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, 15.01.2024 Andreas Korb

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Abstract

Zero Trust is a cybersecurity paradigm in which a network, e.g., an enterprise network, is considered compromised. Therefore, each device of every service request must be verified before the request is served. This is made possible by remote attestation, which is enabled by **TPM!**s (**TPM!**s), for example. For that, they authenticate themselves by propagating their so-called endorsement certificate naming their manufacturer, who guarantees they conform to the TPM specification to ensure their security properties. While this approach is sufficient for hardware TPMs as they are standalone chips, for **fTPM!**s (**fTPM!**s) it is assumed that the manufacturer of the **fTPM!** is the same as that of all firmware components that were booted before the **fTPM!**. This is due to the fact that any previous firmware component can compromise the **fTPM!** during loading. The verifier in the remote attestation procedure lacks the ability of verifying the entire boot chain up to the **fTPM!**. We propose a remote attestation system that provides the verifier with this possibility. To compensate for the lack of a hardware root of trust of an **fTPM!** compared to a hardware TPM, we introduce DICE as the hardware root of trust. The verifier only needs to trust the manufacturer of DICE, while every firmware component beyond is explicitly attested by passing their identities to the verifier. The three benefits of our solution are that (i) the manufacturer of the **fTPM!** and its preceding firmware components can be independent of each other, (ii) detection of modification of **fTPM!** by remote verifier, and (iii) protection of the **fTPM!**'s data-at-rest. DICE measures the first firmware component, which is then repeated up to the **fTPM!**. These measurements are forwarded to the remote verifier, which can then detect potentially malicious changes to each measured component. The **fTPM!**'s data-at-rest is protected by binding it to the identity of the **fTPM!**. This means that the data of an **fTPM!** is only accessible to the **fTPM!** that created it as long as its identity does not change, which makes downgrade attacks and changes to the **fTPM!** less attractive to attackers.

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 [1], 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 [2].

This is solved by remote attestation. In the simplest case, there is a prover and a verifier, as depicted in **??**. 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 manufacturer-controlled so that it cannot be modified without the involvement of the manufacturer, who identifies themselves to a verifier by signing and storing a certificate on the helper components supplied by them. Consequently, the component attests the state of the prover's machine, from which the verifier can deduce whether the prover can be considered trustworthy.

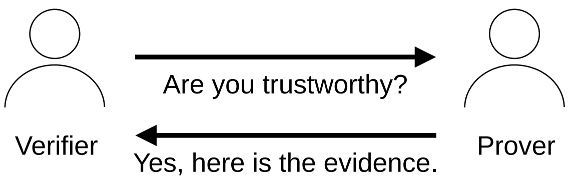


Figure 1.1: Simplified remote attestation process.

For example, this can be done with a **TPM!** (**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 [3], and Microsoft publicized that they require a TPM module for Windows 11 in 2021 [4]. 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 [5].

A **dTPM!** (**dTPM!**) increases cost and hardware complexity—especially for embedded platforms. **fTPM!**s (**fTPM!**s) running in a **TEE!**s (**TEE!**s) 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 their 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. Consequently, trust in an **fTPM!** depends on trusting the entire stack beneath it due to the possibility that its underlying firmware might alter or compromise the **fTPM!**.

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 its provided guarantees, trust is established to its provided components.

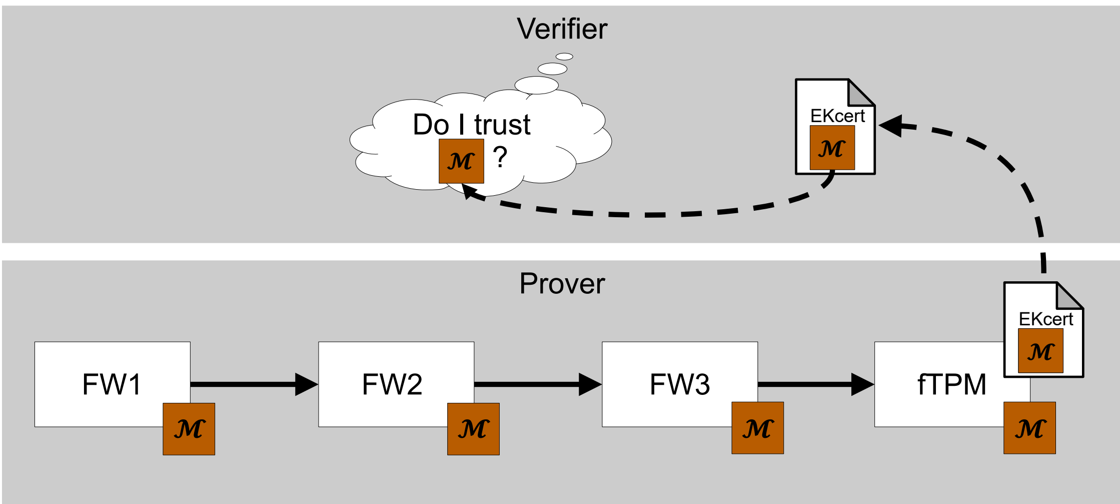


Figure 1.2: The naive process how a verifier establishes trust to an **fTPM!**, which is in fact done by trusting its manufacturer. The brown markers indicate a manufacturer. The firmware (FW) and the fTPM were built by manufacturer $\mathcal{M}$, and the EK certificate indicates this manufacturer.

This process is illustrated in figure **??**. The prover's box shows its boot chain, the verifier's box shows how it evaluates the trustworthiness against the prover's boot chain. The verifier trusts the entire firmware chain if it 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 **fTPM!**s, as confidence in their **fTPM!**s 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.

1.2 Goal

We establish an 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 **DICE!** (**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 **fTPM!**s, 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 attacker we are interested in is able to replace the fTPM or one of its predecessor components. Therefore, there is a risk that a remote party trusts a firmware TPM that is in fact not trustworthy. For example, an attacker could install a malicious update of a relevant firmware component on the target device. However, we assume that the attacker is only able to do this before or during the boot process of the device, but not afterwards. Hardware attacks, side-channel attacks, control-flow attacks, and denial-of-service attacks are out-of-scope.

For the network, we assume the Dolev-Yao attacker model [6]. That is, we consider an attacker who has the ability to perform any active or passive attack on the network. The attacker may also have control over parts or the entire network, e.g., all routers, switches, and connections. Last, they 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 achieve the corresponding objectives.

- **Compromised fTPM cannot fake its identity**
  A compromised fTPM must not be able to lie to the verifier about its identity. It is sufficient for a lie to be recognized, and the verifier can consequently classify the verifier's fTPM as untrustworthy.

- **Small root of trust**
  A root of trust of small size, e.g., in the means of code size, hardware size, and complexity, yields a small attack surface [7]. This is due to the fact that a small component yields less potential implementation errors, and its approaches to guarantee specific security properties are more manageable.

- **Isolation of fTPM storage**
  Data must only be accessible or modifiable within the boundaries of the TPM access controls, i.e., the TPM commands defined by its specification [8]. This includes the protection against other trusted applications running in the same TEE.

- **Protect fTPM data against downgrade attacks on the fTPM**
  The current storage of the fTPM should be sealed to the identity of the fTPM's identity, such that when the fTPM is modified, e.g., by a downgrade attack, even the fTPM cannot access its old data anymore.

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

1.5 Outline

In the **??**, we provide knowledge necessary for a better understanding of the subsequent parts of this thesis. Afterwards, we discuss **??**, i.e., attacks on TPMs to further motivate this work, approaches to hardening TPMs, and work that enables remote attestation similar to ours. Under **??**, we explain the concept of our solution and subsequently present our proof-of-concept implementation. Finally, we discuss our design and implementation, rounded off by **??**.

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 [9]. Thereby, processes are protected against other processes with the same or lower privilege level. However, they are not protected against more privileged processes [10]. This bears problems for example for cloud computing and edge computing. In cloud computing, other services, the hypervisor, or the cloud provider could potentially access sensitive data of the cloud tenant [11]. In edge computing, the edge applications deal with plaintext data, while they are potentially running on insecure edge devices [12]. Hence, protection against more privileged processes is desired.

The **TEE!** (**TEE!**) is a technology defined by GlobalPlatform[1] as an integrated hardware extension to processors. By that, the execution environment is separated into the **REE!** (**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 [13]. 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 (TAs). It focuses on resisting software-based attacks generated in the **REE!**, however, also protects against some hardware attacks [14].

Previous, mostly software-based technologies ensure confidentiality and integrity protection of data-in-transit and data-at-rest [15], while a **TEE!** additionally protects data-in-use in hardware [15, 16].

?? illustrates the motivation of a **TEE!**. 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.

