SCHOOL OF COMPUTATION, INFORMATION AND TECHNOLOGY — INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Master's Thesis in Informatics

Establishing trust in an updatable fTPM using remote attestation

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Establishing trust in an updatable fTPM using remote attestation

Herstellung von Vertrauen in ein aktualisierbares fTPM durch Remote Attestierung

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I confirm that this master's thesis is my own work and I have documented all sources and material used.

Munich, 15.12.2023 Andreas Korb

Acknowledgments

Abstract

TPMs are authenticated by getting to know their manufacturer, who guarantees the fulfillment of the TPM specification to ensure its security properties. While this approach is sufficient for hardware TPMs since they are self-contained chips, it assumes for firmware TPMs that the manufacturer of the firmware TPM is the same as the one of all firmware components booted before the firmware TPM. That is due to the fact that each preceding firmware component can compromise the firmware TPM while loading it. The verifier in the remote attestation process has no way to verify the entire boot chain up to the firmware TPM. We propose a remote attestation system which enables the verifier to do that. For that, we leverage a new hardware root of trust implementing DICE. The verifier only needs to trust the manufacturer of DICE, while everything beyond is explicitly attested by propagating their identity to the verifier. This allows the manufacturer of the firmware TPM and every preceding component to be independent. Our system also binds the fTPM's data to the fTPM's identity, such that its data is not accessible anymore when the fTPM or any preceding firmware component is modified, or potentially compromised. In summary, our system ensures potentially malicious modifications of a system during its boot process are detected, and that the fTPM's data is only accessible as long as the identity of the fTPM does not change, making downgrade attacks and modifications of the fTPM less attractive to attackers. Conversely, this ensures that the data is only accessible to the exact fTPM, and not to another fTPM.

Contents

1 Introduction

This chapter includes an explanation of the exact problem we are addressing, and why, a brief overview of our solution, and the attacks we are trying to fend off.

1.1 Motivation

Modern trust relationships, such as Zero Trust [**isaca2021**], require trustworthy platforms, which can reliably report their system state. In such models, trust is no longer implicitly assumed, e.g., by the fact that a device is located within the boundaries of a company. Instead, each device is considered compromised until proven otherwise on a per-request basis for resource (e.g., printers) and data access [**Rose2020**].

This is solved by remote attestation. In the simplest case, there is a prover and a verifier, as depicted in Figure 1.1. The challenge is that the verifier observes nothing but bytes from the prover, and while a benign prover will tell the truth about its state, a compromised prover will lie about its state and claim a trustworthy one. Therefore, the verifier must establish trust to a helper component on the prover's side. This component must be independent of the rest of the prover's machine and immutable, so that it can be trusted by trusting its manufacturer. The manufacturer is commonly propagated by certificates stored on such helper components and signed by the corresponding manufacturer. Consequently, the component attests the state of the prover's machine, from which the verifier can deduce whether the prover can be considered trustworthy.

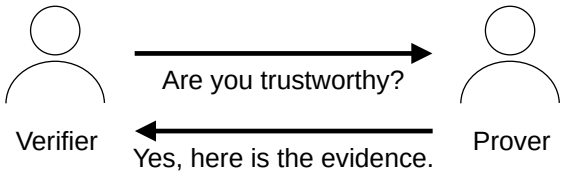


Figure 1.1: Simplified remote attestation process.

For example, this can be done with a Trusted Platform Module (TPM) on the prover's side. They rise in their deployments and importance, e.g., in 2013 the President's Council of Advisors on Science and Technology encourages the adoption of TPMs [**usa**], and Microsoft publicized that they require a TPM module for Windows 11

in 2021 [**win11req**]. They provide remote attestation mechanisms of system states, and their applications are still expanding beyond their traditional use-cases. For example, they are used in anti-cheat software for games [**valorant**].

A dedicated hardware TPM (dTPM) increases cost and hardware complexity — especially for embedded platforms. Through Trusted execution environments (TEEs), such as Arm TrustZone, a firmware TPM (fTPM) can be used to provide similar security guarantees as a dTPM chip.

For a dTPM, which consists of an independent hardware unit manufactured by a single manufacturer and is directly activated by power, it is sufficient to identify its manufacturer and understand his provided guarantees. In contrast, an fTPM runs atop other firmware components and is started later in the boot chain, making its security dependent on the underlying firmware stack. As a result, the fTPM can only be trusted if the entire underlying firmware stack is also trusted, since the underlying firmware could modify, i.e., compromise, the fTPM component which is then not detected.

However, while a TPM-compliant component provides an infrastructure with which trust in it can be established remotely, i.e., an endorsement (key) certificate (EKcert), the underlying firmware stack is not represented by this.

Currently, this is solved by the manufacturer providing not only the fTPM, but also the entire underlying firmware stack. Consequently, by establishing trust to the manufacturer of the fTPM, one can implicitly trust the underlying firmware as well by assuming they also originate from this manufacturer. This is possible since in the most general sense, one can derive from an endorsement certificate the endorser, i.e., manufacturer, and if the attester trusts the manufacturer and the guarantees he provides, trust is established to his provided components.

This process is illustrated in figure Figure 1.2. The prover's area shows its boot chain, the verifier's area shows how it evaluates the trustworthiness against the prover's boot chain. The verifier trusts the entire firmware chain if he trusts the manufacturer of each individual component. Note how the verifier must assume that the manufacturer of the firmware components is the same as the manufacturer of the fTPM. To the best of our knowledge, this is what manufacturers like Intel and AMD implement for their fTPMs, as confidence in their fTPMs is also only established through an EKcert.

In summary, with the current approach, the endorser, usually a CPU manufacturer, provides the firmware up to the fTPM and guarantees the firmware is not modifiable by untrusted parties. This enables trust to the other firmware components this manufacturer provided without knowing the firmware. This approach is limited, as with this mechanism, independent verifiers have to blindly trust the firmware manufacturer, which drastically limits trust relationships.

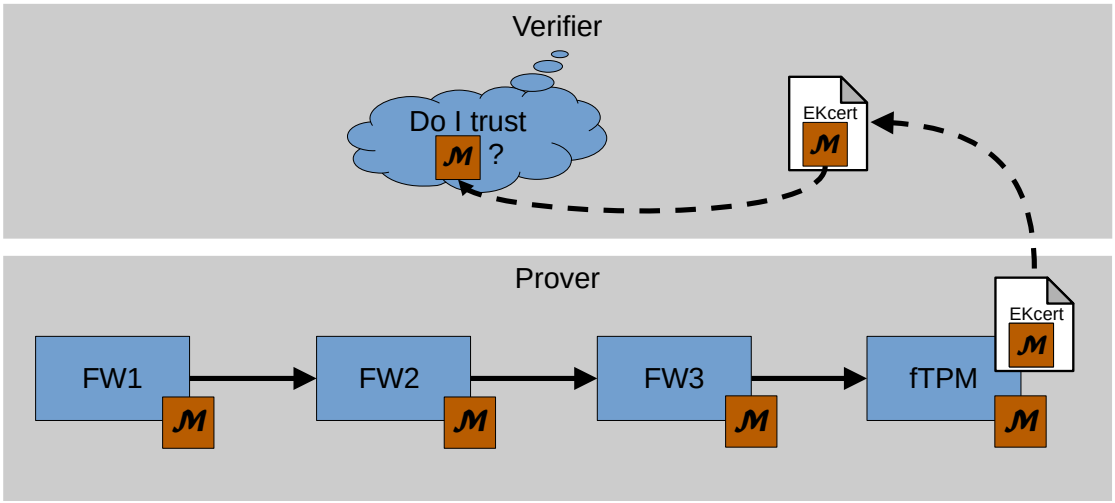


Figure 1.2: The naive process how a verifier establishes trust to an fTPM, which is in fact done by trusting its manufacturer. The brown markers indicate a manufacturer. The firmware (FW) and the fTPM were built by manufacturer $\mathcal{M}$, and the EK certificate indicates this manufacturer.

1.2 Goal

We establish independently verifiable fTPM stack, rooted in a hardware root of trust, that can be leveraged in a zero trust environment with little hardware requirements and no compromising on security. The goal of this approach is to break the requirement of the underlying firmware and the fTPM to originate from the same manufacturer, by providing the exact firmware component identities to the verifier, such that it can decide for itself whether they are trustworthy without relying on their manufacturer. Instead, it is sufficient to trust the independent manufacturer of the hardware root of trust, which in contrast requires no assumptions.

One mechanism enabling firmware attestation is the Device Identifier Composition Engine (DICE), focusing on resource-constrained devices. Although this mechanism shifts trust from the firmware provider to the hardware provider by allowing firmware attestation through a hardware root of trust, the exclusive use of this integrated solution is unsuitable for large dynamic systems, for example Linux based devices. Nevertheless, the advantage is that the identity of each component of the firmware boot chain is represented.

We propose a hybrid solution, combining the advantages of DICE and fTPMs, yielding an independently verifiable certificate chain representing the boot chain up to and including the fTPM. This enables a verifier to establish trust in an fTPM if the

underlying firmware is benign as well and thus, providing a way to independently assess the properties of the fTPM.

The research questions we aim to answer are listed below.

- What constitutes the identity of an fTPM?
- How to combine the DICE and TPM infrastructure?
- How to manage an fTPM's persistent data securely?
- How to enable privacy for this attestation mechanism?

1.3 Threat Model

The main threat is trusting a remote firmware TPM which is in fact not trustworthy. For that, an attacker could inject a malicious update of a relevant firmware component at the developer's website, which is then possibly blindly installed by device vendors. Or the attacker could exchange the SD card storing the firmware including the fTPM which has stored old versions with easily exploitable vulnerabilities. However, we assume that the fTPM cannot be modified by malicious parties after the boot process regardless of whether the fTPM is benign or compromised because we trust the TEE environment. Out-of-scope are hardware attacks, side-channel attacks, control-flow attacks, and Denial of Service attacks.

For the network, we assume the Dolev-Yao attacker model [**Dolev1983**]. That is, we consider an attacker who has the ability to perform any active or passive attacks on the network. The attacker may also have control over parts or the entire network, e.g., all routers, switches, and connections. They also cannot break cryptographic primitives, e.g., encryption, signing, and hashing.

1.4 Security goals

In this section, we want to formally describe the security goals of our solution so that we can later briefly discuss whether and how we have achieved the corresponding objectives.

1. **Compromised fTPM cannot fake its identity**
2. **Small root of trust**
3. **Isolation of fTPM storage**

4. **Protect fTPM data from downgrade attack of the fTPM**

5. **Privacy of attestation process**;
   The verifier should be able to establish trust in the authenticity of an fTPM without having to know the identity of the fTPM, i.e., its EK.

1.5 Environment

This work was created at the 'Fraunhofer-Institut für Angewandte und Integrierte Sicherheit AISEC' in Garching. It is part of the 'Fraunhofer Society for the Promotion of Applied Research e. V.', which is an organization distributed over Europe with main focus on applied research. In the roughly 35 years of its existence, it rose to become the largest research institute in Europe with around 30,000 employees.

1.6 Outline

2 Background

This chapter discusses the relevant background knowledge required to understand the remainder of this work.

2.1 Trusted execution environment

One of the core security concepts of operating systems are the privilege levels of processes [**Linden1976**]. Thereby, processes are protected against other processes with the same or lower privilege level. However, they are not protected against more privileged processes [**Bratus2009**]. This bears problems for example for cloud computing and edge computing. In cloud computing, other services, the hypervisor, or the cloud provider in general could potentially access sensitive data of the cloud tenant [**Nimgaonkar2012**]. In edge computing, the edge applications deal with plain text data, while they are potentially running on insecure edge devices [**Ning2018**]. Hence, protection against more privileged processes is desired.

The Trusted execution environment (TEE) is a technology defined by GlobalPlatform[1] as an integrated hardware extension to processors. By that, the execution environment is separated into the Rich execution environment (REE) and the TEE by hardware. The REE runs commodity software, e.g., a Linux-based operating system with user applications. The TEE is an isolated tamper-resistant execution environment that guarantees the authenticity of the executed code, and the integrity of runtime states, e.g., memory [**Sabt2015**]. Since a TEE is integrated into the processor, there is no separate chip required. Moreover, the TEE commonly follows the same user and kernel space separation as a rich OS. The kernel space is running a trusted OS, and the user space is running the trusted applications. It focuses on resisting software-based attacks generated in the REE, however, also protects against some hardware attacks [**GPSysArch**].

Previous, mostly software-based technologies ensure confidentiality and integrity protection of data-in-transit and data-at-rest [**Pecholt2022**], while a TEE additionally protects data-in-use in hardware [**Pecholt2022**, **Lee:EECS-2022-96**].

[1] `https://globalplatform.org/`

Figure 2.1 illustrates the motivation. In the traditional architecture, i.e., without a TEE, if an attacker compromises the REE the full system is affected. With a TEE, the attacker is limited to the REE, while the TEE continues to protect the secure assets, such as encryption keys. This results from the observation that the attack surface of a rich OS is much larger than that of a trusted OS, e.g., due to its network connectivity and the high dynamics of software installations, while the attack surface of a trusted OS is rather small and has tightly controlled interfaces.

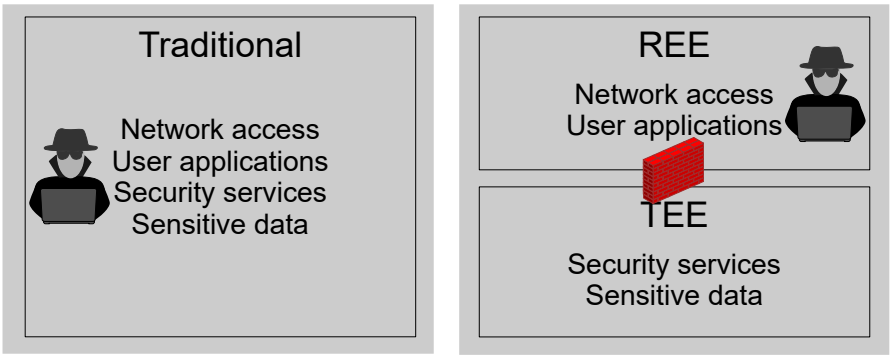


Figure 2.1: Comparison between a traditional architecture, and an architecture separating the REE and TEE. This illustrates the motivation of a TEE.

