protection to the users and software on the platform without restricting the users’ ability to run software and access platform resources. The sovereign smartphone offers flexibility in the deployment of new apps and functionalities and aligns the interests of users, phone manufacturers, cellular network operators, and even OS vendors.

Our design builds on the recent advances in trusted execution environments (TEEs). We discuss how it can be implemented on top of ARM and RISC-V TEE architectures. We outline several critical technical challenges in realizing sovereign smartphones.

## 2 Need for Sovereignty

### 2.1 Prominent Examples of Restrictions

**Restricted resource access.** Bluetooth-based contact tracing apps periodically receive and process Bluetooth Low Energy (BLE) beacons to measure the distance to other smartphones and register contact. Due to concerns about privacy and power consumption, iOS and Android did not permit apps running in the background to freely broadcast and receive BLE beacons, effectively disallowing BLE-based approaches preferred by some countries [38, 44, 45]. Instead, the introduction of such contact tracing apps almost entirely depended on Apple and Google implementing and providing an API for a particular decentralized contact tracing approach [5, 38]. Clearly, these companies can always disable this API.

**Censored app availability.** App store providers control which apps are offered on their app stores. They may reject or remove apps based on company policies [4, 24], public pressure, or executive authority. There have been several notable instances of apps being removed from official Apple and Google app stores. Examples include the ad-blocker Adblock Fast [47], the game Fortnite over a feud on payment restrictions [48], the right-wing app Parler after civil unrests in the US [17, 22], and the HKmap Live app used by protesters during the Hong Kong protests [12]. If an app is not available through the official app stores, iOS users cannot easily install it. On Android, developers may circumvent this restriction by offering their app as a side-loaded package. Even if technically users can side-load apps, iOS and Android can easily take this privilege away, either by selectively blocking apps or preventing any side-loading [49]. Furthermore, it might be technically feasible that OS vendors are legally compelled to disclose if banned apps are running on a user’s phone [6].

**Forced Ecosystem.** When an app is distributed through the official app stores, all payment transactions, even in-app purchases, must be processed through the respective billing service offered by Apple and Google [46]. This forces developers to use a specific payment API and subdues them to any fees imposed, as they cannot easily avoid offering their apps on these app stores [16, 28].

**Data privacy concerns.** Users face uncertainty about when and what kind of data is collected by their phone, for example through the phone sensors, and how it is processed [14]. While the OS allows the user to manage peripheral permissions for apps or to disable access to some resources globally, e.g., by turning off GPS or Bluetooth, they have to trust the OS. Intentional or unintentional misuse of such OS-level privileges or opaque policies can put the user data in danger without the user’s knowledge. For example, Google gathered location information even when the location history feature was turned off [3, 42].

### 2.2 Advantages of Existing Ecosystems

OS vendors invest large amounts of effort, money, and thought in developing a phone OS. By acting as a central authority in their ecosystems, they simplify management and engineering tasks. For instance, they can quickly react to zero-day vulnerabilities or new classes of attacks [26, 33]. They can avoid fragmentation of their ecosystem because they provide a unified system, consistent APIs, and central app stores.

Apple and Google aim to protect their users’ security and privacy against third parties. Specifically, they vet apps and weed out potential malware before releasing them on the official store. To enhance security, the OSs restrict user permissions, enforce strict inter-app isolation, and suppress direct access to certain peripherals. Further, they provide useful security services, e.g., protection for digital copyright content, Google SafetyNet, secure OS boot, OS tamper detection, and app-specific data protection. In summary, a tightly controlled system preserves

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2 On iOS, custom apps can be installed with a special developer account and the app’s source code through XCode.
users’ and apps’ usability, security, and privacy while providing a good developer experience.

2.3 Bypassing App Stores and OS Vendors

**Rooting/Jailbreaking.** Users can gain root permissions on their phones by bypassing security mechanisms or exploiting vulnerabilities. They can run privileged apps and circumvent hardware manufacturer or OS vendor restrictions. However, this approach is not user-friendly, might brick the phone, and voids device warranty [7, 43].