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

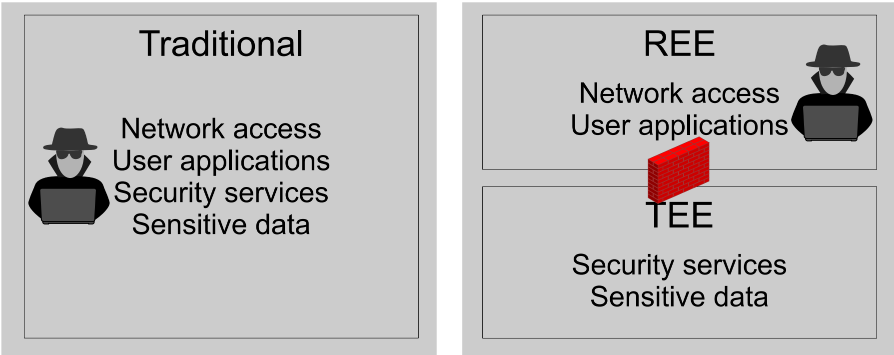


Figure 2.1: Comparison between a traditional architecture, and an architecture separating the REE and TEE. This illustrates the motivation of a TEE.

Arm TrustZone One such **TEE!** is Arm's TrustZone [17, 18]. It partitions all software and hardware resources of the containing system into the **NW!** (**NW!**) and the **SW!** (**SW!**), as shown in **??**. 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 Internet of Things (IoT) devices with a market share of 86 % as of 2022 [19], many of the approaches in this field of research use Arm TrustZone [20].

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).

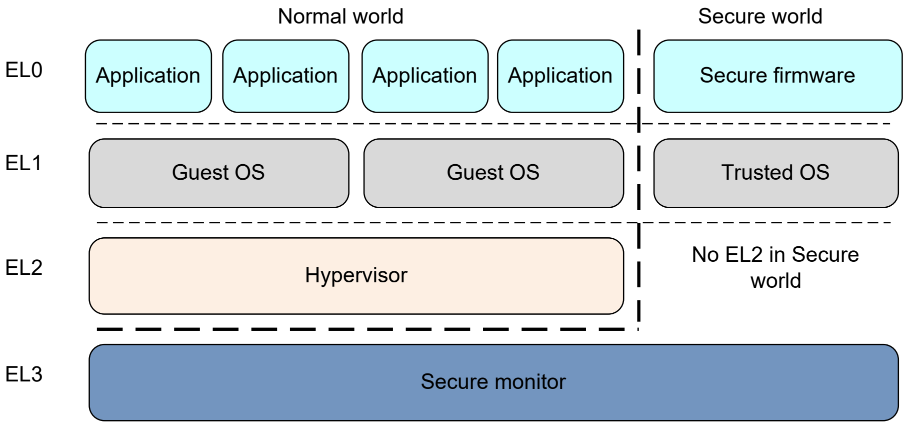


Figure 2.2: The architecture of Arm TrustZone for AArch64 [21]. The exception levels (EL) indicate the privilege levels.

2.2 Remote Attestation

According to NIST SP 1800–19B [22] 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."

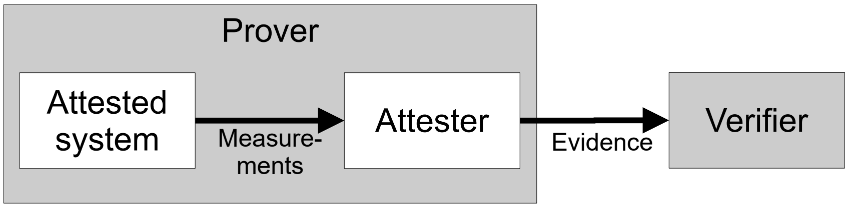


Figure 2.3: Data flow of attestation data for a remote attestation [23].

Remote attestation is a challenge-response protocol initiated by a remote party—the verifier—to verify that a target environment, i.e., the attested system, on the end-device—the prover—has not been tampered with [24, 25]. **??** depicts a simplified overview of its data flow.

In a typical remote attestation procedure, the attester measures the attested system during its boot process. A verifier initiates the remote attestation protocol by sending a challenge with a nonce to the prover. The prover then signs the measurement data combined with the nonce, with the final data structure usually referred to as the evidence. The nonce forces a fresh response and thus prevents replay attacks on the evidence. The evidence is then transmitted to the remote verifier, where it is evaluated.

The attester acts here as the **RTM!** (**RTM!**) for the verifier. Most importantly, it must be isolated from the attested system such that it cannot be compromised by it. The verifier establishes trust to the attester by getting to know its manufacturer and the security properties that they guarantee. Consequently, the verifier can trust the statements the attester conducts about the attested system.

Remote attestation commonly consists of two steps [26]. (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 further be divided into two categories—implicit and explicit attestation [27]. In implicit attestation, the state of the prover is implicitly inferred from the fact that it has control over a signing key that is only accessible if the prover is in a known state. That is, the sole ability to create the evidence defines the properties of trustworthiness. With explicit attestation, the state of the device is explicitly described in the evidence. The solution we propose carries out an explicit attestation.

2.3 Trusted Platform Module

The **TCG!** (**TCG!**)[2] published the first TPM specification (v1.1) in August 2000 [28], and the most current specification to date (v2.0 Revision 01.59) 19 years later in November 2019 [8]. It describes a cryptographic coprocessor that increases trust in the host platform. Specifically, this means that the TPM exhibits the expected behavior and that this behavior can be trusted. For that, the TPM maintains a separate 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. **??** summarizes the main features of TPMs.

Table 2.1: TPM main features.

Feature	Explanation
Device identification	Identify a machine, e.g., before granting it access to resources
True Random Number Generator	Seed key generation algorithms
Key Storage	Store secret keys
Platform Configuration Registers	Store measurements of system components
Sealing	Bind access to data to state of host system i.e., specific PCR values

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 [8], some alternative names behind them in brackets, as they are sometimes referred to, and the intended use-case of the hierarchies [29].

- **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 (privacy 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.

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

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

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.

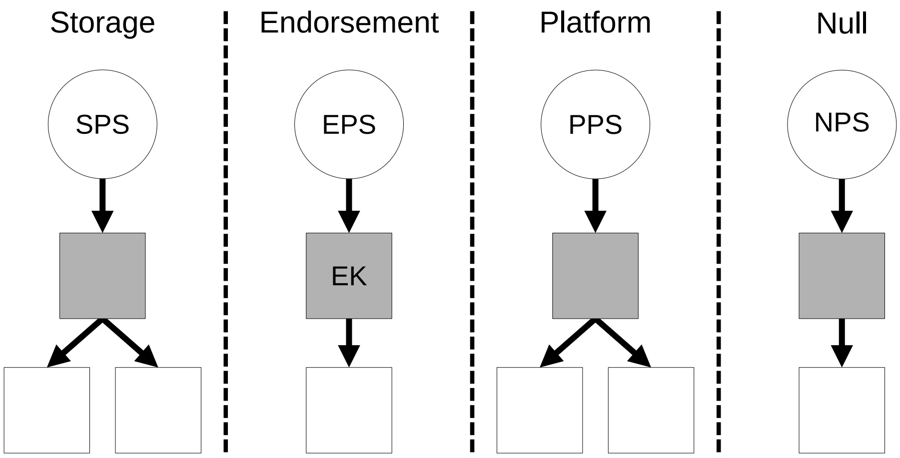


Figure 2.4: The source of entropy of the keys generated in a TPM for each hierarchy. Circle: primary seed, e.g., the storage primary seed (SPS); gray rectangle: primary key, e.g., the endorsement key (EK); white rectangle: ordinary key.

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 **??**. Note that the number of children and the hierarchy depth in this figure are exemplary and there are no technical restrictions for this in the TPM specification.

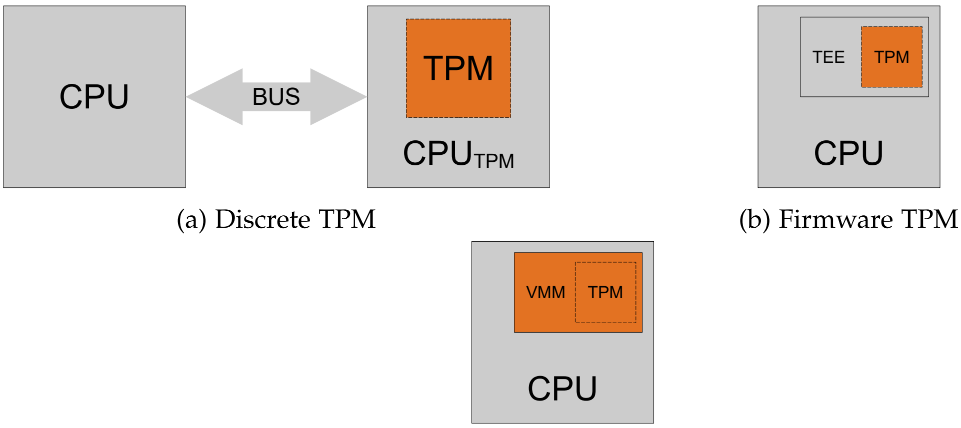
A template contains metadata of the key, such as the type of the key like RSA-2048, and the object attributes, for example, whether the key can be used for encryption or signing. Keys can be `restricted`, which limits the key to be used with data generated by the TPM [8]. For signing keys, this prevents an attacker from asking the TPM to sign an artificially constructed quote. Analogously, restricted encryption keys can only be used to encrypt data generated by the TPM, e.g., other keys created on the TPM.