2.1.1 Arm TrustZone

One such TEE is Arm's TrustZone [**ARM09**, **Ngabonziza2016**]. It partitions all software and hardware resources of the containing system into the Normal world (NW) and the Secure world (SW), as shown in Figure 2.2. The secure monitor is triggered by the dedicated instruction Secure Monitor Call (SMC), which then manages the context switches between the NW and the SW. While the SW can access the resources of the SW and the NW, the NW is restricted to its own assigned resources. Since Arm is the dominant processor architectures for IoT devices with a market share of 86 % [**eclipse**], many of the approaches in this field of research use Arm TrustZone [**Valadares2021**].

Our implementation also leverages TrustZone to enable the execution and the remote attestation of an fTPM.

2.1.2 Further TEE technologies

Other TEE technologies are Intel Software Guard Extensions (SGX), and AMD Secure Encrypted Virtualization (SEV), in the future also Intel Trusted Domain Extensions (TDX), and Arm Confidential Computing Architecture (CCA). Since we focus on

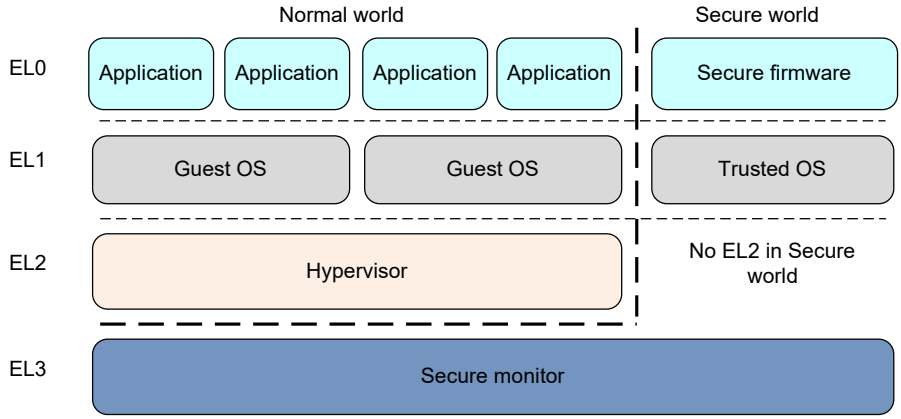


Figure 2.2: The architecture of Arm TrustZone for AArch64 [**TZArch**]. The exception levels (EL) indicate the privilege levels.

the implementation of our concept with Arm TrustZone, we do not go into detail about these other technologies here. However, since our concept is not tied to Arm processors and can also be applied to others, they are mentioned for the sake of completeness.

2.2 Attestation

According to NIST SP 1800–19B [**Bartock2022**] an attestation is "the process of providing a digital signature for a set of measurements securely stored in hardware, and then having the requester validate the signature and the set of measurements." Specifically in our context, attestation is a mechanism for software to prove its identity. In the following, the two types are discussed.

2.2.1 Local attestation

Local attestation is a procedure in which the state of a computer is measured, whereby the measurement result does not leave the computer but is used directly by a local component. One such example is a TPM that releases data, e.g., an encryption key, only when the computer is in a known state. This feature is known as sealing [**tpm**].

2.2.2 Remote attestation

In contrast to that, the measurement, usually called evidence, leaves the measuring machine, and is transmitted to a remote verifier for a remote attestation. This in-

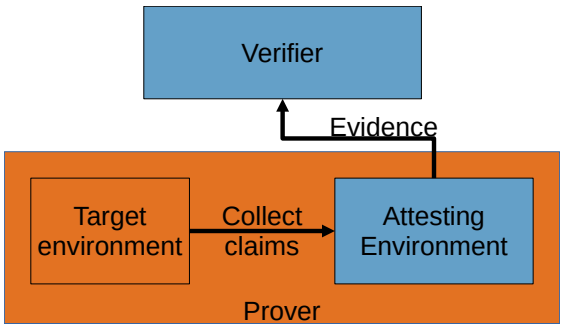


Figure 2.3: Data flow of remote attestation [**rfc9334**]. Initially, only the blue areas are trusted by the verifier. With the attestation, the verifier can choose to trust the target environment based on its measurements.

volves cryptographic primitives to establish trust into this evidence which is generally transmitted through an untrusted network.

Remote attestation is a challenge-response protocol initiated by a remote attestor. Figure 2.3 depicts a simplified overview of the data flow of a remote attestation. The process is initiated by a remote trusted party (called "verifier") to verify that a target environment on the end-device (called "prover") has not been tampered with [**Menetrey2022**, **Coker2011**]. This challenge contains a nonce, enforcing a fresh response. The response must be an evidence of the challenged system that it is trustworthy. To build that, an attesting environment on the prover device generally inspects the following properties of a program: (i) its code and data has been correctly loaded into memory for execution, and (ii) its data has not been maliciously modified at runtime.

The attesting environment acts a root of trust for measurements (SRTM). It is required on the prover because at least one trusted component is necessary to conduct trusted measurement of the prover. In many cases, the SRTM is running within the TEE, since thereby it is better protected from attacks.

It typically consists of two parts [**McCune2008**]. (i) The attestation, and (ii) the accompanying establishment of a secure channel. In this work, we focus on the first step.

A remote attestation procedure can also be divided into two categories, implicit and explicit attestation. In implicit attestation, the state of the verifier is implicitly inferred from the fact that the verifier has control over a signing key that is only accessible in a known state. With explicit attestation, the state of the device is explicitly described in the evidence.

2.3 Trusted Platform Module

The Trusted Computing Group (TCG)[2] published the first TPM specification (v1.2) in 2009 [**ISO11889**], and the most current specification (v2.0 Revision 01.59) ten years later in 2019 [**tpm**]. It describes a cryptographic coprocessor that increases trust in the host platform. Specifically, this means that the platform exhibits the expected behavior and that this behavior can be trusted. For that, the TPM maintains a separated state from the host platform, which enables the TPM to take measurements of the host platform. It is also a passive device, meaning it only does something when prompted. Table 2.1 summarizes the main features of TPMs.

Table 2.1: TPM main features and exemplary use-cases.

Feature	Use-case
Device identification	Identify a machine before granting it access to resources
Key Storage	Store encryption keys securely
Random Number Generator	Seed the key generation algorithms
Platform Configuration Registers	Store measurements of system components

Each key created and stored on a TPM is part of one of four hierarchies. The following list shows the official names of the hierarchies as defined in the TPM specification [**tpm**], some alternative names behind them in brackets, as they are sometimes referred to, and the intended use-case of the hierarchies [**Arthur2015**].

- Storage hierarchy (owner hierarchy);
  This is the hierarchy mainly used by the end user of a TPM, e.g., to store SSH keys.
- Endorsement hierarchy;
  Therein are stored privacy-sensitive keys, most importantly the EK.
- Platform hierarchy;
  It is intended to be used by early boot code like the UEFI. For example, the UEFI can store its configurations under this hierarchy.
- Null hierarchy (ephemeral hierarchy);
  Used for temporary keys, e.g., when the TPM is being used as a cryptographic coprocessor. Keys in this hierarchy are discarded when the TPM is restarted.

[2] `https://trustedcomputinggroup.org/`

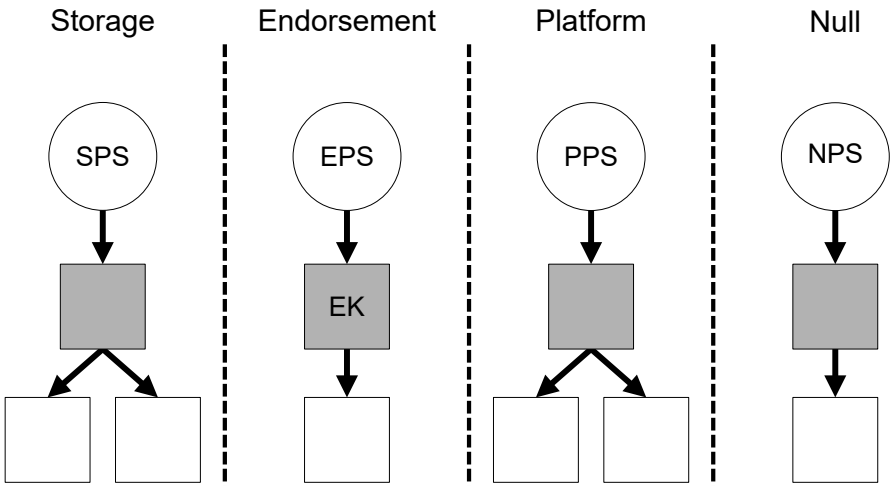


Figure 2.4: The source of entropy of the keys generated in a TPM for each hierarchy. Circle: primary seed, e.g., the storage primary seed (SPS), gray rectangle: primary key, e.g., the endorsement key (EK), white rectangle: ordinary key.

The hierarchies are separated in order to provide actors with finely granular access to the TPM. For example, a privacy administrator can only have access to the endorsement hierarchy, while the end user only has access to the owner hierarchy. They possess different behaviors as well. The Null hierarchy, for example, cannot be restricted, while the Platform hierarchy is unlocked each time the TPM is restarted, i.e., has an empty password, and is intended to be locked by the early boot code by setting a password only known to the early boot code.

A TPM derives keys from two parameters, a source of object entropy and a key template. The object entropy for a primary key comes from the according primary seed, for an ordinary key from the parent key, as depicted in Figure 2.4. Note that ordinary keys can also have children, so there can be more levels than in Figure 2.4.

A template contains metadata of the key, such as the type of key, e.g., RSA, and the object attributes. The attributes assign for example whether the key can be used for encryption or signing. Keys can also be restricted, which restricts the key to be used with data generated by the TPM [**tpm**]. For signing keys, this prohibits the TPM to sign data with it which seems to be generated by the TPM, but are actually not. This prevents an attacker from asking the TPM to sign an artificially constructed quote. And restricted encryption keys can only be used to encrypt TPM generated data like keys.

The Platform Configuration Registers (PCRs) are the fundament for the remote system attestation. They are one-way registers, which values can never be written to an exact value, but only be extended. This operation is known as 'hash extend' [**Arthur2015**]. Its design prohibits the removal of extensions, which would cause the TPM to forget

a measurement, and the arbitrary writing of values, which would overwrite any previously conducted measurements. A PCR value holds a hash representing the platform state. Thereby, a remote verifier can request a so-called 'quote' from the TPM on the host in question. A quote contains the hash of all requested PCR values and is digitally signed. Typically, a TPM contains 24 PCR registers, as defined as the minimum by [**tcgPcClient**], with the lower PCR values representing the system boot process and the higher ones representing the events after the kernel is booted [**Arthur2015**]. The fixed length of the PCR values is important for the memory-constrained nature of TPMs [**Arthur2015**].

The PCR value at index i can only be modified, i.e., extended, by adding together the currently contained hash value and the new hash, as depicted in Equation 2.1 [**tpm**]. For the sake of correctness, it should be noted that not every PCR is initialized with zero, as implied in the equation. For example, the TPM PC Client Platform specification [**tcgPcClient**] defines that PCRs 1–15 are initialized with all bits set to 0, while PCRs 17–22 are initialized with all bits set to 1.

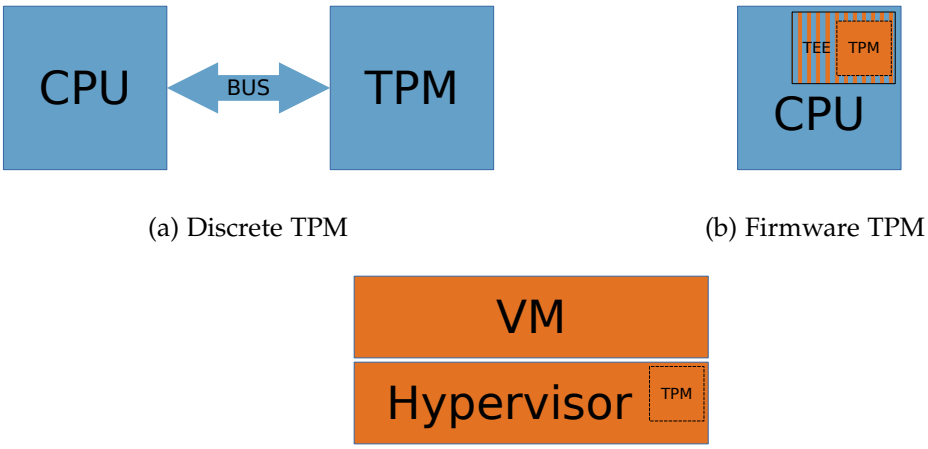
$$PCR(i)_{t=0} := 0, \quad PCR(i)_{t+1} := hash(PCR(i)_t \parallel new\ value) \tag{2.1}$$

TPM 1.2 is limited to SHA-1 hashes which are considered broken [**cryptoeprint:2005/010**, **Wang2005**, **Stevens2017**]. Although the SHA-1 uses in TPM 1.2 were analyzed to be not affected [**sha1tpm12**], cryptographic algorithms only become weaker over time [**Arthur2015**]. In reaction, TPM 2.0 offers crypto-agility and allows newer algorithms such as SHA-256. In general, TPM 2.0 is more flexible, and is always turned on, while a TPM 1.2 needed to be turned on manually. Also, TPM 2.0 is more consistent across different implementations because of broader specifications. TPM 2.0 is the focused version nowadays, e.g., Microsoft recommends TPM 2.0 over TPM 1.2 because of security advantages [**micrec**], and also requires TPM 2.0 for Windows 11 with SHA-256 PCR registers [**win11req**].

There are three types of TPMs, as illustrated in Figure 2.5. They all offer the same functionality, but with different security guarantees and performance characteristics.

2.3.1 Discrete TPM

This is the classical form of a TPM. It is a dedicated piece of hardware, connected to the CPU via a bus. It is designed and manufactured to be highly temper-resistant against hardware attacks. The TPM specifications [**tpm**, **tcgPcClient**] do not demand a specific bus system, however, they define the interfaces between the TPM and the following bus systems: LPC, I^2C, and SPI.



(a) Discrete TPM

(b) Firmware TPM

(c) Virtual TPM

Figure 2.5: Schematic illustration of the different TPM types in their pure form. Blue: Hardware, Orange: Software.

2.3.2 Firmware TPM

An fTPM [**Raj2015**, **197213**] is executed directly by the CPU within a TEE. This isolates it from the REE, which means that even the operating system in the REE cannot arbitrarily access the memory of the fTPM. The REE can only send commands to the fTPM via controlled interfaces. These commands are piggybacked by calls from the REE to the fTPM in the TEE. The trend is moving towards fTPMs, which can also be seen by the increasing efforts to bring an fTPM to the RISC-V processor family [**Boubakri2021**].