**Unlocking the bootloader.** Users can unlock the bootloader on some Android phones and install a different OS. In theory, the user then has full control over the OS functionality, drivers, and the apps they want to install. However, alternative OSs lack compatibility with common apps and key proprietary functionality [10]. In addition, even though unlocking the bootloader is supported by some hardware vendors, it still voids the warranty in many cases and irreversibly prevents particular apps from running, such as Samsung’s security framework Knox [40].

**Side-loading.** Android allows side-loading, i.e., the installation of code distributed by other means than the official app store [39]. However, the user depends on OS vendor support for this feature, which can be potentially discontinued [49]. Furthermore, this approach does not allow unrestricted access to resources. For example, side-loading a contact tracing app would not have resolved the lack of functionality at the OS level.

3 Sovereign Smartphones

Reducing OS vendors’ control in the phone market necessitates shifting it to other entities, i.e., users, governments, or independent oversight committees. We argue that the users, as device owners and as those whose information is primarily processed on the devices, should be in control of their data and able to freely use their devices without OS vendor restrictions.

Giving users full control over their phone has some trade-offs. First, it would simplify illegal activities on phones which could not be prevented by authorities. However, criminals already have ways of circumventing these limitations, such as using PCs or open stack devices. Law enforcement has other ways of control, e.g., through ISPs. Second, an average phone user may not have the technical expertise or necessity to configure a sovereign phone. Such a user can use configurations offered by a trusted party (e.g., independent committees). Alternatively, they can continue using an existing OS as is, if the sovereign phone platform is compatible with current OSs. While this essentially delegates the control from the user to another entity, the choice is still up to the user.

3.1 Desired Properties

We envision that a sovereign smartphone should maintain compatibility with current OSs such as iOS and Android, referred to as legacy operating system (LOS) in the following. Users can continue to execute existing apps, which are hereafter referred to as legacy apps. We introduce the notion of sovereign app (sapp), an app that runs outside the LOS. A user can run a sapp when (i) it is not available in the LOS app store and side-loading might pose a security risk to the LOS; (ii) they do not trust the LOS; or (iii) the sapp needs access to resources prohibited by the LOS.

**(P1) Full user control.** The user can assign certain shares of compute time to LOS and sapps. The user can deny or grant exclusive peripheral access to LOS or sapps.

**(P2) LOS protection.** The LOS and legacy apps continue to have the same guarantees as they would in the absence of sapps. The LOS is still in charge of protecting legacy apps and enforcing permissions within its domain, legacy apps cannot directly access resources or bypass LOS protections, and the LOS can inspect and censor legacy apps. The LOS and legacy apps are guaranteed to maintain their existing confidentiality, integrity, and availability even in the presence of sapps.

**(P3) Sapp protection.** Each sapp has confidentiality, integrity, and availability guarantees in the presence of LOS, legacy apps, and other sapps.

**(P4) Execution without leaking sapp identity.** Neither the LOS nor sapps should have access to information that reveals the identity of other sapps on the device.

**(P5) Limited trusted computing base (TCB).** The design should assume only a small amount of code to be trusted and bug-free. The TCB should be around few thousand LoC i.e., within the realm of formal verification.

Satisfying P1–P5 enables several use-cases. For example, a contact tracing sapp can be granted exclusive access to the Bluetooth card and guaranteed a certain periodic runtime by a user policy (P1). As another example, a user could install a messaging app that is not offered on the official app stores. They are assured that sapp confidentiality and integrity is protected (P3) on the phone. Technically, the legislation cannot force the LOS, other legacy apps or sapps on the phone to disclose that the user has installed or is running a particular sapp (P4). In both instances, the user can continue to use the LOS with the same confidence in its properties as before (P2).

3.2 Strawman Approaches

**Giving users full root permission** to install an sapp as an app in the LOS can be a legitimate alternative to rooting. However, as the LOS is still mostly in charge, this approach satisfies neither of our properties: The user cannot assign resources (P1), the LOS and sapps are not
Our proposal

| Solution           | P1 | P2 | P3 | P4 | P5 |
|--------------------|----|----|----|----|----|
| Root permissions   | ✗  | ✗  | ✗  | ✗  | ✗  |
| Extending LOS      | ✓  | ✓  | ✓  | ✓  | ✓  |
| Hypervisor         | ✓  | ✓  | ✓  | ✓  | ✗  |
| Traditional TEEs   | ✗  | ✓  | ✓  | ✓  | ✓  |
| Our Design         | ✓  | ✓  | ✓  | ✓  | ✓  |

Table 1: Properties provided by different solutions. P3 (✓) implies confidentiality and integrity, without availability.

protected from each other (P2, P3), and the LOS can monitor which sapps are installed and running (P4).