The **PCR!**s (**PCR!**s) are the fundament for the remote system attestation They are one-way registers, which values can never be written explicitly, but only be extended; this operation is known as *hash extend* [29]. 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 2.0 contains 24 PCR registers, as defined as the minimum by [30], with the first eight representing the firmware boot process and the higher ones representing the OS or applications [31]. The fixed length of the **PCR!** values is important for the memory-constrained nature of TPMs [29].

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 **??** [8]. For the sake of correctness, it should be noted that not every PCR is initialized with zero, as stated in the equation. For example, the TPM PC Client Platform specification [30] defines that PCRs 1–16, 23 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 [32–34]. Although the SHA-1 uses in TPM 1.2 were analyzed to be not affected [35], cryptographic algorithms only become weaker over time [29]. In reaction, TPM 2.0 offers crypto-agility and allows newer algorithms such as SHA-256. Also, TPM 2.0 is more consistent across different implementations because of broader specifications. Therefore, Microsoft recommends TPM 2.0 over TPM 1.2 [36] due to its security advantages, and also requires TPM 2.0 for Windows 11 with SHA-256 PCR registers [4].



(a) Discrete TPM

(b) Firmware TPM

(c) Virtual TPM

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

There are three types of **TPM!**s—**dTPM!**s, **fTPM!**s, and virtual TPMs—as illustrated in **??**. They all offer the same functionality, but with different security guarantees and performance characteristics, explained in the following sections.

2.3.1 dTPM!

This is the classical form of a TPM. It is a dedicated piece of hardware, connected to the CPU via a bus. They have their own processor, memory, and storage so that they are completely isolated from the host system and can only be accessed via the bus system.

The TPM specifications [8, 30] 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.

2.3.2 fTPM!

An fTPM [37, 38] is executed directly by the host 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 [39]. Common implementations are the Intel® Platform Trust Technology (Intel PTT) [40], and AMD's Secure Processor (AMD-SP), with the latter being an Arm-based coprocessor on the die with TrustZone [41].

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. Furthermore, they are started later in the host's boot chain than a **dTPM!** that is accessible from the beginning. Consequently, the measurements of the components booted before the fTPM have to be cached and later forwarded to the **fTPM!** once it is available. Trusted Firmware-A[3]—which is Arm's reference implementation of the boot software in the **TEE!**—protects this cached event log by keeping it in secure memory [42] only accessible by the **TEE!**. Last, fTPMs depend on more components for its security than single-component **dTPM!**s, 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 [37, 43]. Raj et al. [37] and Cheng et al. [44] independently conclude that firmware TPMs executed on main processors are generally much faster than **dTPM!**s. **fTPM!**s 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 [45, 46].

2.3.3 Virtual TPM

A vTPM is a software-based TPM provided by a virtual machine manager (VMM) for one or many of its managed VM's [47]. They can be realized purely in software [47], or backed by dTPMs [48]. A characteristic feature of virtual resources are their migration capabilities, i.e., they can be suspended and later continued on another machine. vTPMs do not inherently have their own security properties as these depend entirely on the vTPM implementation of the hypervisor.

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

2.4 Secure Boot and Measured Boot

Secure Boot [49–51] is a security system that verifies components of the boot chain directly at boot-time. For that, the system is equipped with a public key that is used to verify the digital signatures of the boot components ensuring their authenticity. Alternatively, merely the hashes of the components can be measured and compared with benign references values, which only ensures integrity and not authenticity. The first boot component stored in ROM needs to be trusted without verification, and therefore forms the root of trust. Nonetheless, Secure Boot does not prevent downgrade attacks, since only the authenticity, but not the concrete versions of boot components are verified [52].

In contrast, Measured Boot conducts precise measurements of the booted software for retrospective evaluations [53]. This allows a verifier to learn about the exact software booted during a remote attestation process. It is a concept that is implemented in interplay with a TPM. Just as with Secure Boot, each boot component hashes the subsequent component. Instead of directly locally verifying the measured value, the hash value is passed to the TPM to extend a **PCR!** value. Consequently, as described in **??**, the TPM can create a quote propagating the state of the measured system.

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 IoT (RIoT) architecture [54]. In 2017, the DICE specification was published by **TCG!** [55], 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 low hardware requirements.

DICE operates on a boot process layered into components [27]. Each layer must only assume the lower layers to be trustworthy. Later components typically include more features and are more 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 to prevent time-of-check to time-of-use attacks (TOCTTOU) [56, 57]. The union of all security-relevant components of a device form its **TCB!** (**TCB!**). Their individual identities are called **TCI!** (**TCI!**), which are usually the hashes of the according firmware binary, but could also consist of a hardware product identifier. The TCI must also represent security-relevant configurations of a component. Compilation flag configurations affect the binary file and are therefore inherently included in its TCI. There are also configurations that are not part of the binary usually provided in well-known formats such as `json` or `xml`. They must be measured in conjunction with the corresponding binary file or represented by two separate **TCI!**s.

The DICE layer is the first to be booted. Its specification [58] states three hardware requirements. The DICE layer

1. has to store a read-only **UDS!** (**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 provide a basis for long-term identification and derivation of the device's own secrets. (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 be realized with eFuses [58], for example. (3) Moreover, the misbehavior of the DICE layer cannot be detected since it is the root of trust meaning it is not preceded by anything that could measure it. Therefore, it must be immutable to ensure that it remains in the trusted state in which the manufacturer provided it.

While the **UDS!** is exclusive to the DICE layer, each later component retrieves a **CDI!** (**CDI!**) from its predecessor. 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 components. Therefore, if any component is modified, this reflects in the permutation of the **CDI!**s of all subsequent components, as implied by **??**.

Just as the DICE layer must ensure to have exclusive access to the **UDS!**, each later layer must ensure no subsequent layer has access to its **CDI!**. The layers can derive further secrets using their **CDI!** as a seed, such as the Device ID key pair (**??**) or an alias key pair (**??**).

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

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

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

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

The end result of a boot process using **DICE!** is a certificate chain, which can be seen in **??** and **??**. Here, each certificate represents a layer by embedding the **TCI!** of the layer. The certificate chain is built up progressively during the boot process, with the first two certificates—the manufacturer and DeviceID certificate—being static and stored on the device, and the remaining 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, and is typically self-signed.

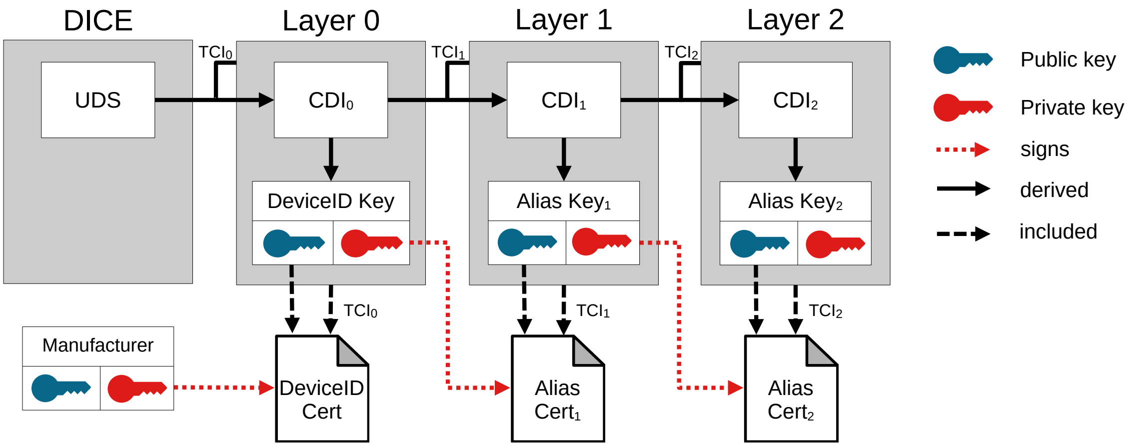


Figure 2.6: The generation of the **CDI!**s and the certificates for each layer in a **DICE!** architecture. Note that the diagram could be continued for an arbitrary number of layers.

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 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 openly stored on the device as part of the DeviceID certificate, the corresponding private key still must be generated during the boot process. It can only be generated if the identity of layer 0 remains unaltered, which allows the certificate chain to be continued.

The remaining alias certificates in the chain each represent the identity of a layer. They contain the measured **TCI!** of layer n and are signed with the private key of the measuring layer $n-1$.

The generation of the **CDI!** values and certificates is shown in **??**. There, the **CDI!**s and certificates are associated with their ultimate usage or the entities they represent, rather than the layer of their creation. E.g., CDI_n and AliasCert_n are both created by layer $n-1$, but passed to and used by layer n.

For remote attestation, the prover forwards this DICE certificate chain to the verifier. The verifier must understand the manufacturer part of the DeviceID certificate from DICE and decide whether it is trustworthy. If this is the case and the signatures of the certificate chain can be verified with the corresponding public keys, the verifier can derive the running software of the prover from the **TCI!**s part of the certificates. Finally, they can decide whether this list of **TCI!**s is trustworthy.

To the best of our knowledge, **DICE!** is so far considered secure apart from physical attacks, only implementation problems can bear security problems [56, 59].

3 Related Work

In this chapter we provide a collection of scientific work that relates to this thesis. For each, we provide a brief overview and how they are connected to our work.

