SCHOOL OF COMPUTATION, INFORMATION AND TECHNOLOGY — INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Master's Thesis in Informatics

Establishing Trust in an Updatable fTPM Using Remote Attestation

Andreas Korb

SCHOOL OF COMPUTATION, INFORMATION AND TECHNOLOGY — INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Master's Thesis in Informatics

Establishing Trust in an Updatable fTPM Using Remote Attestation

Herstellung von Vertrauen in ein aktualisierbares fTPM durch Remote Attestierung

Author:	Andreas Korb
Supervisor:	Prof. Dr. Claudia Eckert
Advisors:	Albert Stark, Johannes Wiesböck
Submission Date:	15.01.2024

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

Acknowledgments

I want to take this opportunity to thank all those who have supported me in preparing this thesis. My thanks go to my supervisor Prof. Dr. Claudia Eckert, who gave me the opportunity to write this thesis. I would also like to thank my advisors, Albert Stark and Johannes Wiesböck, who patiently stood by my side and answered all my questions. Without their help and support, this thesis would not have been possible, and I am sure they have helped me immensely to start my journey in the field of cyber security. Lastly, I would like to thank all my friends who have been patient and understanding while writing this thesis and have sacrificed their time to proofread my work.

This work was created at the 'Fraunhofer-Institut für Angewandte und Integrierte Sicherheit AISEC' in Garching. It is part of the 'Fraunhofer Society for the Promotion of Applied Research e. V.', an organization distributed over Europe focusing mainly on applied research.

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 Trusted Platform Modules (TPMs), for example. To do this, they are authenticated by retrieving their endorsement certificate, which links the TPM to its manufacturer. This manufacturer guarantees that it complies with the TPM specification to ensure its security properties. While this approach is sufficient for hardware TPMs as they are standalone chips, for firmware TPMs (fTPMs), any preceding firmware component can compromise the later loaded fTPM. Therefore, it must be assumed that the manufacturer of the fTPM is the same as that of all firmware components booted before the fTPM to establish trust in them. The underlying problem is that the verifier in the remote attestation procedure cannot verify the entire boot chain up to the fTPM. We propose a remote attestation system that provides the verifier with this capability. To compensate for the lack of a hardware root of trust of an fTPM compared to a hardware TPM, we introduce Device Identifier Composition Engine (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 the fTPM by a 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 explains the problem we are addressing, 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 to 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 resources (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 Figure 1.1. The challenge is that the verifier observes nothing but bytes from the prover, and while a benign prover will tell the truth about its state, a compromised prover will lie about its state and claim a trustworthy one. Therefore, the verifier must establish trust in a helper component on the prover's side. In a typical setup, this component is immutable without the involvement of its manufacturer, which reveals itself to a verifier by signing and storing a certificate on the helper components supplied by it. This allows the verifier to establish trust in the helper component by knowing its manufacturer. Consequently, the component attests to the state of the prover's machine, from which the verifier can deduce whether the prover can be considered trustworthy.

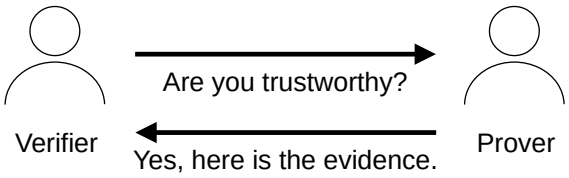


Figure 1.1: Simplified remote attestation process.

For example, this can be done with a Trusted Platform Module (TPM) on the prover's side. They rise in their deployments and importance, e.g., in 2013, the President's Council of Advisors on Science and Technology encouraged 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 discrete TPM (dTPM) increases cost and hardware complexity—especially for embedded platforms. Firmware TPMs (fTPMs) running in a Trusted Execution Environments (TEEs) 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, 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 because 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), this does not represent the underlying firmware stack.

Currently, this is solved by the manufacturer providing not only the fTPM, but also the entire underlying firmware stack. Consequently, by establishing trust in the manufacturer of the fTPM, one can implicitly trust the underlying firmware 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. If the attester trusts the manufacturer and its provided guarantees, trust is established in its provided components.