As of now, a fTPM is strictly bound to the processor manufacturer, such that you can trust the underlying firmware as well which is provisioned by the manufacturer, e.g., Intel, too. For example, common implementations are the Intel® Platform Trust Technology (Intel PTT) [**intelProcessorSecurity**], and AMD's Secure Processor (AMD-SP), with the latter being an Arm-based coprocessor on the die with Arm's TrustZone [**Khalid2020**]. Running on the main processor, e.g., a fully-fledged Arm Cortex core, entails advantages and disadvantages.

A disadvantage is that running on the same processor as the rest of the system means less isolation from the remaining system, while a dedicated TPM (dTPM) brings its own processor, memory, and storage that is completely isolated from the main system. Also, fTPMs cannot provide true RNG, since hardware is required for that [**Stipcevic2014**]. Furthermore, they are started later in the host's boot chain than a dTPM that is accessible from the beginning. This has the consequence that the

measurements of the components booted before the fTPM have to be cached and later be forwarded to the fTPM as soon as it is available. Arm's Trusted Firmware-A[3], which is the Arm's reference implementation of software in the TEE, protects this cached event log by keeping it in secure memory [**tf-a-measured-boot**], i.e., memory which is only accessible in the TEE. Last, fTPMs depend on more components for its security than single-component dTPMs, e.g., the hardware-provided isolation between the REE and the TEE, and the boot chain.

However, since they require only a TEE which is mostly already available at currently used processors, they are cheaper for manufacturers as they require less extra hardware. In addition, TPM processors are weak [**Goh2013**, **Raj2015**]. Raj et al. [**Raj2015**] and Cheng et al. [**Cheng2020**] independently concluded that firmware TPMs executed on main processors are generally much faster than dTPMs. They are also a viable option for adding TPM functionality to older devices through software updates rather than hardware replacements, which is particularly valuable in times like the recent chip supply shortage [**Voas2021**, **casper2021**].

2.3.3 Virtual TPM

A vTPM is a software-based TPM provided by a hypervisor for one of its managed virtual machines [**268868**]. The vTPMs can be realized fully in software [**268868**], or backed by dTPMs [**Liu2010**]. The hypervisor can provide a (theoretically) unlimited number of vTPMs. For the virtual machines it seems that they have exclusive access to their own private TPM, even though all vTPMs are managed by the same hypervisor. A characteristic feature of virtual resources are their migration capabilities, i.e., they can be suspended and later continued on another machine. Virtual TPMs support this as well. Note that a vTPM does not inherently have its own security properties, but that these depend entirely on the vTPM implementation of the hypervisor.

2.4 Secure Boot and Measured Boot

When the system is started, the root component, e.g., from ROM, is executed. This subsequently launches the next component, and so forth. This boot structure is called the boot chain. Typically, the first component turns on the memory, the second stage initializes the platform, and finally, the last stage boots the operating system [**Yao2020**].

Secure Boot [**Hendricks2004**, **UEFI**, **Frazelle2020**] is verifying components of the boot chain directly at boot-time. For that, the boot component is equipped with a public key. With that, they verify the digital signature of the respective subsequent

[3] `https://www.trustedfirmware.org/`

component, before handing over the execution. This ensures the authenticity of the boot components. Alternatively, merely the hashes of the components can be measured and compared with known values, which only ensures integrity and not authenticity. The first boot component, usually stored in ROM, needs to be trusted without verification, i.e., it acts as the root of trust. However, Secure Boot does not prevent downgrade attacks, since only the authenticity, but not the concrete versions of boot components are verified [**272306**]. Hence, further defenses like Measured Boot have been designed.

Measured Boot [**tcgMeasuredBoot**] is a concept that is implemented in interplay with a TPM. It allows remote attestation to a later time. Just as with Secure Boot, each boot component hashes the subsequent component. However, instead of directly locally verifying the measured value, the hash value is passed to the TPM to extend a PCR value. As described in Section 2.3, these values can be used by a remote attestor to verify the state of the software on the system. The goal is to detect manipulated system configurations.

Secure Boot and Measured Boot are often used in conjunction.

2.5 Device Identifier Composition Engine

DICE was originally proposed by Microsoft as part of their Robust Internet-of-Things (RIoT) architecture [**England2016**]. In 2017, the DICE specification was published by TCG [**tcg-microsoft-tpm**], of which Microsoft is a member. Its purposes are to detect firmware tampering and enable device identification for a remote party, while its main attribute is its minimal hardware requirements.

DICE operates on a boot process layered into components [**dice-layering-arch**]. Later components are typically more feature rich and complex than earlier ones. Each component is measured prior becoming active by the preceding component. Great care must be taken to ensure that the identity of the measured and thereafter executed component is consistent [**Hristozov2022**, **Carpent2018**]. The union of all security-relevant components of a device form its Trusted Computing Base (TCB). Their identities are called TCB Component Identifier (TCI). They are usually the hashes of the according firmware binary, but could also consist of a hardware product identifier.

The first component is the DICE itself, which consists of software and hardware. The DICE specification [**dice-hardware-reqs**] states the three hardware requirements, the DICE layer

1. has to store a read-only Unique Device Secret (UDS),
2. has exclusive access to the UDS,
3. and is immutable.

These requirements can be justified intuitively. (1) The UDS must be read-only and unique to the device to enable a base for long term identification. (2) The DICE layer reads and uses the UDS, and then needs to erase the UDS from memory while preventing other components from retrieving this secret during the power-on time. Otherwise, other entities can forge measurement or identification values. This lock mechanism can, for example, be realized with eFuses **[dice-hardware-reqs]**. (3) Moreover, the misbehavior of the DICE layer cannot be detected since it is not preceded by anything that could measure it, i.e., it is the root of trust. Therefore, it must be immutable so that it remains in the trusted state in which the manufacturer provided it.

While the UDS is exclusive to the DICE layer, each other component retrieves a Compound Device Identifier (CDI) from its previous component. The CDI of each layer depends on two variables combined in a one-way function (OWF). (i) The own TCI, binding the CDI to the current layer's identity, i.e., the hash of itself, and (ii) the CDI of the previous layer, making each CDI depending on the identities of all previous component identities. Therefore, if any component is modified, this reflects in the permutation of the CDIs of all subsequent components, as implied by Equation 2.2.

Just as the DICE layer must ensure to have exclusive access to the UDS, each later layer must ensure to have exclusive access to its CDI. The layers can derive further secrets using their CDI as a seed, such as the Device ID key pair (Equation 2.3) or an alias key pair (Equation 2.4).

$$CDI_n = \underbrace{UDS \circ TCI_0}_{CDI_0} \circ \ldots \circ TCI_n \tag{2.2}$$

$$DeviceID\_KeyPair = KDF(CDI_0) \tag{2.3}$$

$$Alias\_KeyPair_n = KDF(CDI_n) \tag{2.4}$$

where $a \circ b = OWF(a, b)$, $\circ$ being a left-associated operator, and KDF being a key derivation function.

The end result of a boot process using DICE is a certificate chain, which can be also seen in Figure 2.6 and Equation 2.5. Here, each certificate represents a layer by embedding the identity of the layer, i.e., its TCI. The certificate chain is built up step by step during the boot process, with the first two certificates (manufacturer certificate and DeviceID certificate) being static and stored on the device, and the remaining certificates (Alias certificates) being generated during boot time.

$$Manufacturer\ Cert \rightarrow DeviceID\ Cert \rightarrow Alias\ Cert\ [\rightarrow Alias\ Cert]^* \tag{2.5}$$

The chain's root is the certificate of the DICE manufacturer. It is either provided by the device or can be retrieved from the manufacturer itself, e.g., via its website.

The next certificate is the DeviceID certificate. It is generated during device provisioning by the manufacturer, and signed by the manufacturer's private key. This links the DICE implementation to a manufacturer, which is important to retrieve the guarantees the manufacturer conducts for its DICE implementation to protect its UDS value, which is the hardware root of trust. This certificate also represents the long term identity of the device. The UDS alone cannot be used for this because it is kept strictly secret, whereas the DeviceID certificate is public. Since thereby the identification relies on asymmetric cryptography, the manufacturer does not need to maintain a database of UDS values, but only needs to keep and protect its private key.

While the DeviceID's public key is publicly stored on the device as part of the DeviceID certificate, the corresponding private key still must be generated during the boot process. Only if the matching private key is generated, which is only the case if the identity of layer 0 did not change, the certificate chain can be continued. This continues the chain of trust, because if layer 0 changes, the DeviceID's private key also changes. This invalidates the signature of the next certificate for the public key in the DeviceID certificate.

The remaining alias certificates in the chain each represent the identity of a layer. Recall that a measurement is always conducted from the previous component. Hence, the previous component also has to create the AliasCert, since the just measured component is not trusted to do that. Each DICE layer must only assume the lower layers to be trustworthy. Measured TCIs are persisted in alias certificates signed with the private key of the measuring layer.

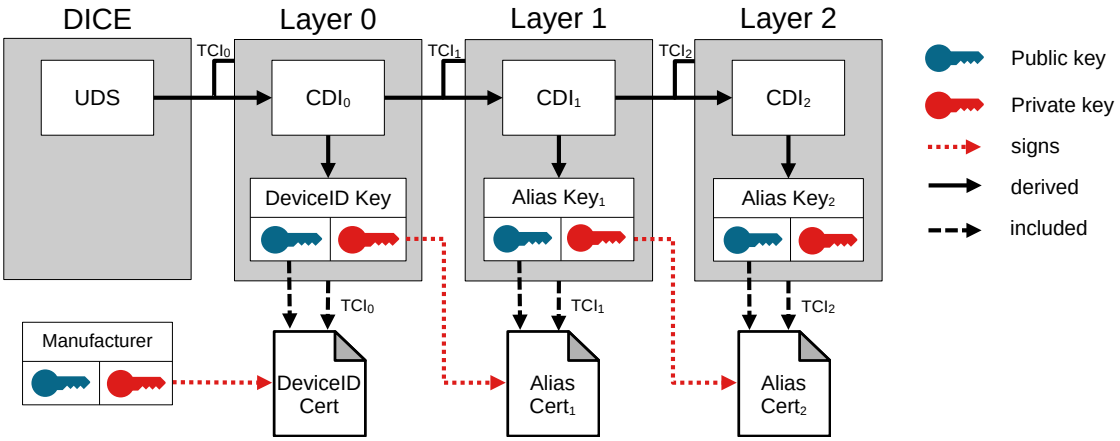


Figure 2.6: The generation of the CDIs and the certificates for each layer in a DICE architecture. Note that the diagram could be continued for an arbitrary number of layers.

The generation of the CDI values and certificates are shown in Figure 2.6. There, the CDIs and certificates are drawn where they are eventually used or what they represent, not where they are created. E.g., CDI_n and Alias $Cert_n$ are both created by layer $n-1$.

To the best of our knowledge, DICE is so far considered a secure concept apart from physical attacks, only implementation problems can bear security problems [**Jaeger2020**, **Hristozov2022**].

3 Related Work

3.1 Attacks on TPMs

3.1.1 Dedicated TPM

The well-known 'TPM Reset Attack' was independently described in [**kauerBernhard**, **sparks2007**]. It requires minimal hardware, precisely only a wire connecting the reset line of the LPC bus [**lpc**] to ground. This results in a reset signal for the TPM, yielding predictable values for the PCR registers. This allows an attacker to replay the measurement log of a benign boot process to achieve valid PCR values, even though a modified chain has been booted. Since TPM 1.2, TCG provides a mitigation specification for this reset attack [**tcgResetFix**], requiring the BIOS to overwrite sensitive data after each unexpected reset, preventing an attacker to gain a valid measurement log. However, this mitigation is still vulnerable to cold boot attacks [**Halderman2009**, **Winter2013**].

Winter and Dietrich [**Winter2013**] demonstrate a bus modification attack at TPMs integrated with the LPC bus or the I^2C bus. Their approach, labeled 'Active LPC frame hijacking', allows them to "lift" commands to a higher locality than the one they were originally sent with. This allows them to evolve the 'TPM Reset attack' from being only usable for S-RTM, to also D-RTM systems. They also introduce a new approach of circumventing the TPM's measurement feature. Instead of resetting the TPM as previously described [**kauerBernhard**, **sparks2007**], they reset the main device, i.e., the user's device like a desktop PC while preventing the TPM from receiving the reset signal. This keeps the state of the TPM, e.g., the valid PCR values of the previous boot procedure, and the attacker can hijack the boot procedure triggered by the platform's reset and boot a malicious operating system or firmware, while the TPM still stores the old and valid PCRs. While its conceptually easier since the attacker does not need to know the measurement log since the valid PCR values are already in-place, it requires active manipulation of bus transmissions to shield the TPM from the reset signal.

Seunghun Han et al. [**aBadDream**] report two attacks on discrete TPMs to reset the PCR registers. The first targets a gray area in the power management section of the TPM 2.0 specification. The TPM shall store its state into its non-volatile random access memory (NVRAM) before shutting down when the host platform goes to sleep,

and restore it when it wakes up. However, the specification is missing a concrete description how to handle a lack of a stored state when waking up. Therefore, some implementations simply reset the state. Their second attack targets a DRTM, namely an implementation flaw in tboot [**tboot**], the most widely used measured boot environment used with Intel's Trusted Execution Technology. However, in their work, they found that some mutable function pointers are not measured, which allows attacks.

A time-based side-channel attack [**Moghimi2019**] during signature generation based on elliptic curves allows an attacker to recover 256-bit private keys for ECDSA and ECSchnorr signatures.

A passive sniffing attack is shown in [**Kursawe2005AnalyzingTP**]. It is applicable to TPM 1.1 connected to an LPC bus. They observed that the data of some operations like unsealing are transmitted via the bus in plain text. Since TPM 1.2, however, the modules no longer send sensitive data unencrypted [**Winter2013**].

That invasive hardware attacks against dTPMs are possible was already shown by Tarnovsky in 2010 [**tarnovsky**]. However, this requires a lot of time, knowledge and resources, i.e., hardware and money.

3.1.2 Firmware TPM

As seen in the previous section about discrete TPMs, the bus between the CPU and a TPM is a typical attack vector. An fTPM circumvents this by being directly executed by the CPU within a TEE, revealing no easily accessible bus.