3.1 Attacks on TPMs

Generally, attacks on **TPM!**s target one of two goals. Either to reveal secrets stored on the TPM, or to decouple the host system's actual state and the state measured by the **TPM!**. From now on, the latter will be referred to as *state decoupling*.

dTPM! The *TPM Reset Attack* on TPM 1.1 is described independently in [60, 61] conducting state decoupling. It requires minimal hardware, precisely only a wire connecting the reset line of the LPC bus [62] to ground. The TPM understands this as a reset signal, yielding predictable values for the **PCR!** registers. This allows an attacker to perform a boot process with malicious components, later resetting the **PCR!** values to a known value with the reset attack, and then replay the measurements of a benign boot process. This not only spoofs the attestation process, but also allows the attacker to access secrets stored on the TPM, which is sealed to the benign state of the host machine. **TCG!** mitigated this problem by introducing localities with TPM 1.2 which restrict the extension of specific **PCR!**s to special hardware modes that are no longer accessible in the later boot process [63].

Winter and Dietrich [64] circumvent this counter measurement with an attack on **dTPM!**s integrated with the LPC bus or the I^2C bus. Their method—labeled *Active LPC frame hijacking*—allows them to "lift" commands to a higher locality than the one they were originally sent with. In addition, they introduce a new approach for state decoupling. Vice versa to the *TPM Reset Attack*, they reset the main device, e.g., a personal computer, while preventing the TPM from receiving the reset signal. This keeps the benign measurements stored by the TPM, while the attacker can compromise the newly booting system without being measured. However, it requires active manipulation of bus transmissions to shield the **TPM!** from the reset signal. The original work is from 2013 and therefore focuses on TPM 1.2. Despite only having access to TPM 2.0 emulators in 2014, Winter mentions in his master's thesis that initial tests indicate that these attacks also apply to TPM 2.0 [65]. To the best of our knowledge, this is the only statement done about these attacks for TPM 2.0.

fTPM! As seen in the previous section, the bus between a CPU and a **dTPM!** is a typical attack vector on **dTPM!**s throughout their history. An **fTPM!** circumvents this by being directly executed by the CPU within a **TEE!**, revealing no easily accessible bus. Nevertheless, there are also attacks against **fTPM!**s.

Moghimi et al. [66] demonstrate a time-based side-channel attack. It applies to Intel's **fTPM!** before the corresponding software patch in November 2019, and allows an attacker to recover 256-bit private keys for ECDSA and ECSchnorr signatures.

Seunghun Han et al. [67] report two further state decoupling attacks. The first targets a gray area in the power management section of the TPM 2.0 specification. If the host platform goes into sleep mode, it can send a command to the **TPM!** demanding it to store its current state including its **PCR!**s in its non-volatile RAM. When the host platform wakes up again, it can request that the saved state be restored with a corresponding command. Yet, the specification lacks a concrete description of the behavior if the **TPM!** has not saved any state before going to sleep, but still receives the command to restore its saved state when waking up. It merely states that the **TPM!** implementation is expected "to take corrective action" which also applies to the latest version of the **TPM!** specification at the time of writing [8]. Hence, some implementations simply reset the **TPM!** which resets its **PCR!**s. Software updates from the manufacturers are required to close this vulnerability in their implementation. Their second attack targets an **fTPM!** running with Intel's Trusted Execution Technology. They exploit that some mutable function pointers are not measured in its measuring boot environment allowing arbitrary code execution. Thereby, the **PCR!**s can be reset. The authors fixed this issue upstream with a software patch.

Jacob et al. [68] target proprietary AMD fTPMs by attacking their **TEE!**, namely the AMD Secure Processor (AMD-SP). By that, 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 **fTPM!**s 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.

Cohen from the Google Cloud Security team also targets AMD's fTPM running with the AMD-SP [69]. 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. According to the author, this bug is limited to vendors that diverge from the **TPM!** specification, as this issue does not appear in **TCG!**'s reference code. AMD resolves this issue with a software patch.

These attacks on **fTPM!**s show that they need to be updatable to respond to the disclosure of future vulnerabilities. They should also be measured to understand for a remote relying party which known vulnerabilities are patched and which are not.

3.2 Remote attestation schemes

The SMART attestation mechanism proposed by Defrawy et al. [70] is similar to **DICE!**. Their only hardware requirement is a ROM containing a secret key only be accessible by SMART, which corresponds to DICE's **UDS!**. This key is directly used to sign attestation data, while for **DICE!** the **UDS!** acts as entropy to derive firmware-specific secrets. Therefore, it does not allow data to be bound to the identity of a firmware component, as the only key is intended for signing instead of encryption, and covers the entire device instead of being individual for each firmware component.

An abstract design similar to ours was proposed by **TCG!** back in 2014 [71]. The lack of an update since then suggests that it has not been adopted much. Perhaps also because they do not make any suggestions for a concrete implementation. **DICE!** could not be used as it was proposed a year later in 2015.

TCG! offers an adaption of **DICE!** with symmetric cryptography which conducts implicit attestation [72]. There, the final symmetric key—also called alias key here—derived from the compound identity of the whole firmware and its **UDS!** represent the prover's identity, without propagating the individual identities of each firmware layer like the **TCI!**s do. The verifier and the prover must have shared secrets due to the nature of attestation based on symmetric cryptography. Depending on the desired flexibility of the verifier, the **UDS!**, the **CDI!**, or the alias key have to be shared. If the alias key is leaked, trust into the system breaks unrecoverable since the same key is generated on each boot, provided no changes have been made.

DICE+ proposed by Jia et al. [73] solves this by equipping the prover with a monotonic counter, which is incremented on each reboot. The prover shares its UDS and also the initial value of its counter with the verifier during provisioning in an out-of-band manner. The counter influences the alias key, which consequently alters the attestation result derived from it after each reboot as well. The verifier can calculate the expected attestation data by combining the original shared secrets, and the expected firmware identity. Replay protection is achieved by requiring that there is only a single verifier, who knows the received values of all previously conducted remote attestations, and can therefore detect replay attacks. While their approach is practical for low-end devices that are not capable of asymmetric cryptography, we are targeting machines with a processor with a **TEE!**, which implies a certain amount of computation power. We also do not want to require pre-shared secrets between the verifier and the prover. In addition, the TPM's infrastructure demands asymmetric cryptography for signing the EK certificate, and the monotonic counter would change the TPM's identity on each reboot, effectively hindering the binding of the fTPM's data to its identity. Hence, we use DICE with asymmetric cryptography instead.

Bravi et al. [74] propose an attestation system with DICE without TEE. While we combine DICE with the TPM infrastructure, they combine it with the Manufacturer Usage Description (MUD). This allows a device to signal to the network what kind of access and network functionality it requires for access control [75]. Their design is orthogonal to ours, in that they do not integrate any data binding to software identities.

3.3 DICE implementation

Jäger, Petri, and Fuchs [76] describe how the remote attestation procedure described in the DICE specification can be put into practice by discussing implementation options. Thereby they complement our work by evaluating how to implement **DICE!**. Jäger and Petri continue their work later [59] because they observed a limitation in their initial implementation, allowing to jump into **DICE!** code possibly leaking the **UDS!**. Lorych and Jäger carried on exploring the design space of DICE [77] later on. As with SMART, the goal of all these publications is not to attest an **fTPM!** and therefore do not describe how to combine the infrastructure of DICE and **fTPM!**s.

Just as we presented a paper proposing a formally verified **fTPM!** implementation, Tao et al. [52] propose a formally verified **DICE!** implementation called DICE*. They focus on the software side of the first DICE layer and are agnostic to the actual hardware used. Therefore, it can be used together with the hardware designs from the previously listed works.

Bravi, Sisinni, and Lioy [74] explain how DICE can be implemented with the novel RISC-V technology Physical Memory Protection (PMP).

3.4 Software TPM!s implementation

fTPM! The official **TCG!** reference implementation of the TPM 2.0 specification is provided by Microsoft.[1] Raj et al. [37] wrap it with code attaching it to the interfaces required for Arm's TrustZone, yielding an **fTPM!**.[2] It is the implementation we base our work on. In their analysis they call for hardware entropy for a secure **fTPM!** implementation, but do not elaborate on how this can be achieved.

Gross et al. [78] propose backing an **fTPM!** with hardware without requiring a **dTPM!**. For that, they provide cryptographic and entropy support through hardware. This inherits the downsides of **fTPM!**s which are not related to a lack of hardware, but to the nature of software. For example, the resulting **fTPM!** is still started later in the boot chain than a **dTPM!**. Despite that, it is easier to update than hTPM since the lack of a dTPM, and the overall design is simpler.

In contrast, Kim and Kim [79] propose an abstraction layer on top of an **fTPM!** and a **dTPM!**—the hybrid TPM (hTPM)—which enables switching between the hardware and software module as required. They aim to combine their advantages, e.g., by making the dTPM the source for the hardware entropy, and by using the significantly better performance in **fTPM!** mode due to the use of modern CPU features. In addition, due to the availability of the **dTPM!**, it as available as soon as the system launches, while an **fTPM!** is booted later on. But for all that this comes at the cost of increasing complexity.