**Extending the LOS** with the capability of loading user-provided kernel modules, i.e., drivers, would allow users to configure resource access (P1). However, the LOS and sapps would not be isolated from each other. Furthermore, the LOS would still be in charge of launching and scheduling all apps, allowing it to inspect sapps and deny service to sapps (P3, P4). We cannot trust the entire LOS (P5).

**Hypervisors** can virtualize resources and isolate the LOS in a VM [2, 11], thus fulfilling P2 and P3. Sapps can then execute in their own VM. However, the hypervisor itself executes with the highest privileges. It can directly inspect VM memory and interfere with its execution. Moreover, typical hypervisors have large code bases, up to 1M LOC (P5) [11]. More importantly, hypervisor vendors may resort to similar tactics as current OS vendors and curtail user’s control over their device.

**Executing sapps in traditional TEE enclaves** can provide confidentiality and integrity to LOS and sapps (P2) [18, 31] with a minimal TCB (P5) [30]. As the LOS controls scheduling, availability is only guaranteed for the LOS, not for sapps (partial P3). Furthermore, the LOS can fingerprint a sapp or detect which sapps are executed (P4). Current TEE proposals do not allow access to system resource without mediation by the LOS (P1).

## 4 Our Design

Our approach is based on a TEE design with a small security monitor (SM) containing the software TCB [31] (see Figure 1). The SM runs with special privileges and is responsible for configuring isolation and peripheral access during context switches between the LOS and sapps. However, there are key differences to TEEs. First, the SM is not omnipotent in our approach: It can manage sapps and the LOS, but not inspect their memory or interfere with their execution. Second, sapps are able to access system resources such as Bluetooth without the LOS being able to inspect or interfere. And third, we aim to provide availability guarantees to both the LOS and sapps.

**Management without inspection.** Maintaining existing security guarantees and functionality of the LOS (P2) is critical. Thus, we try to reduce the SM’s capabilities by removing its access permissions to the LOS or sapps. Similar solutions exist in cloud computing, where a hypervisor cannot inspect the private memory of its guests [1, 29]. Traditional ARM or RISC-V platforms have partial support for such hardware-based protection. We discuss how to enable this primitive for smartphones in Section 4.1.

**Resource sharing.** Traditionally, OSes manage system resources. Adding these management capabilities to the SM would bloat the TCB and only shift problems to a lower layer. Instead, we propose the LOS to remain in charge of management, but it can concede control of a peripheral to a sapp. From that point on, the SM enforces the sapp’s exclusive control over the peripheral by configuring a hardware access control mechanism to restrict access to the peripheral memory ranges. In a mobile phone, all peripherals are set statically at design time. Their memory-mapped addresses and version numbers are included in a device tree file burned into ROM on the SoC. Thus, the SM can consult the trusted device tree to ensure that a particular peripheral is exclusively controlled by a sapp. Note that this approach only allows one sapp or the LOS to exclusively access a single peripheral at a time. We are investigating proposals that allow for more flexibility.

**Mutual Progress.** Ensuring availability can be achieved by adding a scheduler to the SM. However, such scheduling functionality must be immutable, i.e., an attacker cannot update it without getting detected. On the other hand, the LOS has a sophisticated scheduler that is well-suited for legacy apps and hardware but is not trusted. Therefore, we propose a middle-ground: The user or the sapp can specify policies, e.g., a sapp should be assigned a certain amount of runtime during a specified interval. The LOS performs the scheduling. The SM verifies that it is done as per the sapp- or user-defined policies by recording the runtime that was granted to the sapp upon context switches. Since policy verification may be expensive for complex policies, we propose periodic checks. The SM merely verifies that these periodic checks have been performed regularly on every context switch. If the SM detects violations to the policies or no periodic checks,
it can impose sanctions (e.g., user notification or locking the device operation). We assume that this is a lose-lose situation that all sides want to prevent. Moreover, once informed, the user can replace the uncooperative LOS.