Of course, there are also attacks against fTPMs. The previously mentioned side-channel attack [**Moghimi2019**] against dTPMs, can also be applied to fTPMs.

Jacob et al. [**Jacob2023**] target proprietary AMD fTPMs by attacking their TEE, namely the AMD Secure Processor (AMD-SP). Thereby, they can expose the full internal state of the fTPM bypassing any authentication mechanisms. To do so, they leak the secret key from the BIOS flash chip which is used to derive the encryption and signature keys for the fTPMs non-volatile data. They achieve this by using a voltage fault injection that bypasses the authenticity check in the host's boot process and allows them to boot their own firmware component that leaks the required information.

Cfir Cohen from Google's cloud security team has uncovered an attack on fTPMs that run within AMD-SP [**cohen**]. They store a maliciously crafted payload — a certificate — on the fTPM and trigger a function with a stack-based overflow error that accesses this payload, giving them full control over the program counter.

3.2 Hardening of TPMs

3.2.1 Virtual TPMs

Because of the increasing popularity of cloud computing, the research of vTPMs focuses less on specific attacks, and more on reducing the trusted computing base, i.e., privacy-focused. The initially proposed design [**268868**] has a large trusted base, e.g., the operating system and the hypervisor need to be trusted.

Wang et al. [**Wang2019**] bring the vTPM into the TEE, namely Intel SGX, essentially creating an fTPM and vTPM hybrid. They launch each vTPM in a private hardware-protected enclave. This reduces the trusted computing base to the individual enclaves and SGX itself, enabling the host operating system and hypervisor to be untrusted.

Pecholt and Wessel [**Pecholt2022**] describe a design named CoCoTPM where the hypervisor and the host's operating system do not need to be trusted as well. This is realized by establishing an integrity-protected secure channel with end-to-end encryption between the driver in the VM and the software TPM on the host.

Stateless ephemeral vTPMs [**Narayanan2023**] eliminate the need of manually establishing a secure channel by leveraging the confidential VM memory encryption provided by AMD's SEV-SNP, a variant of AMD secure encrypted virtualization (SEV) technology. Ephemeral vTPMs support the remote attestation of virtual machines. However, they intentionally do not support persistent storage to preclude exfiltration attacks on stored TPM state, which has the disadvantage that persistent keys or nonvolatile indexes cannot be stored.

3.3 Attestation schemes of TPMs

In the following, we describe defense mechanisms for fTPMs that can be seen as complementary to our approach. They all have in common that they offer no way for a third party to ensure that the hardened fTPM is actually running on the device under test, which is exactly what our work aims to cover.

One approach is to verify the code of fTPMs [**Mukhamedov2013**]. Here, the TPM 1.2 code is written in a functional programming language that enables automatic verification.

There exist efforts to improve the security of TPM by introducing the concept of hybrid TPMs [**Kim2019**, **Gross2021**]. Kim and Kim [**Kim2019**] extend a hardware TPM with software support, which they name hTPM. This increases the defense of the TPM, e.g., circumventing side-channel attacks, and also enables more secure TPM functions, e.g., enabling true random number generation. Their hTPM implementation also shows significantly better performance due to the use of modern CPU features.

Vice versa, Gross et al. [**Gross2021**] propose the reverse approach of backing an fTPM with hardware. While their implementation has similar properties to hTPM, it inherits some downsides of fTPMs. For example, their fTPM is still started later in the boot chain than a dTPM, which is not the case for hTPM. However, it is easier to update than hTPM since the lack of a dTPM, and the overall design is simpler.

4 Methodology

4.1 Terminology

Before we dive into technical explanations, we want to clear some potential terminology confusion.

In the original DICE release from Microsoft **[England2016]**, the identifier of a component is called the Firmware ID (FWID). The TCG consortium later renamed it TCB Component Identifier (TCI). We believe this is to emphasize that the TCI does not necessarily have to be the hash of a firmware binary, but could also be, for example, the embedded ID of a hardware component. However, TCG has not fully implemented this terminology renaming. Their DICE Attestation Architecture [**TCGAttestation2021**] defines an X.509 extension that contains the TCIs. They continue to be referred to as FWIDs in the formal definition of this extension, while everywhere else they are referred to as TCIs. In personal correspondence with TCG, we have learned that this is due to backwards compatibility. The old term FWID is retained whenever it is used in something that is alive in the long term, like formal definitions, and the new term TCI in assets that can be updated more quickly, such as the specification text. Therefore, we will use the term TCI in this theoretical chapter, and in the implementation chapter (Chapter 5) we will use the term FWID, just as it is common practice at the TCG. This ensures that the explanation of our implementation better matches the actual code, where FWID is the term as it is used by automatically generated code.

4.2 Architectural overview

The architecture of our proposed and later implemented system is illustrated in Figure 4.1. As you might notice, it is similar to our overview picture of DICE (Figure 2.6). This is to be expected, since our system uses DICE. We leverage the DICE as our static root of trust for measurements (S-RTM). Static in this context means that it uses the trusted state that a device has at the always same point in time, here after switching on, for further measurements. This is in contrast to a dynamic RTM (D-RTM), which is able to do this at any time, e.g., Intel SGX.

The boot process continues from here in the usual DICE manner until the firmware

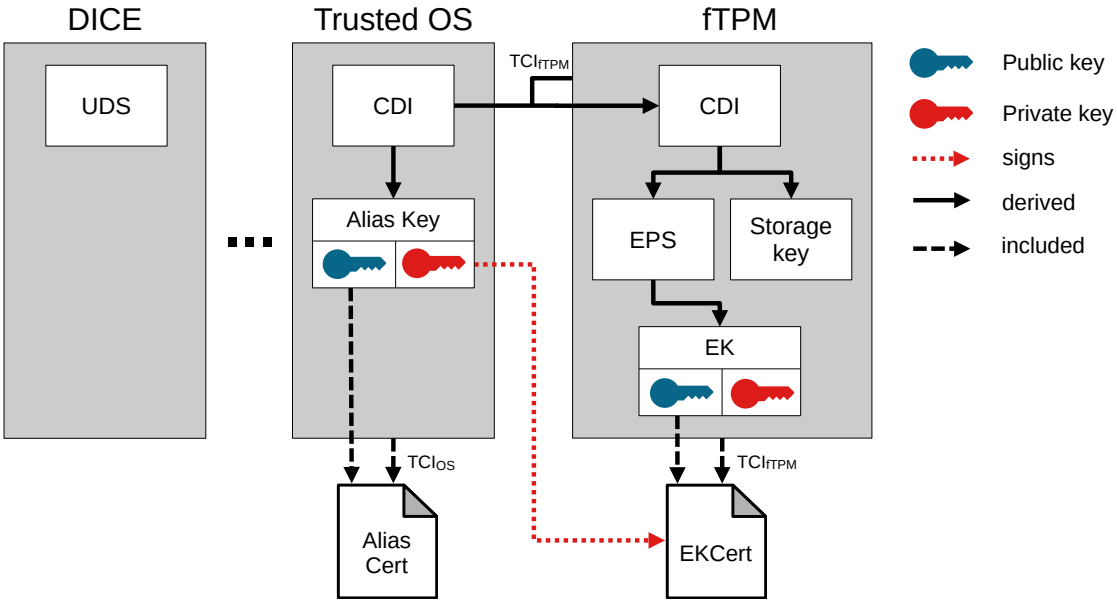


Figure 4.1: The architecture of our system.

TPM is reached. The component that measures the fTPM is usually the trusted operating system running in EL1 in the secure world, as seen in Figure 2.2. Like any other DICE component, the fTPM receives its secret Compound Device Identifier (CDI) from its predecessor layer. Recall that the CDI is tied to the identity of the fTPM including the entire underlying firmware stack and the UDS. Two values are derived from the CDI.

First, the storage key is generated. This is a symmetric encryption key that is used to encrypt the fTPM storage space in RAM before it is written to a persistent storage space such as a hard disk drive (HDD). At no time does the HDD see plain text data (Figure 4.2). Since the storage key is derived from the CDI, the old storage data is inaccessible if the identity of the TPM changes, e.g., due to a TPM modification or an update of a previous firmware component, which results in a full manufacturer reset of the fTPM. This enables the property that an fTPM storage must never be accessible to another TPM. Note that an attacker could thereby easily trigger a data loss. This must be avoided by integrating the good-practices with working with a TPM, which includes having secrets stored also elsewhere. Microsoft recommends backing up all secrets stored on the TPM before clearing it [**MicrosoftClearRecommendations**], what can be generalized to the backup of the fTPM data in all cases where data loss causes serious damage.

Establishing the storage key also prevents an attacker from accessing an fTPM's data by downgrading the fTPM. For example, if an attacker wants to access data stored in a

particular fTPM and can exploit a vulnerability of an earlier version of that fTPM, it is not possible to replace the fTPM with its old version, as neither the attacker nor the fTPM itself will be able to decrypt the previous data.

However, it does not protect against the isolated downgrade of the fTPM itself or solely its data. When the fTPM is downgraded, as previously described, the data is reset. Nevertheless, new data generated by the downgraded TPM might still be leakable by vulnerabilities of the downgraded fTPM. Our storage key also does not protect the fTPM data from a rollback attack, i.e., the freshness of the fTPM data is not guaranteed. This attack can be attractive for malicious actors to reset the try count of PINs to work around the lockout mechanism of the TPM. Another example is to restore the data wherein a secret was stored, however, not yet protected by a PIN. The protection against the rollback of fTPM data or the fTPM itself can be achieved by storing them in a Replay Protected Memory Block (RPMB) partition [**eMMC**, **UFS**]. For this reason, an RPMB partition is part of Microsoft's hardware requirements for a firmware TPM [**Raj2015**].

Only the TEE can write to the RPMB (authenticated write). And the TEE can ensure that received data really originates from the RPMB (authenticated read). Each command is unique due to a nonce (for read operations) or a write counter (for write operations), which prevents replay attacks. The secure channel to the RPMB is established by a secret key shared between the TEE and the RPMB. Hence, every component within the TEE can arbitrarily access and modify the data on the RPMB, and must therefore be trusted. This is different to our approach with the storage key, whereby we bind the access to the data to the identity of the fTPM, i.e., we trust only the identity of the fTPM instead of the entire TEE. In other words, we seal the data of the fTPM with the identity of the fTPM instead of allowing the entire TEE to access the data at any time. However, RPMB and our storage key are orthogonal and can be used in conjunction.

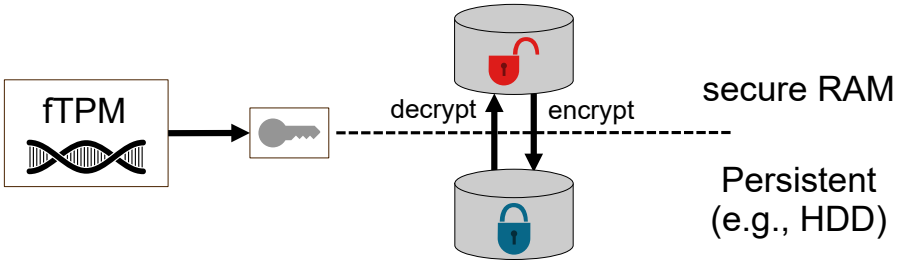


Figure 4.2: The fTPM's storage is protected by a key derived from its identity.

Then, the endorsement primary seed (EPS) is generated based on the CDI. It is the seed that is used to generate the primary endorsement key (EK). A primary key in the sense of the TPM means that it has no parent key, but a parent seed, here the EPS. The

indirection of generating the CDI via the EPS instead of generating the EK directly from the CDI is introduced because the code of fTPMs can be hardcoded to use the EPS during EK generation. And we want our system to require as few modifications to TPM code as possible.

The EK of a dedicated TPM represents the long-term identity of the device as long as the TPM is not soldered away. Our EK does not do this because a firmware TPM is software-based and changes every time the fTPM or the underlying firmware is modified, without the host device changing. Instead, we use the DICE for this, which is hardware-based. Its DeviceID key, as the name suggests, represents the device identity. Note that the DeviceID contains the identity of layer 0 of the boot chain, i.e., the first mutable code. This can also be seen in Equation 2.3. For this reason, the DICE specification suggests keeping the first mutable code as small as possible so that it remains constant throughout the life of the device [**dice-layering-arch**].

By default, the EK is a restricted encryption key. It is not used for signing because the resulting signatures may reveal the TPM's identity. Therefore, the usual procedure is to create a short-lived attestation key (AK) on the TPM. The verifier communicates the public part of the AK to a third party privacy CA who ensures that the holder of the AK is the same as the holder of the EK. The privacy CA then issues an attestation certificate confirming that the AK originates from a genuine TPM, without revealing the identity of the TPM. Finally, the AK can be used by the TPM to sign attestation evidences in a private fashion. We waive this separation and use the EK directly for attestations to avoid the need for a third party CA.

The DICE and the TPM infrastructure intersect at the EK certificate. From the DICE's point of view it is an alias certificate, from the TPM's point of view it is the EK certificate.

4.3 The identity of a firmware TPM

DICE offers two identities for each component. The TCI and the CDI. As shown in Equation 2.2, the CDI of a component changes when (i) the identity of the hardware changes, i.e., the UDS, (ii) the identity of a preceding component changes, or (iii) the component itself changes. In contrast, the TCI is the identity of a single component, considered in isolation, usually the hash of its binary. It only changes when the component itself is changed, regardless of the hardware or preceding components. So, while a CDI should be statistically unique since it is derived from a UDS with this property, a given TCI can be found on many devices if they contain exactly the same software component. Note that the TCI is part of the CDI, as shown in Figure 4.3.

Hence, we decided to derive the identity of an fTPM, i.e., its EK, ultimately from the

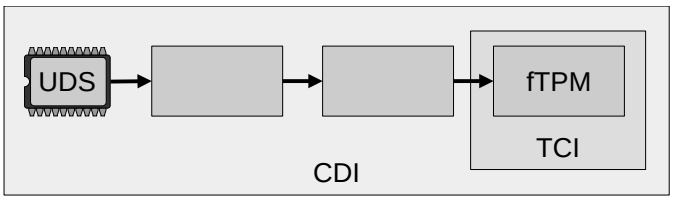


Figure 4.3: Visualizing the difference between the CDI and the TCI from the perspective of an fTPM component. The identity of the hardware is provided in the form of the UDS.