[1] `https://github.com/microsoft/ms-tpm-20-ref`

[2] In the directory `Samples/ARM32-FirmwareTPM`.

Virtual TPM The initially proposed design of virtual **TPM!**s requires the operating system and the hypervisor to be trusted [47].

Wang et al. [80] 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 required trust into to the individual enclaves and SGX itself, enabling the host operating system and hypervisor to be untrusted.

Pecholt and Wessel [15] 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 [81] 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. On the other hand, they intentionally do not support persistent storage to preclude exfiltration attacks on the TPM's data-at-rest, which has the disadvantage that persistent keys or other non-volatile data cannot persist across reboots.

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 [54], the identifier of a component is called the **FWID!** (**FWID!**). The **TCG!** consortium later renamed it **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 adopted this terminology renaming. Their DICE Attestation Architecture [82] defines an X.509 extension that contains the **TCI!**s. They continue to be referred to as **FWID!**s in the machine-readable formal definition of this extension, while everywhere else they are referred to as **TCI!**s. 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 (**??**) 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.

Occasionally, the name of an asymmetric key is suffixed with 'priv', 'pub' or 'cert' to designate the private part, the public part, or the certificate, respectively. For example, EKpriv refers to the private portion of EK. And EKcert corresponds to the certificate with EKpub as its subject key.

4.2 Architectural overview

The architecture of our proposed and later implemented system is illustrated in **??**. As you might notice, it is similar to our overview picture of **DICE!** (**??**). This is to be expected, since our system leverages **DICE!** as our **SRTM!** (**SRTM!**). 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 **DRTM!** (**DRTM!**), 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 TPM is reached. The component that measures the **fTPM!** is usually the trusted

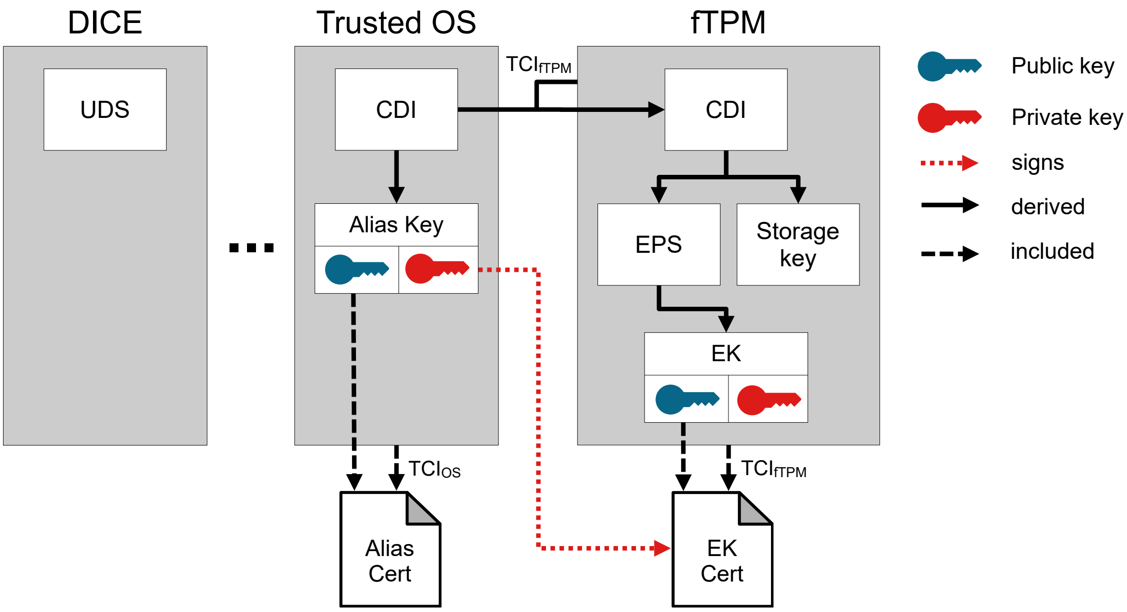


Figure 4.1: The architecture of our system.

operating system running in EL1 in the secure world, as seen in **??**. Like any other **DICE!** component, the **fTPM!** receives its secret **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!**. We derive two values from the **CDI!**.

4.2.1 Storage key

While the trusted OS within the **TEE!** might already encrypt data before it is sent to the storage device, this only binds the data to the **TEE!**, but not the identity to the **fTPM!**. For this purpose, we first derive a storage key from the **CDI!**. 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 plaintext data (**??**). As the storage key is derived from the **CDI!**, the storage data is only accessible to the **fTPM!** with the exact identity with which it was generated. For example, its identity changes 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!**.

An attacker could thereby easily trigger a data loss. This must be avoided by integrating 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 [83], 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

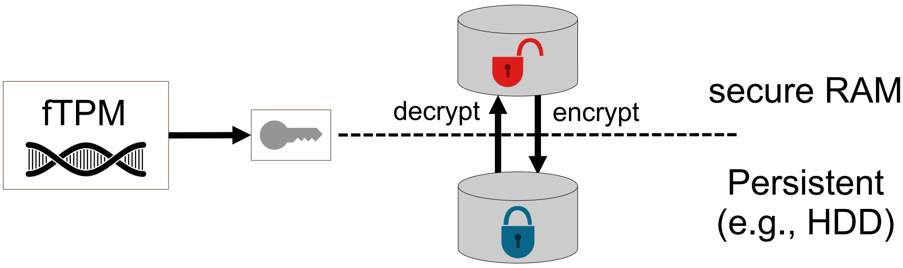


Figure 4.2: The fTPM's storage is protected by a key derived from its identity.

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 [84, 85]. For this reason, an RPMB partition is part of Microsoft's hardware requirements for a firmware TPM [37].

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.

4.2.2 EPS and EK

Then, the **EPS!** (**EPS!**) is generated based on the **CDI!**. It is the seed that is used to generate the primary **EK!** (**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 **EK!** from the **EPS!** via the **CDI!** instead of generating it 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 **CDI!** must also be removed from memory as quickly as possible to reduce the time frame in which leaks are possible, but the **EPS!** must be accessible to the **fTPM!** throughout its entire runtime. It is therefore good practice to extract long-term secrets from the short-term secret **CDI!** and then quickly delete the **CDI!** from memory.

The **EK!** of a **dTPM!** represents the long-term identity of its host device as long as the **TPM!** is not soldered or plugged away. Our **EK!** does not do this because an **fTPM!** 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 **??**. 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 [27].

By default, the **EK!** is a restricted encryption key. It is not used for signing by default because the resulting signatures may reveal the TPM's identity. We deviate from that by creating the **EK!** as a restricted signing key. While this breaks privacy of the prover, it has the advantage of not requiring a third party **CA!** (**CA!**). More details and an extension to our system introducing privacy is provided in **??**.

4.3 The identity of a firmware TPM

DICE offers two identities for each component—the TCI and the CDI. As shown in **??**, 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, i.e., only for case (iii). 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 a component's TCI is part of its CDI, as shown in **??**.

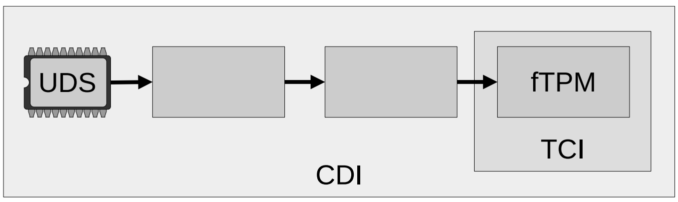


Figure 4.3: Visualizing the difference between the CDI and the TCI from the perspective of an fTPM component. The identity of the hardware is provided in the form of the **UDS!**.

Hence, we decided to derive the identity of an fTPM, i.e., its **EK!**, ultimately from the 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 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, which makes its measurement as part of the TCI pointless.

4.4 Attestation process

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 declared trustworthy, 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 Verifier establishes trust to the prover's fTPM

First, the verifier retrieves the DICE certificate chain generated by our solution from the prover. After verifying that the signatures of the certificate chain are valid, the verifier checks whether the DICE implementation is trustworthy by knowing its manufacturer. This also involves checking if the DeviceID certificate issued by the manufacturer was revoked. Such an event might occur if the security of an old DICE implementation is broken, and the manufacturer wants to reflect this.

At this point, the verifier must 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 **??**. Therefore, trusting the fTPM requires to trust all underlying firmware components.

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

The *trusted* function of **??** 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.

After doing all 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 subsequent protocols where the prover is challenged to be in control of EKpriv which corresponds to the EKpub of the EK certificate. For example, by verifiying the subsequently retrieved quote. Although this is not explicitly part of our proposed solution, we nevertheless describe it for better understanding and provide a comprehensive explanation of the entire attestation process.

4.4.2 Verifier establishes trust to the prover's quote

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 also needs to trust that the fTPM did not leak EKpriv, as this would not only allow to replay a whole certificate chain, but even succeed the subsequent protocols with the leaked EKpriv. The verifier can derive whether it considers the EKpriv 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.

To trigger the protocol, the verifier sends a nonce to the prover, which includes it 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 manufacturers in that they only sign an 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, the verifier needs to derive from the fTPM's TCI embedded in the EKcert that the EK is restricted. For the EK's attributes to be represented in the TCI, the template containing the EK's attributes must be generated in the firmware TPM's code. This ensures that the TCI also represents the template.