**Attestation.** In our proposal, a local user wants to attest and verify the code running within a sapp. In addition, the user wants to verify the scheduling policies and resource accesses permissions of the sapp are initialized correctly. Remote attestation of traditional TEEs has the basic mechanisms to provide such guarantees. We will augment it to include sapp specific information. Moreover, our SM can directly interact with the user through a secure user interface to signal successful attestation.

### 4.1 Feasibility on RISC-V and ARM

On RISC-V, the SM runs in machine mode. It configures physical memory protection (PMP) entries to isolate sapps and the LOS running in the less-privileged user and supervisor modes respectively [31]. We will use existing hardware mechanisms to restrict the SM from inspecting sapp and LOS memory. Specifically, the SM locks the PMP entries after sapp creation with a sticky bit (which is only cleared on full system reset) such that it does not have access to the respective memory regions [50].

On ARM, the SM runs in the secure world. It configures the TrustZone address space controller (TZASC) [13] to provision isolated execution environments in the normal world for the LOS and sapps. To restrict the SMs capability to inspect memory, we are investigating a combination of features from two different TZASCs: TZC-380 for locking configurations [8] and TZC-400 for per-core memory isolation [9]. Peripheral access can be enforced by leveraging the TZASC as proposed in [32].

### 4.2 Analysis

**Threat Model.** In general, we assume the SM and the hardware to be trusted. A malicious SM could deny running certain sapps or monitor the user’s activities. Therefore, the SM should remain as small as possible and should potentially be implemented purely in hardware.

One has to consider at least two perspectives when discussing the threat model of the sovereign smartphone. First, the LOS and sapps consider a malicious user against whom they want to protect their internal secrets. This means that a local physical adversary is in scope in this scenario. However, we note that current smartphones also consider such an adversary. Second, from the user’s perspective, the LOS is considered malicious, e.g., the LOS might be under societal or even legal pressure to censor some sapps, or even report the user to law enforcement for the usage of an illegal sapp. In the worst case, the LOS is entirely malicious and tries to leak the users’ data. In this scenario, the user remains in physical possession of the phone, and thus, there is no physical adversary. We also assume that the foremost goal of the LOS is that users keep running it, as a complete refusal to cooperate might hurt both the user and the LOS.

**Security Analysis.** The user needs to be able to assign system resources to sapps (P1). In our approach, the LOS can concede control of individual peripherals to sapps, which the user can then verify. The SM enforces exclusive access to these peripherals as per the trusted device tree burned into ROM.

As in traditional TEEs, the sapps or the LOS cannot access each other’s private memory (P2 and P3). However, the SM can always read all memory on the system. To address this gap, we plan to remove the SM’s capability to inspect memory by using once-set-never-unset mechanisms in the hardware (until hard-reset) [50].

While our proposal does not grant absolute availability, it guarantees mutual progress of the LOS and sapps. Moreover, we prevent selective denial-of-service of an individual sapp. The SM will notice such violations by the OS and take necessary actions to disincentivize this.

We require that sapps can be installed and executed on our platform without being identified by entities other than the user and the SM (P4). We stress that this is a known hard problem [34] and may be impossible for sapps with clearly distinct resource usage patterns. However, there are multiple probabilistic approaches leveraging obfuscation to hide sapp identities. We also note that the anonymity property might conflict with the flexibility, policy expressiveness, and the attestation mechanism.

Many sapps and the SM will require user interaction. The security of this user interaction is critical to prevent various user-interface attacks [15, 23]. There have been various studies on the effectiveness of security indicators [41, 51], and recent work has proposed secure LEDs [20] or extra buttons [32]. However, it is unclear if these proposals are fully applicable to our scenario, or if there are more lingering issues.

Thus, designing a sovereign smartphone that fulfills our outlined properties presents a unique set of non-trivial technical challenges. Our analysis shows that, although not straightforward, such a design is feasible.

### 5 Outlook

In our proposal, we lay the foundation for a sovereign smartphone architecture. It combines handing users control over their devices with advantages of current ecosystems in a secure manner. It highlights important challenges that need attention from the technical community.
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