CDI. This binds the identity of the fTPM to any security-relevant component preceding it. The rationale for this is that once a previous component has changed, it is unknown whether it has gone into a benign or malicious state. And if it is malicious, it could change the firmware TPM and thereby access its sensitive material such as private keys. Although this is later recognized by the verifier during remote attestation, sensitive data could still be leaked. If the identity of the firmware TPM is extended to everything prior to the fTPM, its data is no longer accessible as soon as something preceding it changes. This is due to the derivation of the storage key from the CDI. And this behavior should also be reflected in the EK, so that the storage key and the EK should always change together or not change at all.

The TCI (and thus the CDI too) must also represent security-relevant configurations. Compilation flag configurations are already inherently part of the TCI, as they are embedded in the final binary and are therefore automatically measured as part of the measurement of the binary. Of more interest are the configurations that are not part of the binary. They are usually provided in well-known formats such as `json` or `xml`. However, Microsoft's fTPM reference implementation does not contain such configurations, which simplifies the TCI generation of our fTPM by limiting it to the measurement of the fTPM binary data. The TPM's storage cannot be part of its identity as it changes during runtime after each data write, e.g., storing an arbitrary key. This is a problem because DICE only runs during the boot time in which the identity of the fTPM is measured. The identity of the fTPM must not change afterwards, otherwise the identity reported by DICE and the actual identity of the fTPM would be inconsistent. We also do not want to restrict the permissible values of the working data of an fTPM.

4.4 Attestation process

EKpriv = private portion of EK EKpub = public portion of EK EKcert = certificate with EKpub as subject

We use an explicit attestation procedure. This makes it sufficient for the verifier to know its trusted TCIs, whereas implicit attestation would require a database of trusted Alias public keys representing a trusted component. And since each Alias public key is device unique, as it roots in the device's unique UDS, the verifier would need to know all Alias public keys for each component on every device he trusts, which we consider unrealistic. Also, this would be a hindrance as the verifier should be able to establish trust into an unknown device by trusting the DICE manufacturer, and knowing the identities of trustworthy firmware.

4.4.1 Does the verifier trust the prover's fTPM?

It is exactly the purpose of our system to make this question answerable for the verifier. First, the verifier needs to verify whether the signatures of the DICE certificate chain are valid, and that the root certificate from the manufacturer is considered trusted. This also involves checking if the manufacturer certificate or the Device ID certificate was revoked. Such an event might occur if the security of an old DICE implementation is broken, and the manufacturer wants to reflect this. Then, the verifier can traverse the certificate chain starting from the root and verify whether each component represented by a certificate is trusted, by checking the embedded TCI. An untrusted component must be assumed to lie about its conducted measurements. For example, it can modify the subsequent component without reflecting this in the measurement of the TCI. Consequently, as soon as a component is untrusted, all subsequent components have to be considered untrusted as well. This behavior is also represented mathematically in Equation 4.1. Therefore, trusting the fTPM requires to trust all underlying firmware components.

$$C_{i,\,trusted} \coloneqq \bigwedge_{k=0}^{i} trusted(C_k) \tag{4.1}$$

After doing this, the verifier can only state that "I trust the certificate chain and the components of *some* machine represented by it." This is due to the possibility of any actor to simply replay the certificate chain. But we need to promote the *some* to *the machine I communicate with*. This is solved in higher level protocols where the prover is required to be in control of the private part of the EK which corresponds to the EK of the EK certificate, e.g., this is answered as part of whether the verifier can trust the quote. Hence, the verifier also needs to trust that the fTPM did not leak the EK private key, as this would not only allow to replay a whole certificate chain, but even succeed the higher level protocols with the leaked EK private key. The verifier can derive whether it considers the EK private key of the fTPM as not leaked based on the

fTPM's TCI value, as one requirement of trusting a TCI must be whether the verifier considers the component to keep its security guarantees.

Example security policies for a component

The *trusted* function of Equation 4.1 checks the information provided by a certificate C against security policies defined by the verifier. In the following, we would like to present some example policies for improving comprehensibility for the reader.

- We generally do not trust the component's manufacturer and therefore, do not trust the component.
- The component is up-to-date, and there are no known vulnerabilities and therefore, we trust the component.
- The component is outdated, but all updates are only functional instead of security-relevant, so we still trust it.
- We do not know the TCI of the component. We follow a 'Deny by default' policy. Therefore, we do not trust the component.

4.4.2 Does the verifier trust the quote from the prover's fTPM?

For that, the verifier needs to know that the quote was signed with the restricted EKpriv corresponding to the EKpub in EKcert, and that the fTPM is in control of EKpriv.

The verifier sends a nonce, which the receiving prover includes in the quote request sent to the firmware TPM, i.e., `TPM2_Quote`. The nonce prevents replay attacks. The verifier also needs to know that the EK is restricted. Otherwise, a compromised prover could generate quotes representing arbitrary states which do not represent the prover's actual state.

Usually, this is ensured by the manufacturer in that he only signs the EKcert for a restricted EK. Of course, this cannot be applied to our solution, as our EKcert is dynamically created without a TPM manufacturer asserting specific attributes of the EK. Instead, we use the fTPM's TCI embedded in the EKcert to allow the verifier to be ensured that the EK is restricted. For the EK's attributes to be represented the TCI, the template containing the EK's attributes must be generated in the firmware TPM's code. And, the verifier must only trust fTPM TCI's which have the restricted attribute of the EK baked in code.

4.5 Combining TPM and DICE infrastructure

The result of our DICE boot process is a certificate chain, starting with the manufacturer certificate and DeviceID certificate, and ending with the EK certificate. In between can be an arbitrary number of Alias certificates for "ordinary" firmware components (see Equation 4.2).

$$Manufacturer\ Cert \rightarrow DeviceID\ Cert\ [\rightarrow Alias\ Cert]^* \rightarrow EKCert \tag{4.2}$$

As stated earlier, the EK certificate is where the DICE and the TPM infrastructure meet. So, this EK certificate needs to fulfill the requirements for an Alias certificate from the DICE specification [**DICE_certs**], and the EK certificate requirements from the TPM specification [**tcg-ek**]. Therefore, we need to ensure that these two specifications declare no conflicting requirements. DICE [**DICE_certs**] defines the requirements for various certificate types. Our certificate is referred to as an attestation certificate in their specification.

We only consider restrictions for the X.509 fields that are absolute requirements, i.e., declared as "MUST" according to RFC 2119 [**Bradner1997**], and common fields that can occur in both specifications. In general, the EK certificate specification "does not preclude the use of other certificate extensions." The alias certificate specification leaves this undefined, i.e., it makes no statement whether this is permitted or prohibited. However, it is irrelevant for us, since the EK certificate specification does not define any own X.509 extensions. The requirements about the certificate's validity depend on whether the measuring firmware has access to a secure real-time clock (SRTC) containing the absolute physical time. We assume the firmware to not having access to an SRTC, keeping the requirements low. The restrictions of our certificate also depend on its further usage. It is a leaf of the certificate chain. Therefore, we do not consider requirements for a certificate representing a certificate authority (CA) signing further certificates.

We present the result of our compatibility study in Table 4.1. In summary, there are mostly no conflicts since both certificates expect the same value, both requirements can be satisfied with the same value, or only one of the certificates dictates a restriction for a specific field.

The only conflict is in the subject name. An Alias certificate must either identify the TCB class (general) or instance (specific), an EK certificate allows only a value uniquely identifying the TPM (specific) or empty otherwise. So, a general term like "fTPM" is prohibited by the EK certificate specification, and an empty subject by the DICE specification. The only common denominator is a unique identifier. However, that is already part of the TCI embedded in our EK certificate. We chose to favor the

Table 4.1: Comparing the requirements for an Alias and endorsement key certificate. If not otherwise stated, the source of these requirements are the previously noted specifications, i.e., [**DICE_certs**, **tcg-ek**]. The upper half contains basic certificate fields, and the lower half certificate extensions.

Field	Alias Cert	EK Cert	Conflict
Version	3	3	No
Subject name	identify TCB class or instance	Uniquely identify TPM or empty	Yes
Issuer name	embedded CA issuing the certificate	entity that vouches that TPM is genuine	No
Validity not before	Known time in recent past e.g., build time	–	No
Validity not after	No expiration	No expiration for non-user TPMs [**tcgPcClient**]	No
Authority Key Identifier	–	Must be present	No
Key Usage	keyCertSign unset	digitalSignature set	No
Certificate Policies	Local Attestation	At least one policy	No
Basic Constraints	–	Not a CA	No

EK certificate specification here, and leave the subject name empty. This ensures that the EK certificate is also as expected for systems that do not know our solution and do not know the TCI part of the certificate. It also seems to be common practice, since all endorsement certificates we observed have an empty subject name. This should not be regarded as representable, however, since the sample size is three.

The Subject Alternative Name extension is required to contain the TPM Manufacturer, model, and version by the EK certificate specification [**tcg-ek**]. It is assumed that the EK certificate is generated by the manufacturer who has this knowledge about the TPM. In our system, however, the DICE layer measuring the firmware TPM and ultimately generating the EK certificate does not know these values, as they are not constant and can change any time when the firmware TPM is exchanged. One possible solution is to keep these values in the metadata of the fTPM's binary, which the preceding layer can read and embed in the certificate. But this increases the complexity and the maintenance burden for the firmware TPM, which is usually not required since all this information (manufacturer, model, version) can be deduced from the TCI part of the certificate. Therefore, if a verifier trusts a TCI, he should also know which manufacturer, exact code and TPM specification it conforms to. Furthermore, the TCI is more accurate and reliable because it is an exact independent measurement of the firmware TPM rather than relying on information propagated by the manufacturer. For example, an underlying firmware component could alter the firmware TPM to pretend it is compliant with a newer specification (with potential security updates) than it actually is. This cannot happen with the TCI, which is part of the certificate chain, as this malicious firmware component would be detected as long as it is not the first DICE layer. To still fulfill the EK certificate specification, we suggest to use general terms. For example, the manufacturer could be defined as "DICE", the model as "FW", and the version as TPM 2 compliant, whereby the minor version is not specified, i.e., zero.

4.6 Updating the fTPM

We consider it as critical that the fTPM is updatable. This is due to the history of fTPMs showing vulnerabilities which have been patched consequently. Our fTPM can be only updated with the system shut down. This ensures that the TCI part of the EKcert generated at boot-time does not become obsolete, in other words, keeps representing the state of the currently running fTPM.

The code of the fTPM is replaced during an update. The fTPM therefore retrieves a new CDI and then a new storage key. The old data can therefore no longer be accessed, which effectively leads to a manufacturer reset.

This mechanism is common practice as this is also described in the manuals for

TPM upgrades by Lenovo [**LenovoTpmUpgrade**] and Intel [**intelTpmUpgrade**]. It is underpinned by the importance of pausing BitLocker before upgrading a TPM due to its upcoming data loss [**BitlockerTpmUpgrade**]. Thereby, the encryption key is temporarily stored in plain text on the hard drive, which is consequently restored on the TPM after its update.

4.7 Privacy

First, we elaborate what reveals the identity of the device when conducting a remote attestation, and then suggest a modification to our architecture to integrate privacy.

In an ordinary remote attestation process with our system as described in Section 4.4, the verifier retrieves the certificate chain and a TPM quote. After the root certificate, the certificate chain is continued with the DeviceID certificate, whose subject key provides the long-term identity of the device. It then continues with Alias certificates, each of which contains subject keys that represent the identity of the hardware and the firmware components that have already been executed. The closing EK certificate of the chain contains the key representing the identity of the fTPM. The quote's signature is also relevant to the prover's privacy, as the signature is generated with a unique EKpriv. Consequently, all these keys have to be hidden to preserve privacy, and the signature of the quote must be generated with a key that does not represent a long-term identity, e.g., with an ephemeral key.

Both is solved by introducing a new key — the attestation key (AK) — which is used for signing the quote. It is created by the prover's TPM, and is an ephemeral key. Hence, the prover can generate any number of attestation keys at any time, e.g., for each remote attestation process. This prevents the correlation of signatures, i.e., the proof that multiple signatures originate from the same TPM. The AK also has to be certified to originate from an authentic TPM, just as the EK. In contrast to certifying EKs, manufacturers cannot be called upon to vouch for AKs. This is because if they certify an AK, the manufacturer of the TPM (or rooting DICE) which generated the AK will still be known to the verifier, since the verifier needs to know the manufacturer's certificate. This can be a privacy-relevant information. Instead, we rely on a third-party Certificate Authority (CA), commonly referred to as privacy CA. Also, our EK is changed from a signing key to an encryption key, since signing with the EK can reveal the TPM's identity.

The privacy CA replaces the DICE manufacturer as the root of trust for the verifier. For this purpose, it first retrieves the original certificate chain and an AK from the prover. In a pure TPM system, the privacy CA must verify that the EKcert represents an authentic TPM by verifying the certificate chain and retrieving the manufacturer from

the EKcert. In our system the only difference is that it is about the DICE manufacturer. The privacy CA must then ensure that the AK provided by the prover comes from the same TPM as the EK of the just retrieved EKcert. In short, this works by the privacy CA generating a challenge encrypted with EKpub, which can only be solved with AK. This process also allows the privacy CA to verify that the AK is restricted. The procedure is described in more detail in the TPM specification [**tpm**] under "Attestation Key Identity Certification" and "Credential Protection."

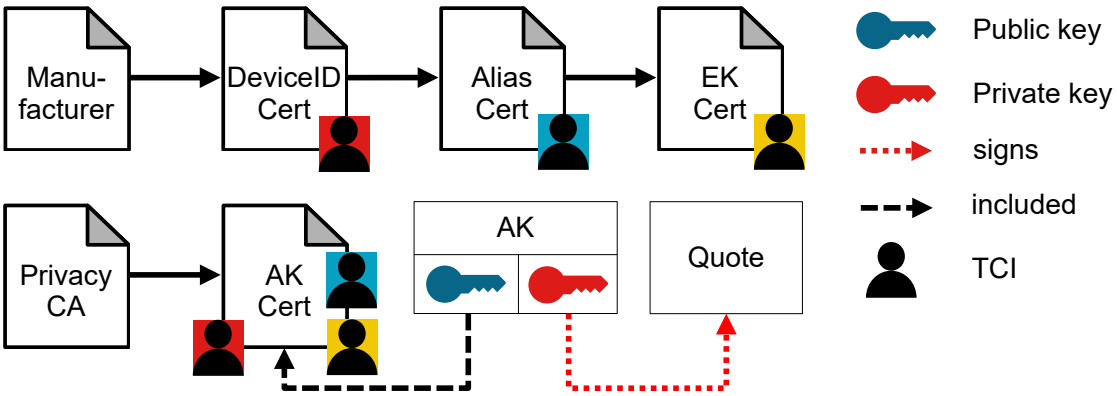


Figure 4.4: The adapted architecture integrating privacy.