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 **??**).

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

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. So, this certificate needs to fulfill the requirements for an Alias certificate from the DICE specification [86], and the EK certificate requirements from the TPM specification [87]. Therefore, we need to ensure that these two specifications declare no conflicting requirements. DICE [86] 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 [88]. 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 **CA!** signing further certificates.

We present the result of our compatibility study in **??**. 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

Table 4.1: Comparing the requirements for an Alias and **EK!** certificate. 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
Subject Alternative Name	–	TPM details	No
Validity (not before)	known time in recent past e.g., build time	–	No
Validity (not after)	no expiration	no expiration	No
Authority Key Identifier	–	must be present	No
Key Usage	not to verify signatures of certificates	verify signatures other than those on certificates	No
Certificate Policies	Local Attestation	at least one policy	No
Basic Constraints	–	not a CA	No

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 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. An empty subject names also appears to be common practice in EK certificates, as this is the subject name chosen for all EK certificates we observed. 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 [87]. 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 verifiers trust a TCI, they 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 embedded by the TPM's manufacturer. For example, an underlying firmware component could change these details embedded in the firmware TPM to pretend that 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 **fTPM!**s 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 identity 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 [89] and Intel [90]. It is underpinned by the importance of pausing BitLocker before upgrading a TPM due to its upcoming data loss [91]. Thereby, BitLocker's encryption key is temporarily stored in plaintext on the hard drive, which is consequently restored on the TPM after its update.

Apart from the associated loss of data, there is no other obstacle to updating the **fTPM!**. Updating in this sense even means replacing, e.g., with the fTPM of another manufacturer. As it is explicitly measured, it can be replaced at will without changing the manufacturer of the **DICE!** or **TEE!**.

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 **??**, 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.

Both is solved by introducing a new signing key—the **AK!** (**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 **AK!**s 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. However, the AK also has to be certified to originate from an authentic TPM, just as the EK. In contrast to certifying **EK!**s, manufacturers cannot be called upon to vouch for **AK!**s. This is because if a manufacturer is referenced in the certificate of an AK, it is disclosed to the verifier, which means that privacy-relevant information is revealed. Instead, we rely on a third-party **CA!**, commonly referred to as privacy **CA!**.

The privacy **CA!** replaces the DICE manufacturer as the root of trust for the verifier. For this purpose, this **CA!** 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 it is about the DICE manufacturer referenced by the DeviceID certificate. 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 constructed with AKpub and encrypted with EKpub, which can only be solved by an entity who has control over AKpriv and EKpriv. 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 [8] under "Attestation Key Identity Certification" and "Credential Protection."

In addition, this privacy extension removes the need for a custom template of **EK!**, resetting it from a signing key to an encryption key, as signing with the EK can reveal the identity of the TPM.

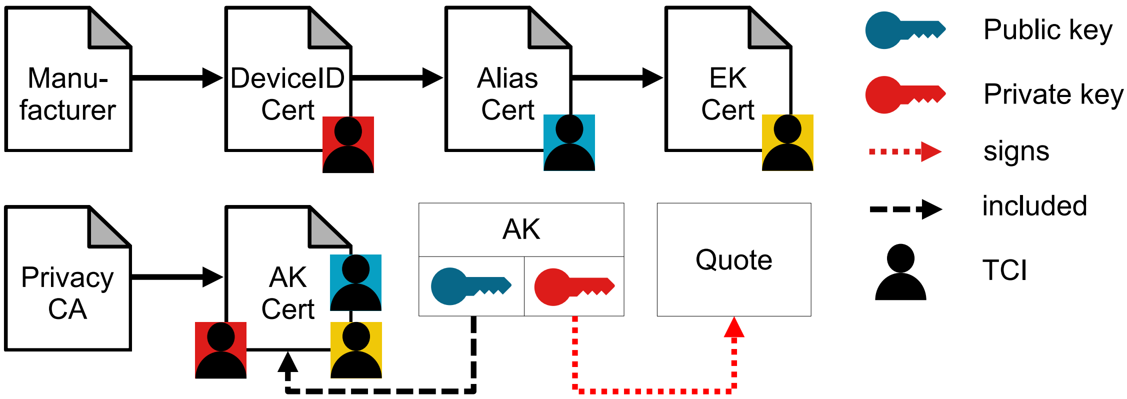


Figure 4.4: The adapted architecture integrating privacy.

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 **??**. 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 **??**, 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 **??**. For that, the verifier must trust the issuer of the AK certificate to have verified that the **AK!** is stored on an authentic TPM. However, the privacy CA does not need to check whether AK is restricted. This can be carried out by the verifier itself, as it continues to receive the TCI of the fTPM.

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. The privacy of the prover is guaranteed by the fact that the prover does not transmit any data derived from its **UDS!** to the verifier.

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 [8]. 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 plaintext 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 **??**, from now on the term **FWID!** (**FWID!**) will be used instead of the previously used term **TCI!** (**TCI!**). Also keep in mind that while **TEE!** and **REE!** are the technology independent terms, we mainly use **SW!** (**SW!**) and **NW!** (**NW!**) here because of our implementation with Arm's TrustZone.

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 and FVP do 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 **??**. 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`

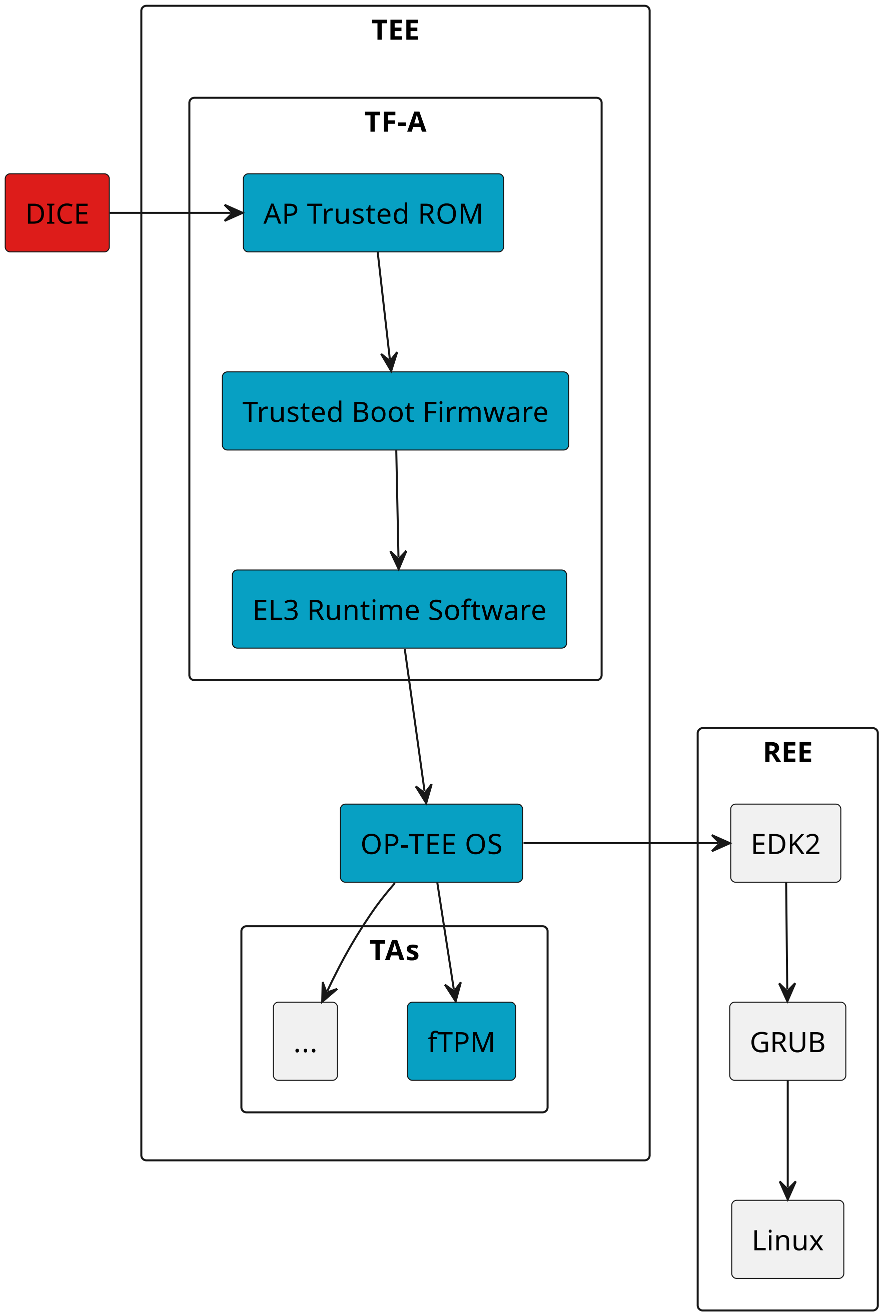


Figure 5.1: The boot chain of our system running in Arm's FVP. Blue: Represented by our yielding certificate chain. Red: Root of trust for verifier, and also just assumed to be present.