We also need to transfer the DICE information from the old certificate chain to the new private one. After performing the formerly described actions, the privacy CA creates a certificate vouching for that the AK was generated by an authentic TPM, hiding which exact TPM, even the manufacturer. The privacy CA also copies each TCI of the old certificate chain into the AK certificate, as depicted in Figure 4.4. The yielding private certificate chain is returned to the prover, who can forward it to a verifier without revealing its identity.

Whether the verifier trusts the firmware TPM is conducted in the same way as described in Subsection 4.4.1, with the only difference is that the TCIs are all embedded into a single certificate, i.e., the AK certificate.

The verifier must also be able to trust the prover's quote as explained in Subsection 4.4.2. For that, he must trust the issuer of the AK certificate that he has verified the properties of the AK, i.e., that it stored on an authentic TPM and restricted.

Ultimately, this adapted privacy architecture changes the statement a verifier can make from "I am communicating with this authentic TPM in control of this EK", to "I am communicating with some authentic TPM in control of this AK." In other words, the verifier does not know exactly which TPM they are communicating with. It is guaranteed by the fact that the prover does not transmit any data derived from its UDS

to the verifier. This protects the privacy of the prover.

Nevertheless, privacy is not fully ensured because of the TCI values revealed to the verifier. The order and values of the TCIs of an AK certificate might be sufficient to identify that it communicated with this particular prover before. This can only be prevented by transferring the evaluation of the TCIs from the verifier to another entity, e.g., the privacy CA. One possible realization is for the privacy CA to add to its policy that it will only certify AKs if they originate from a prover it considers trustworthy based on the TCIs it provided. However, this makes the verifier dependent on another entity that decides whether the TCIs provided are trustworthy or not, which we consider undesirable.

We also want to highlight that the AK does not need to be a child of the EK, it does not even have to be part of the endorsement hierarchy. In fact, it should not be part of the endorsement or platform hierarchy, since the TPM behaves differently when signing a quote depending on the hierarchy of the signing key [**tpm**]. If the signing key is part of the endorsement or platform hierarchy, the TPM assumes that privacy is irrelevant and embeds the TPM's firmware version, reset count, and restart count in plain text in its generated quote. This tuple might identify the TPM. If the key is part of another hierarchy, this data is obfuscated by adding random offsets to each value, which is desirable if privacy is a concern.

5 Implementation

As explained in Section 4.1, from now on the term Firmware ID (FWID) will be used instead of the previously used term TCB Component Identifier (TCI).

5.1 Overview

We run our implementation on Arm's Fixed Virtual Platform (FVP)[1] which is a complete simulation of the Armv8-A architecture including TrustZone.

To do this, we use the software infrastructure provided by OP-TEE for various platforms, including FVP. OP-TEE uses the TrustedFirmware-A (TF-A)[2] package from Arm as firmware boot components. However, we mock their attestation, i.e., their Alias certificates are statically compiled into the binaries instead of being dynamically generated, as TF-A does not implement DICE. The development efforts to implement that exceeds the benefits, as the concept can also be demonstrated with mocked certificates. For that, only the certificates up to the OP-TEE OS are mocked, including OP-TEE OS's private key to sign the subsequent Alias certificate, which is our EKcert.

Our implementation with compilation and running instructions can be found on GitHub[3].

5.2 Boot chain

The boot process is depicted in Figure 5.1. DICE is the root of trust, because incorrect behavior remains undetected and would jeopardize the security of our attestation process.

DICE Theoretically, the boot chain begins with the DICE hardware, but this is not included in FVP. Therefore, we simply assume its presence by mocking the first few certificates of the yielding certificate chain. Furthermore, it is independent hardware, and therefore, neither part of the TEE nor the REE.

[1] `https://developer.arm.com/Tools%20and%20Software/Fixed%20Virtual%20Platforms`
[2] `https://www.trustedfirmware.org/projects/tf-a/`
[3] `https://github.com/akorb/master-thesis-meta`

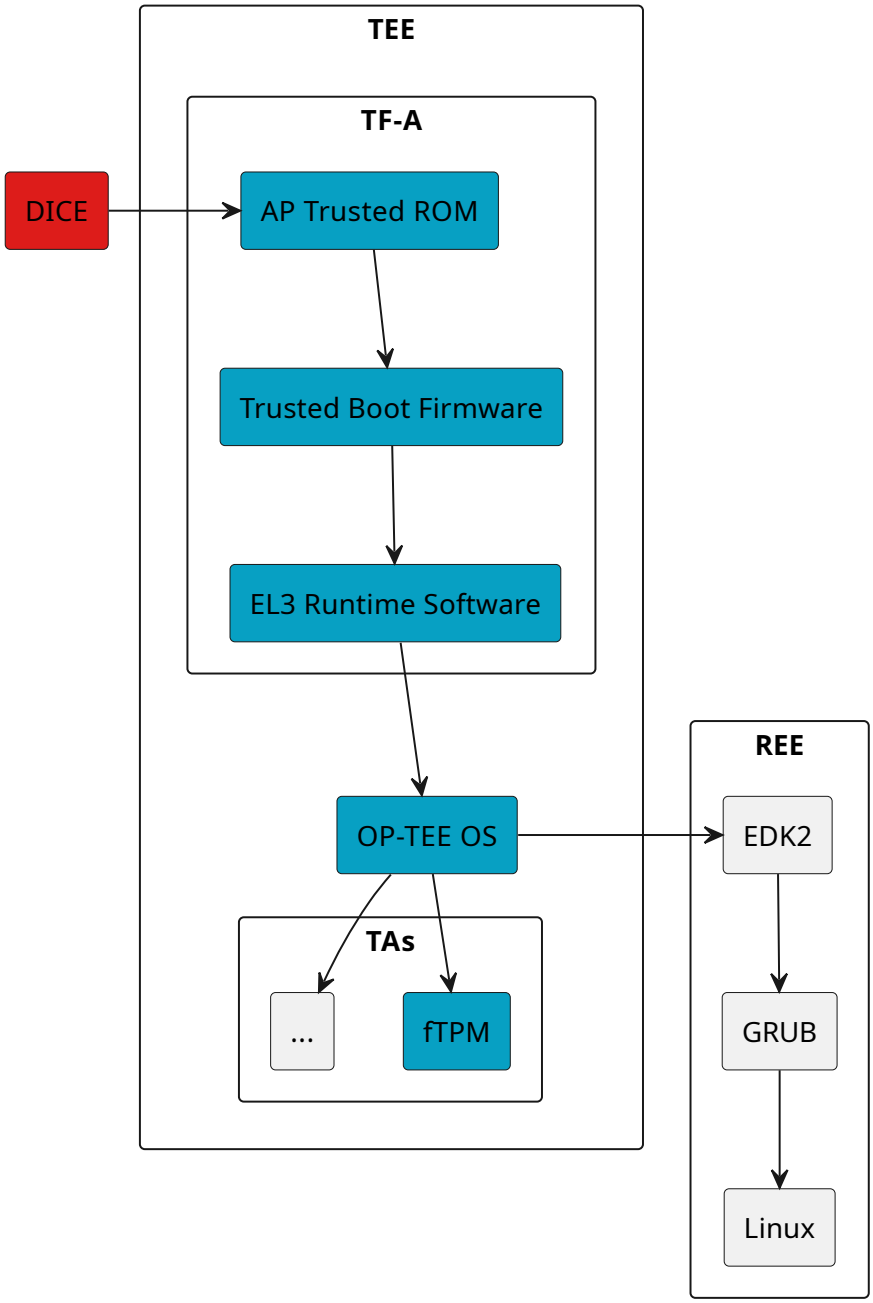


Figure 5.1: The boot chain of our system running in Arm's FVP. Blue: Represented by our yielding certificate chain. Red: Root of trust for verifier, and also just assumed to be present.

TF-A After reset, the CPU executes within the secure world. That is also the reason why machines that are unaware of the separation between secure world and normal world are running in the secure world, as they never modify the execution environment of the processor. This also ensures that TrustZone unaware systems have all expected privileges, which would be restricted in the normal world. The Application Processor (AP) Trusted ROM sets up the platform-specific exception vectors. The Trusted Boot Firmware enables the MMU, performs the platform security setup, and other tasks. The final component of TF-A — EL3 Runtime Software — replaces the simple and rudimentary initialization performed by the AP Trusted ROM with more complete configurations by detecting the system topology, and enabling normal world software to function correctly. The EL3 Runtime Software also provides the monitor which conducts the context switches between the secure world and the normal world. More complete and detailed information can be found in the TF-A documentation[4].

OP-TEE OS Finally, the OP-TEE OS[5] is loaded and executed. Just like an ordinary operating system, it initializes its functions offered to the user space of the secure world, i.e., the trusted applications.

Trusted Applications Our TA in focus is the firmware TPM[6]. It consists of the reference code by Microsoft which implements a TPM, and the stub code, which provides and implements the interfaces required to be a TA of OP-TEE. This fTPM only allows a single connection at any time, i.e., it prohibits concurrent access as this could lead to inconsistent states. This also mirrors hardware TPMs, which are usually attached via serial buses like SPI to the processor. Typically, the only entity that communicates with the fTPM is a Linux kernel module[7], so it is transparent to the user applications whether the TPM is implemented in firmware or hardware. Note that TAs are not started automatically. In fact, we are not aware of any function provided by OP-TEE OS to register a TA to be started during the boot process. Instead, TAs are initialized the first time someone wants to interact with them.

EDK2 TianoCore EDK II[8] is the first component launched in the normal world. It is a reference implementation of UEFI [**UEFI**] by Intel.

[4] `https://trustedfirmware-a.readthedocs.io/en/latest/design/firmware-design.html`
[5] `https://github.com/OP-TEE/optee_os`
[6] `https://github.com/microsoft/ms-tpm-20-ref/`
[7] `https://docs.kernel.org/security/tpm/tpm_ftpm_tee.html`
[8] `https://github.com/tianocore/edk2`

GRUB The GNU GRand Unified Bootloader[9] is a bootloader which is responsible for loading and transferring control to OS kernel software.

Linux As expected, the final component to boot is the Linux[10] operating system.

5.3 Firmware TPM initialization

Initialization begins with the derivation of all secrets from the CDI. Note that we mocked the CDI that would be passed from OP-TEE OS to the fTPM in practice. However, OP-TEE OS does not implement DICE.

We use the Mbed TLS library[11] providing cryptographic primitives for the derivation of the secrets, and also to build X.509 certificates. Mbed TLS is already part of OP-TEE, and its functionality is modular and allows certain functionality to be activated or deactivated at a fine granular level. Since the target machines are embedded devices with limited resources, the user should only activate the functions that he really needs. We therefore had to activate some functions.

The formulas which derive secrets directly from the CDI (Equation 5.1, Equation 5.2) use a keyed-hash message authentication code (HMAC) function. This is inspired by the CDI derivation proposed in the DICE hardware requirements specification [**dice-hardware-reqs**]. Actually, it proposes two functions to combine information to a new secret. A simple hash function, and the HMAC function. It also states that it recommends the HMAC function which calculation takes a little more time, but protects the CDI with twice the level than the simple hash function. This is backed by Jäger et al. [**Jaeger2017**], and NIST SP 800–57 [**Barker2020**]. We declare the inner hash function used by the HMAC according to the required data size of the secret. For example, for storage encryption, we use AES-256, and therefore, use the SHA256 function to retrieve a key with a sufficient size. The HMAC functions are seeded with a fixed character string that describes the purpose of the output secret, e.g., 'EPS'.

$$K_{storage} = HMAC_{SHA256}(CDI,\ 'DATA\ STORAGE\ KEY') \tag{5.1}$$

$$EPS = HMAC_{SHA512}(CDI,\ 'EPS') \tag{5.2}$$

$$EK = KDF(EPS,\ EK_{template}) \tag{5.3}$$

We must ensure we retrieve exactly the same EK as the TPM would generate by a `TPM2_CreatePrimary` command with our EK template. Therefore, we use the TPM

[9] `https://www.gnu.org/software/grub/`
[10] `https://www.kernel.org/`
[11] `https://mbed-tls.readthedocs.io/en/latest/`

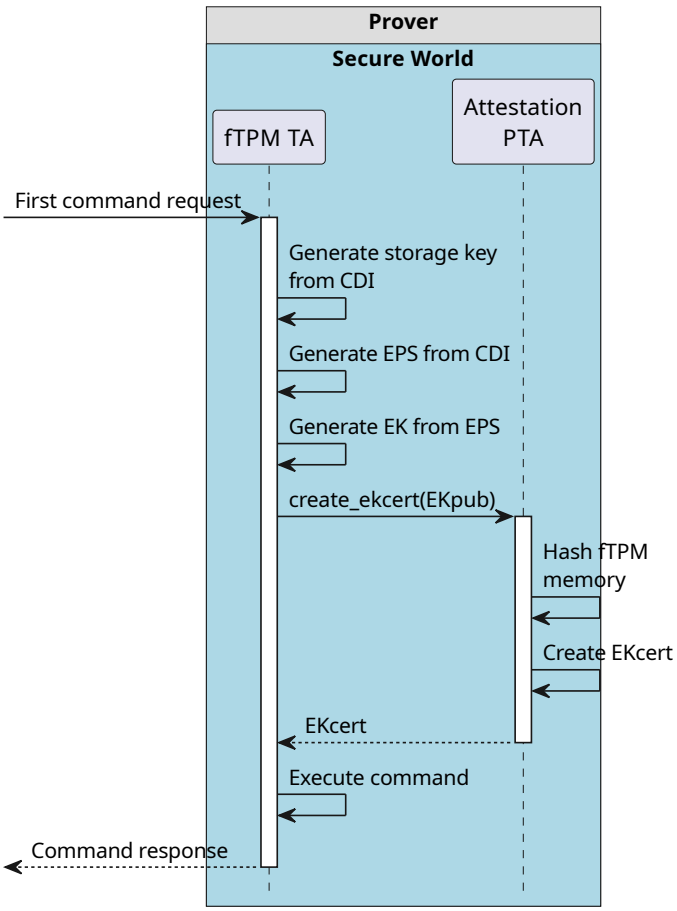


Figure 5.2: A UML sequence diagram describing the initialization of our firmware TPM.

internal functions to generate the EK. The EK consists of a private and a public portion. The private part never leaves the TPM, and the public portion is forwarded to OP-TEE's attestation PTA to be used as the subject key for EKcert, as shown by Figure 5.2. A pseudo trusted application (PTA) provides the same interfaces as an ordinary TA, with the difference that it does not run in user mode of the secure world, but in kernel mode within OP-TEE OS. Therefore, it has more privileges than an ordinary TA. The attestation PTA requires these privileges in order to read the memory of the calling TA, i.e., the fTPM TA, which is processed into the FWID that is finally embedded in the EKcert. The attestation PTA signs EKcert with OP-TEE's private alias key. This key is mocked in our implementation. Note that the fTPM has never access to the private

alias key of OP-TEE OS, so it cannot spoof its alias certificate/EKcert.