TF-A After reset, the CPU executes within the **SW!**. That is also the reason why boot software that is unaware of the separation between **SW!** and **NW!** are running in the **SW!**, as they never modify the execution environment of the processor. This ensures that such systems have all expected privileges, which would be restricted in the **NW!**. 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—the 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 **NW!** software to function correctly. It also provides the monitor which conducts the context switches between the **SW!** and the **NW!**. More complete and detailed information can be found in the TF-A documentation.[4]

OP-TEE OS Just like an ordinary OS, OP-TEE OS[5] initializes its functions offered to the user space of the **SW!**, i.e., the **TA!**s (**TA!**s).

Trusted Applications Our TA in focus is the firmware TPM. We use the reference code[6] by Microsoft which implements a TPM, and the stub code, which provides and implements the interfaces required to be a TA of OP-TEE OS. The combination of the TPM code with the OP-TEE interfaces results in a **fTPM!**. 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.

EDK II TianoCore EDK II[8] is the first component launched in the **NW!**. It is a reference implementation of UEFI [50] by Intel.

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

Linux The final component to boot is the Linux[10] operating system.

[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
[9] https://www.gnu.org/software/grub/
[10] https://www.kernel.org/

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 functions that are needed. We therefore had to activate some functions.

The formulas which derive secrets directly from the CDI (**??**, **??**) use a keyed-hash message authentication code (HMAC) function. This is inspired by the CDI derivation proposed in the DICE hardware requirements specification [58]. Actually, it proposes two functions to combine information to a new secret—a simple hash function, and a HMAC function. It also 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. [76], and NIST SP 800–57 [92]. 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-128, and therefore, use the MD5 function to retrieve a key with a sufficient size. Note that while MD5 is considered broken, HMAC in conjunction with MD5 is not [93]. The HMAC functions are seeded with a fixed character string that describes the purpose of the output secret.

$$K_{storage} = HMAC_{MD5}(CDI,\ \text{'}DATA\ STORAGE\ KEY\text{'}) \tag{5.1}$$

$$EPS = HMAC_{SHA512}(CDI,\ \text{'}ENDORSEMENT\ PRIMARY\ SEED\text{'}) \tag{5.2}$$

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

We must ensure we retrieve exactly the same EK as the TPM would generate by a `TPM2_CreatePrimary` request with our EK template. Therefore, we use the 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 **??**. A pseudo **TA!** (PTA) provides the same interfaces as an ordinary TA, but runs in kernel mode within OP-TEE OS instead of in user mode. 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 hashes the memory pages of the calling TA that are constant, i.e., executable or read-only data. Also, Microsoft's fTPM reference implementation does not contain separate configuration files, which simplifies the TCI generation of our fTPM by limiting it to the measurement of the fTPM itself. The attestation PTA signs EKcert with OP-TEE's private alias key. This key is mocked

[11] `https://mbed-tls.readthedocs.io/en/latest/`

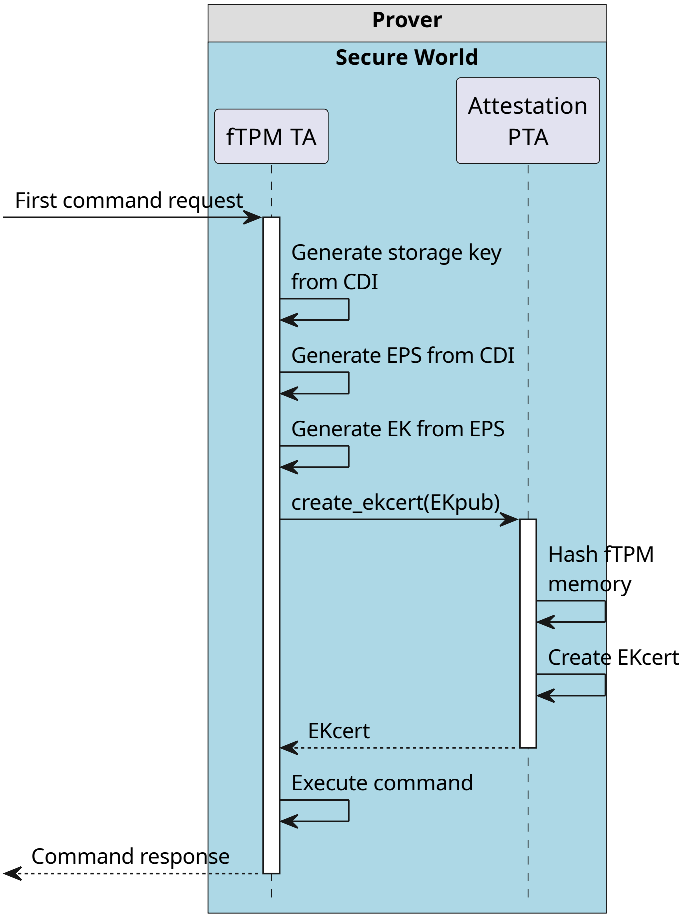


Figure 5.2: A UML sequence diagram describing the initialization of our firmware TPM.

in our implementation. Note that the fTPM has never access to the private alias key of OP-TEE OS, so it cannot fake its alias certificate/EKcert.

Another approach to measure the fTPM is to simply extract the hash embedded in its TA 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 a 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 an X.509 extension defined by the DICE Attestation Architecture [82]—the TCB Info Evidence Extension. It 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

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

warnings with a modern C compiler. While it allows multiple FWIDs to be embedded into an X.509 certificate, our implementation only stores one into each alias certificate. However, the privacy focused architecture explained in **??** 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 SHA-256.

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

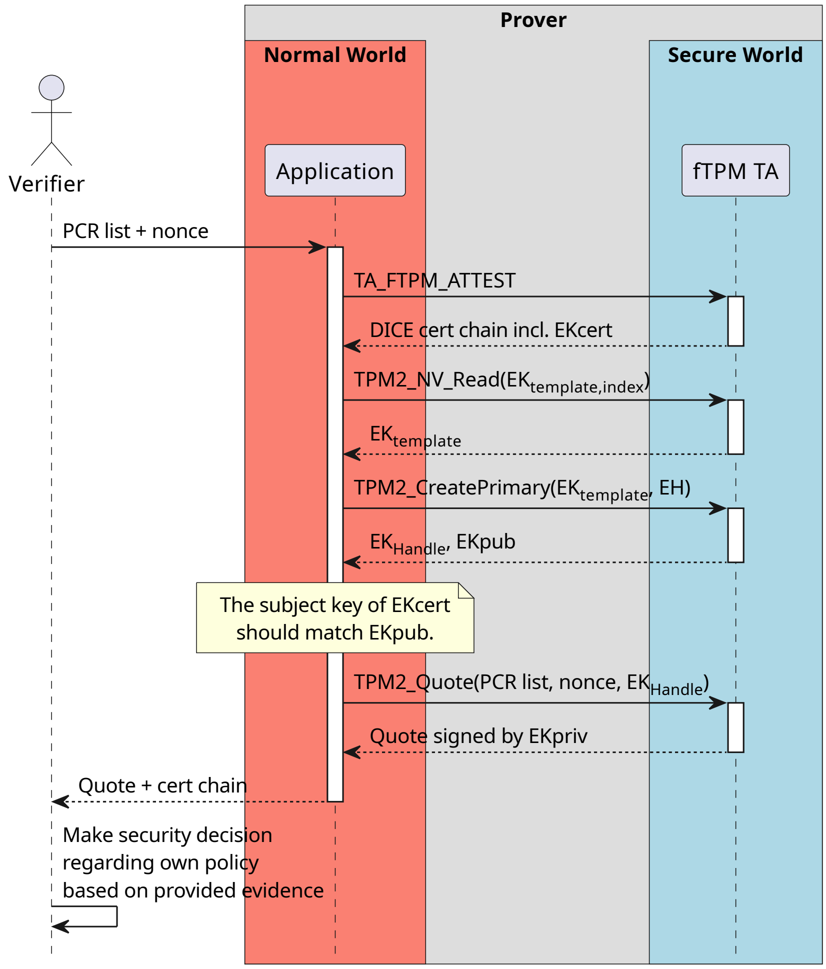


Figure 5.3: A UML sequence diagram describing the attestation of our firmware TPM.

We added a new TA command called `TA_FTPM_ATTEST` to the **fTPM!** 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 **fTPM!** TA only ever allows a single connection to it, which is usually a Linux module that provides 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.

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

Afterwards, the prover wants the **fTPM!** to create the EK including its private portion. To do this, it first reads the EK template from the non-volatile (NV) storage of the fTPM, which was used earlier to create the EK part of the EKcert during the initialization process of the **fTPM!**.

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 and the specified hierarchy is used instead. So, we specify the endorsement hierarchy (EH), which makes the TPM use the **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 plaintext.

Eventually, the prover wants to create a quote to establish trust to the prover's system state in the **NW!**, 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

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

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 plaintext PCR values are transmitted unprotected to the verifier. After validating the quote, the verifier can check whether the hash of the plaintext 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 **??** 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 [8], 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. 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.