The attestation PTA hashes the memory pages of the calling TA that are executable or read-only data, i.e., are constant. It can also simply extract the hash embedded in the TA's binary header. A TA is an ELF binary wrapped in an OP-TEE specific format, which header contains a signature over all metadata and the payload, i.e., the ELF executable. While it is simpler and faster, it does not attest the TA's dynamically linked libraries. Although the reference firmware TPM does not link dynamically to any library, we use the attestation of the memory data to be more future-proof.

To embed the FWID into the EKcert, we use the X.509 extension defined by the DICE Attestation Architecture [**TCGAttestation2021**]. Therein, the TCB Info Evidence Extension is defined. It allows many FWIDs to be embed into an X.509 certificate. Our implementation always only stores one FWID into each Alias certificate or EKcert. However, the privacy focused architecture explained in Section 4.7 could leverage the possibility to store multiple FWIDs in the extension. Each FWID consists of an identifier of the hash algorithm used, and the according digest. We use SHA256. The TCB Info Evidence Extension is defined formally in the ASN.1 description language. Consequently, we use ASN1c[12] to translate this formal definition to C code. In particular, we use a self-compiled version of ASN1c, since its last official release dates back to 2017, whereby its generated C code throws various warnings with a modern C compiler.

The resulting certificate generated by the attestation PTA is returned to the firmware TPM, which also has access to all preceding certificates. In our implementation, these preceding certificates are simply mocked.

5.4 Firmware TPM attestation

We added a new TA command called `TA_FTPM_ATTEST` to the firmware TPM to obtain the entire certificate chain from any application. Normally, this command is issued by the application that performs the prover part of the remote attestation. We would like to emphasize that we do not refer to a new TPM command that would imply an extension of the TPM specification, but a new TA command that is intercepted by the OP-TEE stub code of the fTPM and processed without the involvement of the TPM-specific core code.

Recall that we earlier described that the firmware TPM TA only ever allows a single connection to it, which is usually a Linux module that provide the `/dev/tpm0` and `/dev/tpmrm0` nodes to communicate with the fTPM. We have therefore implemented the prover's side of the remote attestation with the ability to unload this Linux module before issuing `TA_FTPM_ATTEST`, and then load the Linux module again.

[12] `https://github.com/vlm/asn1c`

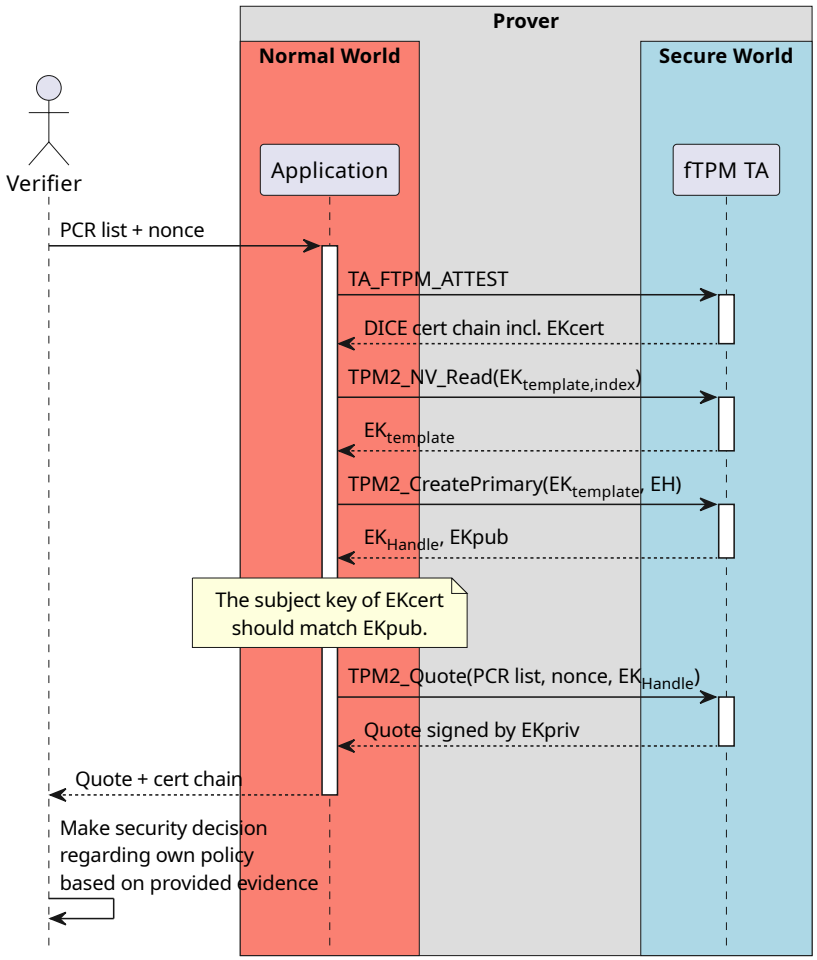


Figure 5.3: A UML sequence diagram describing the attestation of our firmware TPM.

The prover's user space application starts with issuing the `TA_FTPM_ATTEST` command to the firmware TPM, as shown by Figure 5.3. Consequently, it receives the certificate chain created by DICE with the EKcert as leaf certificate.

Afterwards, the prover wants the TPM to create the EK including its private portion. To do this, it first reads the EK template from the non-volatile (NV) memory of the fTPM, which was also used to create the EK part of the EK certificate.

Consequently, it then sends the template that has just been retrieved back to the TPM as part of the command `TPM2_CreatePrimary`. Since this command creates a primary key, no parent has be specified as the primary seed of the specified hierarchy is used instead. Of course, we specify the endorsement hierarchy (EH), which makes the TPM

use the endorsement primary seed (EPS) derived from the CDI to generate the EK. The TPM returns a handle to the EK just created, which is an integer, as well as the public part of the EK. The private part of the EK is not returned, as this never leaves the TPM in plain text.

Eventually, the prover wants to create a quote to establish trust to the prover's system state in the normal world, and to prove that it is in control of the EKpriv. So, it issues the command `tpm2_quote` to the TPM, specifying the PCR registers requested by the verifier, the verifier supplied nonce, and the handle to the EK just generated.

The prover's application handling the remote attestation is now in possession of the certificate chain, and a quote. It transmits both to the verifier. The verifier extracts the EKpub which is the subject key of the EKcert. With that, it can verify the digital signature of the quote. The ability of creating a quote with a fresh nonce proves the control of EKpriv by the fTPM. Therefore, the verifier can trust that the certificate chain does not have been replayed, and it represents the device it communicates with.

In our implementation of the prover we do not send the TPM commands to the TPM ourselves, but use `tpm2_createek -t` and `tpm2_quote` from the tpm2-tools[13]. Nevertheless, it executes these commands behind the scenes. We also use `tpm2_checkquote` in the verifier's implementation to check the signature of the quote, and to ensure that the nonce in the quote matches the nonce that the verifier has previously generated.

Note that the implementation just described assumes that the quote returned by `TPM2_Quote` contains the values of the PCR registers. While this was the case with TPM 1.2, this changed with version 2.0. Instead, the resulting quote only contains a hash of the values of the requested PCR registers. The corresponding plain text PCR values are transmitted unprotected to the verifier. After validating the quote, the verifier can check whether the hash of the plain text PCR values computed by itself matches the PCR hash from the quote. If this is the case, it can trust them. This is also done by the tool `tpm2_checkquote`. We have omitted it from the previous explanation and Figure 5.3 in order to focus on the important aspects. For the sake of completeness and correctness, we mention it here anyway.

As a small note, we made sure that the property `tpmGeneratedEPS` of our fTPM is set to 1 as it indicates that the EPS was generated by the TPM [**tpm**], which is the case in our implementation as it is derived from the CDI within the TPM.

5.5 Creating and storing our EK template and certificate

The EK is a primary key, so it is derived from the EPS, and also a key template. The template must be provided as part of the command `TPM2_CreatePrimary` to the TPM.

[13] `https://github.com/tpm2-software/tpm2-tools`

The TPM can contain a template for an EK key, which shall be the template with which the EK part of the EKcert was created. This is necessary to be able to reproduce the EK contained in the EK certificate so that the TPM can prove that this EK certificate corresponds to it by being able to generate the corresponding private key.

However, a TPM might not store an EK template. Then, the default template defined by TCG [**tcg-ek**] is used, dictating the endorsement key to be a restricted encryption key, since it is privacy-sensitive, and that it must be an RSA 2048 key. As this is fitting for most TPM's, the definition of the default template removes the burden of most TPM's to provide the template. It is then the duty of the entity communicating with the TPM to provide the default EK template, since it is unknown to the TPM itself. Though, we extended our firmware TPM to be able to generate the default and our custom EK template within code, such that it can create the EK which it forwards to the OP-TEE OS to create the EK certificate.

We want to use the EK as a signing key to sign attestation data, i.e., a quote. Hence, we need to deviate from the default EK template, and also provide our template within the NV of our fTPM. We start with the default EK template and only modify the fields when necessary. In total, we needed to change three aspects. We declare the EK as a (i) restricted signing key. This also requires to specify a (ii) signature scheme where we selected RSASSA-PKCS1-v1_5 [**Jonsson2003**] with SHA-256, and (iii) no inner symmetric key as required by the TPM specification [**tpm**] for signing keys since they are not allowed to have any children keys, as a signing key cannot encrypt its children for storage outside the TPM.

This template will be generated within the TPM after each manufacturer reset, so it will be preserved even after an identity change and a subsequent reset of the firmware TPM. Thus, it is always present. It is stored in the NV index `0x01c00004` as defined by the TPM EK specification [**tcg-ek**] for RSA 2048 EK templates. We set the attributes for this NV index as defined by the TPM PC Client specification [**tcgPcClient**]. Thereby, the EK template in the NV can only be written or deleted if a specific policy is fulfilled. However, the policy is empty, which can never be fulfilled. This results in a non-deletable EK template. We also store the EKcert in the NV index `0x01c00002` as defined by the TCG EK Credential Profile [**tcg-ek**] with the same attributes as the respective template. The template and certificate do not contain any sensitive material and can hence be read by anyone using the command `TPM2_NV_Read`.

Nevertheless, our firmware TPM does not retrieve the EK template from the NV index to create the EK to subsequently forward it to the OP-TEE OS to generate the EK certificate. This would entail an indirection via the NV storage, which is not attested. Instead, we explicitly use the EK template generated by code, which is attested via the fTPM's TCI. The NV storage is not attested as it is working data and not configuration data. Hence, the fTPM's TCI would not only represent the fTPM's behavior, but also its

stored data. Since a TPM can store arbitrary data, this would explode the amount of TCI values that the verifier needs to know in order to derive the trustworthiness.

5.6 Times in certificates and systems

In Table 4.1 we presented the restrictions the Alias and the EK certificate specifications conduct on the valid times of the certificates. Thereby, the period of validity of our certificates must be from a known time in the recent past, e.g., the component's build time, without expiration date.

We initially aimed for using the build time for the start of the validity period. However, this turned out to be infeasible, since the guest machine in the FVP does not have internet access out of the box, and FVP also does not provide an option to use the time of the host. Therefore, the time of the host and the FVP guest would need to be synchronized manually, requiring unnecessary engineering effort. Instead, we fix the times of all entities, i.e., the guest machine and the certificate's validity periods. This ensures that the FVP does not have to be configured for internet access which keeps the effort to launch the demonstration low, and results in a higher stability of the demonstration system.

We use `2023-07-25 00:00:00` as the start period for the certificates. This date has no further meaning and was chosen arbitrarily at some point during development. As required in the specifications, we indicate that the certificates do not have a well-defined expiration date, which is indicated by `9999-12-31 23:59:59` [**Boeyen2008**].

The time of the guest machine is automatically set to `2023-08-02 11:46` with the Linux tool `date` at startup. As before, this date has no further meaning. It is only important that this date is after the start period of the certificates.

5.7 Implementing encrypted storage

Overall, the reference TPM's memory size has a size of 16896 bytes, separated in a NV storage of 16384 bytes, and the admin space of 512 bytes. The admin space is reserved to persist defined data like the TPM's attributes, e.g., `tpmGeneratedEPS`. The NV storage can store arbitrary data, e.g., the EK template, certificate, or an encryption key. For example, Microsoft's BitLocker stores the encryption key for hard disk encryption in the NV storage.

The OP-TEE OS manages storage in blocks. It is only possible to write entire blocks, not partial blocks. Therefore, little changes can be expensive to persist if the according block is big. Hence, the OP-TEE specific code of the reference fTPM splits the memory size of 16896 bytes in 512 bytes blocks resulting in $16896 \div 512 = 33$ blocks.

We use the recommendations of the BSI [**bsi-key-recommendations**] to determine the encryption method. Therefore, we use AES-128 in GCM mode to protect the data's confidentiality and integrity with an initialization vector (IV) and tags of length 96 bits. These are the recommended minimum sizes that we have chosen in order to spare resources. There is one IV and tag for each block, which results in a storage overhead of 792 bytes as shown in Equation 5.4.

$$\frac{33 \times (96 + 96) \text{ bits}}{8} = 792 \text{ bytes} \tag{5.4}$$

The IVs are randomized on every write event. On any mismatch between the stored tag and the tag produced during decryption, the firmware TPM is reset.

The data is loaded from the hard disk and then decrypted only at startup time. And it is written only during shutdown of the TPM or if a command modifies the TPM's storage. As data is mainly written to the TPM during the provisioning time and only read during daily use, we assume that the impact on performance will be small.

5.8 Isolating storage of fTPM in OP-TEE

The data of the individual TAs must be saved somewhere permanently, otherwise they would be lost after each restart. This data must be protected as it is stored in OP-TEE in the REE file system. OP-TEE encrypts the secure storage files before sending them to the REE for permanent storage using a pseudo-randomly generated key, the File Encryption Key (FEK). It is stored in the metadata of the corresponding file, encrypted with a key unique to each trusted application, the Trusted Application Storage Key (TSK). It is derived from the Secure Storage Key (SSK), which is unique to the device.

$$TSK = HMAC_{SHA256}(SSK,\ TA_{UUID}) \tag{5.5}$$

$$FEK = decrypt_{TSK}(File_{metadata}) \tag{5.6}$$

$$data_{plain} = decrypt_{FEK}(File_{payload}) \tag{5.7}$$

Equation 5.5 shows that the TSK depends only on the SSK and the TA's UUID. As said, the SSK is same for the whole device and hence for every TA, and the TA_{UUID} is public. A close look reveals that other TA's on the same device could therefore use the publicly available UUID to generate the fTPM's TSK and consequently, decrypt the FEKs of the fTPM's files and access private data of the fTPM. However, this is prevented by our integration of an additional storage key, which encrypts the data before it is sent to the OP-TEE OS.

The TEE specification offers an ultimate solution for that on the conception level of the trusted OS without requiring a manual encryption step in the TA itself. It is defined in the TEE Management Framework [**GP_ManagementFramework**], which offers the possibility of grouping TAs into domains and subdomains, whereby only TAs in the same domain or subdomain can potentially decrypt each other's data. However, as of time of writing, this is not implemented in OP-TEE OS yet.

5.9 Technical obstacles

5.9.1 tpm2-tools

As mentioned earlier, we use the `tpm2_checkquote` tool to verify the prover's quote on the verifier's side. However, this tool fails to perform an important check to ensure that the quote was generated by the TPM and not externally. This poses a major security risk. We have reported this to the authors of the tpm2-tools via the recommended channel[14].

We would have liked to use RSASSA-PSS which is formally proven to be secure over RSASSA-PKCS1-v1_5. RFC 8017 even requires RSASSA-PSS for new applications [**Moriarty2016**]. However, it is not fully supported by the tpm2-tools, yet[15].

The tool `tpm2_createek` did not adhere to the TPM specification when it created the EK with a template from the NV storage of the TPM. A template always contains a nonce, but it can be overwritten by storing another nonce in a specifically defined NV index. We did not want to deviate from the standard nonce, which is a buffer of 256 bytes all set to 0. Therefore, we did not write a nonce to the NV index, and only the EK template with the default nonce, which conforms to the TPM specification [**tcg-ek**]. However, `tpm2_createek` expected a template and a nonce to be present. We ended up writing an empty nonce in the according NV index of the firmware TPM with the sole aim of circumventing this problem. Then, it turned out that this tool has another bug that caused the address of the nonce to be used instead of the actual nonce. We have fixed this bug[16].

5.9.2 OP-TEE

Initially, it failed to follow the official documentation to create the complete software ecosystem with the reference firmware TPM enabled. Eventually, we determined the

[14] `https://github.com/tpm2-software/tpm2-tools/security/advisories/GHSA-5495-c38w-gr6f`
[15] `https://github.com/tpm2-software/tpm2-tools/issues/3283`
[16] `https://github.com/tpm2-software/tpm2-tools/pull/3280`

problem and fixed it[17].

It was important for us to also test whether our system behaves as expected if the CDI changes. For that, we needed to persist the storage of the firmware TPM between launches of the FVP to modify the CDI during its downtime. However, the FVP version required to accomplish this turned out to freeze when the necessary functionality was activated. It took extensive debugging efforts to find a workaround[18].

The OP-TEE OS provides a libc library which implements only subset of the C standard library. Its authors copy code of the newlib[19] to their libc library on-demand when required. Unfortunatley, the code generated by the asn1c project expects functions not part of OP-TEE's libc. Fortunately, these functions were not critical and could be removed manually in a reasonable amount of time.

5.9.3 Firmware TPM TA

We have enabled a compilation option offered by the fTPM TA which appears not to have been thoroughly tested. When the option is enabled, the TPM uses code written specifically to use the OP-TEE functions to generate the EPS. This resulted in a crash of the fTPM during startup. We fixed the bug and opened a pull request for the fix to be merged upstream[20].

Eventually, we did not use this code. Nevertheless, this bug was found in the context of this thesis, and hence, we want to mention it here.

[17] `https://github.com/OP-TEE/optee_os/issues/6111`
[18] `https://github.com/OP-TEE/optee_os/issues/6162`
[19] `https://sourceware.org/newlib/`
[20] `https://github.com/microsoft/ms-tpm-20-ref/pull/98`

6 Discussion

6.1 Assessment of the fulfillment of requirements

6.1.1 Security requirements

6.1.2 Attestation process requirements

TCG defines as part of their Trusted Attestation Protocol [**tap**] the requirements for an attestation process to provide assurance to a verifier that it is (i) accurate, (ii) interpretable, and (iii) attributable.

Accurate Accurate attestation data represents the actual state of the device. This includes freshness, i.e., the data is not replayed and does not represent an old, outdated state of the device. While our system ensures this not alone, accuracy is established by the higher level protocol, e.g., retrieving a quote, as long as a nonce is involved.

Interpretable Intuitively, the data must be interpretable by the verifier. In other words, the verifier must be able to derive a decision about the trustworthiness of the prover based on the attestation data. Our system ensures that by propagating the TCIs as part of the publicly specified TCB Info Evidence extension. Also, the TCIs constitute of a hash, and the identifier of the used hash algorithm. Both are well-known concepts easily understandable for a verifier.

Attributable It must be possible to assign the attestation data to a specific device, i.e., it must be verifiable that the attestation data originates from the prover. This is solved by the higher level protocol as well, since such protocols usually involve signing of attestation data, usually a quote. The quote must be signed with the private EK corresponding to the public key in the EKcert, i.e., the leaf of the certificate chain. And this private EK can only be created by a device that has the TCIs represented by the previously obtained certificate chain and the according UDS, which is secret and unique for the respective prover.

6.2 Implications of openly propagating system state

An attacker could use the TCIs to find the exact version of the running software and match this to known vulnerabilities [**rfc9334**].

To counteract this, the certificate chain can be transferred from the prover to the verifier via TCP/TLS, which guarantees the confidentiality of the TCI part of the certificates from eavesdroppers. However, a malicious verifier could initiate the entire attestation process, which is then the TLS endpoint that receives the certificates. This can be circumvented by authenticating the verifier. However, this means that the prover only shares its state with certain verifiers. This is a trade-off that must be weighed up by the implementers of our solution.

6.3 Build pool of trusted TCIs

In our proposed solution, the verifiers must know the TCIs they trust. However, these reference values must be obtained from somewhere. This is a general problem of TPM (PCRs) and DICE (TCIs) attestation and not specific to our system. In an ideal scenario, the software developers of boot components publish the TCIs and the corresponding security attributes. The developers would also need to keep these listings up to date, e.g., if a vulnerability was discovered in a particular version to declare it insecure. The verifiers can then collect these TCIs, possibly filter them again with their own security policies, and save them as their trusted TCI pool. To date, however, we are not aware of this being common practice.

Alternatively, verifiers can also create their own trusted TCI pool. This could be a possible solution if a verifier expects a manageable number of possible firmware on the prover. This is the case, for example, if the verifier provisions the devices that will later be the provers themselves.

6.3.1 Closed source vs. Open source

It is counter-intuitive for the acquisition of TCIs that it is irrelevant whether the software is closed or open source. In fact, it can be more difficult with open source software. This is because the calculation of TCIs is based on the binary code and not the source code, since the binary code is eventually loaded in the memory of a device and executed. While closed-source software must always be provided as a binary file, open-source software may only be distributed in the form of its source code. The binary file must then be compiled by the device provisioner itself. If its build environment does not support reproducible builds [**Lamb2022**], there may be many binaries and conversely

many TCIs that differ only in irrelevant details, e.g., embedded timestamps. This is unlikely to appear with closed source software, as there is only a single distributor.

However, closed source software restricts the criteria that can be used to decide whether a TCI is trustworthy or not. The trustworthiness of open source software can be derived independently of its source code, and also its exact change history if an older version is evaluated. With closed source software, you have to rely on the developer of the closed-source software to communicate openly if security problems occur.

6.4 Hardware requirements

A major advantage of firmware TPMs over dedicated TPMs besides the better performance is that they involve less hardware components for the final system. The question at hand is whether the hardware requirements of an fTPM with the addition of the hardware requirements of our solution undermine this advantage.

At the introduction of firmware TPMs by Raj et al. from Microsoft [**Raj2015**], they require a TEE, storage hardware supporting a Replay Protected Memory Block (RPMB) partition, a secure world hardware fuse, and a secure entropy source for the integration of a secure firmware TPM. Thereof, a hardware fuse, a secure entropy source, and a TEE are commonly part of the processor without the need for additional hardware. Raj et al. require a RPMB partition to protect the fTPM's storage from access outside the TEE, and prevent rollback attacks. Rollback attacks of the fTPM's data or the fTPM itself are not prevented by our introduction of the storage key. So, we also recommend using a trusted OS implementing secure storage on a RPMB partition, which involves the additional hardware requirement of an RPMB which is not necessary for dedicated TPMs. However, storage has to present anyway, and a RPMB partition is supported by storage technologies commonly used in embedded devices, e.g., eMMC [**eMMC**] and UFS [**UFS**].

Our solution also involves the hardware requirements of DICE. The purpose of its hardware requirements is to protect the UDS. According to Lorych and Jäger [**Lorych2022**], this is usually implemented in latches which block access to a specific memory area after a bit has been set; such latches are commonly part of processors. They name the STM32G0 based on the Arm Cortex-M0+ or the STM32L4 based on the Arm Cortex-M4 as examples. For a system to be DICE-compatible, it is therefore usually sufficient for the processor to support it without the need for additional external hardware.

So, we are not cancelling out the advantage of less additional hardware components over a dedicated TPM, and instead we add restriction in the choice of processors and storage type.

6.5 Proving the fTPM runs in the TEE

It is important for the verifier to know that the fTPM runs within the TEE and not the REE. Otherwise, the fTPM would not be isolated from the components within the REE, which usually offer a large attack surface because they communicate with the Internet, for example. The remote attestation process we propose enables this by passing the processor's name of the prover within the DeviceID certificate to the verifier. The verifier can then understand, e.g., from the hardware's manual, that the hardware starts in the TEE and can derive from the TCIs part of the certificate chain when the system switches to the REE. It can therefore understand that the fTPM is running in the TEE.

For our proposed architecture with privacy in mind, this check has to be conducted by the privacy CA. That is due to that the verifier must not know details of the prover's hardware, since this might reveal its identity.

6.6 Caveats of a static RTM

The huge disadvantage of a static RTM is that it generally cannot provide guarantees for a system's state at the current time, but can only present the state the system inhibited at boot time [**EURECOM+3536**]. However, attacks can appear during the system's runtime, which is then undetected. Since our solution integrates DICE which does not provide capabilities of a dynamic RTM, we are restricted to a static RTM.

7 Future Work and Conclusion

7.1 Future Work

The logical consequence is the implementation of our solution on real hardware instead of in a simulation environment such as FVP. This allows the interaction with the hardware to be verified, especially with an RPMB partition that requires hardware support. In addition, the impact of our solution on the performance of the system can then be measured in practice.

Although it makes sense to show our solution on Arm hardware first, we are, as mentioned, not limited to it. Therefore, a future work is to concretize the description of our implementation for TEE technologies other than Arm, e.g. Intel TXT.

The system we propose can also be transferred from the DICE architecture to other technologies that also perform firmware measurements. A new technological framework that generalizes DICE is Caliptra [**caliptra**]. It is based on the concept of DICE, but is not limited to it.

As mentioned in Section 4.2, RPMB's rollback protection only protects against attacks from outside the TEE. We would like to establish a design that tightens the rollback protection from the trust of the entire TEE to the identity of the fTPM. This can probably be achieved by encrypting the metadata stored on the RPMB with the storage key derived from the identity of the fTPM, i.e., its CDI, before sending it to the RPMB. This must be implemented in the trusted operating system and not in the fTPM TA, as the trusted operating system normally manages the metadata.

Furthermore, our solution does not protect against runtime attacks on the fTPM. In general, trusted applications in a TEE are not resistant to security problems caused by programming errors, e.g., buffer overflow attacks. Therefore, remote attestation of the control flow integrity of the fTPM may be a desired function. Displaying the current state of the fTPM instead of its identity at boot time would be a useful extension to our solution.

7.2 Conclusion

In this work, we have proposed a novel remote attestation scheme to establish trust in a firmware TPM. fTPMs cannot be trusted based on their isolated identity alone, as their underlying software components are also security relevant, unlike dedicated TPMs which are a separate chip. We therefore use the DICE as a hardware root of trust and measure each component during the boot process up to the fTPM. The verifier can thus learn the measurements of the corresponding components and decide whether they are classified as trustworthy. These measurements are transmitted from the prover to the verifier in the form of certificates. Since it is in the nature of certificates that they are not considered secret and can therefore be easily replayed by malicious provers, the verifier must ensure that the certificates correspond to the device he is communicating with. This is not directly ensured by our system, but should be part of the attestation protocol that runs atop of our system, e.g., the fTPM, which attests the state of the system with a quote. To do this, the prover must prove that he has the private key that corresponds to the public key part of the certificate that describes the firmware TPM. These keys are unique for the identity of the device (the UDS) and the identities of the individual components (the TCIs) and therefore cannot be generated by other, potentially malicious, verifiers. We concluded the presentation of our system with an explanation of a proof-of-concept implementation and a discussion of the feasibility, caveats and limitations of the system.

We believe that our system is an important step towards the independence of the manufacturer of the firmware TPM and its upstream software, whereas today provers trust a single manufacturer who is assumed to have provided all these components. Our system also creates a hardware root of trust for the firmware TPM which, as the name suggests, cannot be provided by the fTPM as it is a software component. In contrast, dedicated TPMs are capable of acting as a hardware root of trust. Our system closes this gap.

Abbreviations

TPM Trusted Platform Module

fTPM firmware TPM

dTPM dedicated TPM

DICE Device Identifier Composition Engine

TEE Trusted execution environment

REE Rich execution environment

PCR Platform Configuration Register

TCG Trusted Computing Group

NW Normal world

SW Secure world

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