A TPM can save an EK template, but is not obliged to do so. Then, the default template defined by TCG [87] is used, dictating the **EK!** 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 [94] with SHA-256, and (iii) no inner symmetric key as required by the TPM specification [8] 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 **fTPM!**. Thus, it is always present and stored in the NV index `0x01c00004` as defined by the TPM EK specification [87] for RSA-2048 EK templates. We set the attributes for this NV index as defined by the TPM PC Client specification [30]. 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 [87] with the same attributes as the respective template, so that it also cannot be deleted. 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 **fTPM!** 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 **??** 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. While the host generates the mocked certificates, the FVP must continue the certificate chain and also check whether the current time falls within the validity period of the resulting certificates. 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 the guest machine and the certificate's validity periods to pre-determined values. 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` [95].

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 16,896 bytes, separated in a NV storage of 16,384 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 16,896 bytes in 512 bytes blocks resulting in 16,896 ÷ 512 = 33 blocks.

We consult the recommendations of the BSI [96] 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 **??**.

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

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 expect that the impact on performance will be small.

5.8 Isolating storage of fTPM in OP-TEE

The data of the individual **TA!**s must be saved somewhere permanently. The OP-TEE OS stores them in the **REE!** file system. Hence, this data must be protected. OP-TEE encrypts the secure storage files before sending them to the **REE!** 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 **TA!**—the **TA!** Storage Key (TSK). It is derived from the Secure Storage Key (SSK), which is unique to the device.

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

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

$$file_{plain} = decrypt_{FEK}(file_{cipher}) \tag{5.7}$$

?? 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 [97], 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 [98]. 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, which conforms to the TPM specification [87]. 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. Later, the maintainers of the `tpm2-tools` fixed it.[16] 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 fixed this issue.[17]

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/issues/3278`
[17] `https://github.com/tpm2-software/tpm2-tools/pull/3280`

problem and fixed it.[18]

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.[19]

The OP-TEE OS provides a libc library which implements only subset of the C standard library. Its authors copy code of the newlib[20] to their libc on-demand when required. Unfortunately, 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 for the OP-TEE platform 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.[21]

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.

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

6 Discussion

6.1 Assessment of the fulfillment of requirements

6.1.1 Security goals

Here, we return to the security goals defined in the introduction and describe how we fulfil them.

- **Compromised fTPM cannot fake its identity**
  The predecessor component of the fTPM, i.e., the trusted OS, performs the measurement of the fTPM, embeds it in the alias certificate representing the fTPM and signs it with its private alias key. As long as the trusted OS behaves correctly, the fTPM has no access to the trusted OS's private alias key. Therefore, the alias certificate representing the fTPM can be trusted if the TCI of the trusted OS is trustworthy since it presents the trusted OS's behavior, as then the fTPM cannot fake the certificate containing its identity. Actually, all TCIs of the preceding components must be trusted for that. In general, each component of the fTPM firmware stack must not have access to the private alias key of the component preceding it.

- **Small root of trust**
  We base the trust in our system on the design and guarantees of the DICE architecture. Its root of trust consists of the **UDS!** and its protection mechanisms. The **UDS!** may only be read once per operating time of the implementing device and only by DICE. As the actual secret is a single integer value that represents a statistically unique value, we consider the root of trust to be small.

- **Isolation of fTPM storage**
  The problem originates from the fact that the File Encryption Key (FEK) for the data of a TA is derived by a TEE-wide secret and the TA's UUID, with the latter being public. Hence, any TA can potentially derive the FEK of any other TA within the same TEE. However, they cannot know the other TA's CDI, since TA's cannot measure each other. Consequently, this prevents other TA's from generating the fTPM's storage key of our solution. If the trusted OS or any other preceding component is modified, e.g., to leak the fTPM's data, the CDI of the fTPM changes, consequently its storage key and its old data cannot be accessed anymore.

- **Protect fTPM data against downgrade attacks on the fTPM**
  The binding of the TPM data to the identity of the fTPM described for the storage

isolation also protects against downgrade attacks. Whether an fTPM is updated, downgraded or otherwise changed with malicious intent is reflected in its CDI, so that the old storage key cannot be restored.

- **Privacy of remote attestation process**
  We have proposed an extension to our system to ensure the privacy of the prover during the remote attestation process. For this purpose, we introduce a proxy, the so-called privacy CA, between the verifier and the prover. In this process, the prover sends its certificate chain to the privacy CA, which must verify that the prover is benign, and then packages the information in a way that preserves privacy by leaving behind information that reveals the prover's identity to the verifier. For example, the privacy CA must verify that the verifier's DICE implementation is authentic with its DeviceID certificate and that the fTPM is actually running within the TEE. This requires information about the prover's hardware, which must not be disclosed to the verifier if data protection is a concern for the prover. If privacy CA honors its promise not to disclose the prover's identity and the verifier trusts the privacy CA, the prover's privacy is protected.

6.1.2 Attestation process requirements

TCG! defines as part of their Trusted Attestation Protocol [99] 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 identity of the device's firmware. 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 freshness not alone, it is established by the subsequent protocol, e.g., retrieving a quote, as long as a verifier-supplied 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. Just like accuracy, this is also solved by the protocol that follows the attestation of the fTPM, since such protocols usually involve signing of attestation data, usually a quote. The quote must be signed with EKpriv corresponding to the EKpub in the EKcert. And EKpriv can only be created by a device that has the **TCI!**s 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 [23].

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 attestation data 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 generated by the device provisioner itself. If its build environment does not support reproducible builds [100], 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 **fTPM!**s over **dTPM!**s 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 **fTPM!**s by Raj et al. from Microsoft [37], 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 **fTPM!**. Thereof, a hardware fuse, a secure entropy source, and a TEE are commonly part of the processor without the need for additional hardware. An RPMB partition is required 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 **dTPM!**s. However, storage has to present anyway, and a RPMB partition is supported by storage technologies commonly used in embedded devices, e.g., eMMC [84] and UFS [85].

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 [77], 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 **dTPM!**, 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 during the boot process. It can therefore understand that the fTPM was launched and 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 attesting the fTPM's identity

The identity of a software component does not contain its current state. While the identity of a software can be derived from its binary file assuming it is statically linked, its state is derived from a snapshot of its memory during runtime.

We attest the identity of the fTPM and not its state. This means that we do not detect attacks that occur after the startup process, i.e., during its runtime.

7 Conclusion

In the final chapter, we briefly answer the originally proposed research questions, present some closing thoughts and also indicate directions for possible future research based on our work.

7.1 Why we did it?/The problem

7.2 Answering research questions

Identity of fTPM! The first question asked what constitutes the identity of an fTPM. We found that it is important for its identity to include its entire underlying software stack. This is due to the reason that each predecessor directly affects the security of an **fTPM!**. Despite that, it is still not unique. Therefore, it must also depend on a unique value, which we integrate by involving the **UDS!**. Only by that, its identity can represent uniquely an **fTPM!**.

DICE! + TPM! Next, we provide a design to combine the infrastructures of **DICE!** and **TPM!**. Here, the most important point is where the both infrastructures meet. While **DICE!** measures and derives thereon dependent secrets from the start of the device, the **fTPM!** is launched later in the boot chain. When it is eventually executed, it retrieves its **CDI!** from **DICE!**, which represents the fTPM's identity as understood previously from the perspective of **DICE!**. Based on that, the **fTPM!** derives its **EPS!**, which is the root seed for its **EK!**, which represents its identity from the perspective of **TPM!**s. In short, the infrastructures meet and are combined at the step from the **CDI!** (DICE) to the **EPS!** (TPM).

Manage the fTPM's data securely Another important question to take care of is what involves managing the fTPM's data securely. The underlying question is what *securely* means in this context. On the one hand, you want to make the data from the fTPM as widely available as possible; on the other hand, the data should be linked as closely as possible to the fTPM. We thereby choose to bind the data to an fTPM as long as its security relevant factors to not change, whether for the better or for the worse. This matches with our definition of the fTPM's identity, which is constant as long as the underlying firmware does not change, which directly affects the fTPM's security. Hence, we derive a storage key from the fTPM's **CDI!**, with which we protect the confidentiality and integrity of its data.

Privacy

7.3 Relevance

7.4 Summary

In this work, we have proposed a novel remote attestation scheme to establish trust in an **fTPM!**. **fTPM!**s cannot be trusted based on their isolated identity alone, as their underlying software components are also security relevant, unlike **dTPM!**s 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. It is in the nature of certificates that they are not secret and can therefore be easily replayed by malicious provers. Hence, the verifier must ensure that the certificates correspond to the device it 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!** attesting the state of the system with a quote. To do this, the prover must prove to be in control of the private key that corresponds to the public key part of the certificate that describes the **fTPM!**. These keys are unique for the identity of the device (the **UDS!**) and the identities of the individual components (the **TCI!**s) 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 **fTPM!** and its upstream software, whereas today verifiers trust a single manufacturer who is assumed to have provided all these components. Our system also creates a hardware root of trust for the **fTPM!** which, as the name suggests, cannot be provided by the **fTPM!** as it is a software component. In contrast, **dTPM!**s are capable of acting as a hardware root of trust. Our system closes this gap.

7.5 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. This is especially interesting since we integrate another storage encryption.

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 SGX.

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 [101]. It is based on the concept of DICE, but is not limited to it.

As mentioned in **??**, 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, **TA!**s 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.

Abbreviations

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