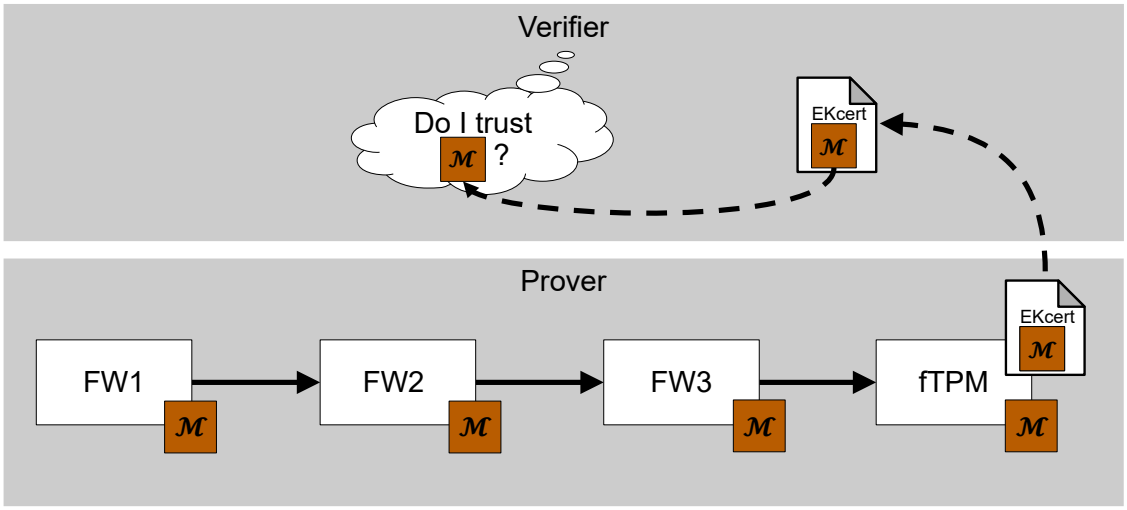


Figure 1.2: The naive process of how a verifier establishes trust in an fTPM is done by trusting its manufacturer. The brown markers indicate a manufacturer. The firmware (FW) and the fTPM were built by manufacturer $\mathcal{M}$, and the EK certificate references this manufacturer.

This process is illustrated in figure Figure 1.2. The prover's box shows its boot chain, and 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 component. Note how the verifier must assume that the manufacturer of the

firmware components is the same as that of the fTPM. To the best of our knowledge, this is what manufacturers like Intel and AMD implement for their fTPMs, as confidence in their fTPMs is also only established through an EKcert [6].

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 in the other firmware components this manufacturer provided without knowing the firmware. This approach is limited, as with this mechanism, independent verifiers have to unquestioningly trust the firmware manufacturer, drastically limiting 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 few hardware requirements and without compromising security. This approach aims 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 whether they are trustworthy without relying on its manufacturer. Instead, it is sufficient to trust the independent manufacturer of the hardware root of trust, which requires minimal assumptions, such as the absence of side-channel vulnerabilities.

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

We propose a hybrid solution, combining the advantages of DICE and fTPMs, yielding an independently verifiable certificate chain representing the boot chain up to and including the fTPM. This enables a verifier to establish trust in an fTPM if the underlying firmware is also benign, thus providing a way to independently assess the properties of the fTPM.

The research questions we aim to answer are listed below.

RQ-1 What constitutes the identity of an fTPM?

RQ-2 How to combine the DICE and TPM infrastructure?

RQ-3 How to manage an fTPM's persistent data securely?

RQ-4 How to enable privacy in this attestation mechanism for the prover?

1.3 Threat Model

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

For the network, we assume the Dolev-Yao attacker model [7], wherein an attacker can perform any active or passive attack on the network. The attacker may also control 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.

SG-1 Compromised fTPM cannot fake its identity
It is sufficient for a fake identity to be recognized by the verifier, who can consequently classify the prover's fTPM as untrustworthy.

SG-2 Small root of trust
A small root of trust, e.g., in code size, hardware size, and complexity, bears less risk in implementation errors, directly affecting security [8].

SG-3 Isolation of fTPM storage
Data must only be accessible or modifiable within the boundaries of the fTPM's access controls, i.e., the TPM commands defined by its specification [9]. This includes protecting against other trusted applications running in the same TEE.

SG-4 Protect fTPM data against downgrade attacks on the fTPM
Data of the fTPM should be sealed to its identity, such that when the fTPM is modified, e.g., by a downgrade attack, even the fTPM cannot access its old data anymore.

1.5 Outline

In the Background, we provide the knowledge necessary for a better understanding of the subsequent parts of this thesis. Afterward, we discuss Related Work, i.e., attacks on TPMs to further motivate this work, approaches to hardening TPMs, and work that enables remote attestation similar to ours. Under Methodology, 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 the Conclusion.

2 Background

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

2.1 Trusted execution environment

Privilege levels of processes are a core security concept of operating systems [10]. Thereby, processes are protected against other processes with the same or lower privilege level. However, they are not protected against more privileged processes [11], causing problems for cloud and edge computing. In cloud computing, other services, the hypervisor, or the cloud provider could potentially access sensitive data of the cloud tenant [12]. In edge computing, the edge applications deal with plaintext data while potentially running on insecure edge devices [13]. Hence, protection against more privileged processes is desired.

The TEE is a technology defined by GlobalPlatform[1] as an integrated hardware extension to processors. By that, the execution environment is separated into the Rich Execution Environment (REE) and the TEE by hardware. The REE runs commodity software, e.g., a Linux-based operating system with user applications. The TEE is an isolated tamper-resistant execution environment that guarantees the authenticity of the executed code and the integrity of runtime states, e.g., memory [14]. No separate chip is required since a TEE is integrated into the processor. Moreover, the TEE commonly follows the same user and kernel space separation as a rich OS. The kernel space runs a trusted OS, and the user space runs the trusted applications (TAs). It focuses on resisting software-based attacks generated in the REE but also protects against some hardware attacks [15].

Previous, mostly software-based technologies ensure confidentiality and integrity protection of data-in-transit and data-at-rest [16], while a TEE additionally protects data-in-use in hardware [16, 17].

Figure 2.1 illustrates the motivation of a TEE. In a traditional architecture without a TEE, the complete system is affected if an attacker compromises it. 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. In contrast, the attack surface of a trusted OS is relatively small and has tightly controlled interfaces.

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

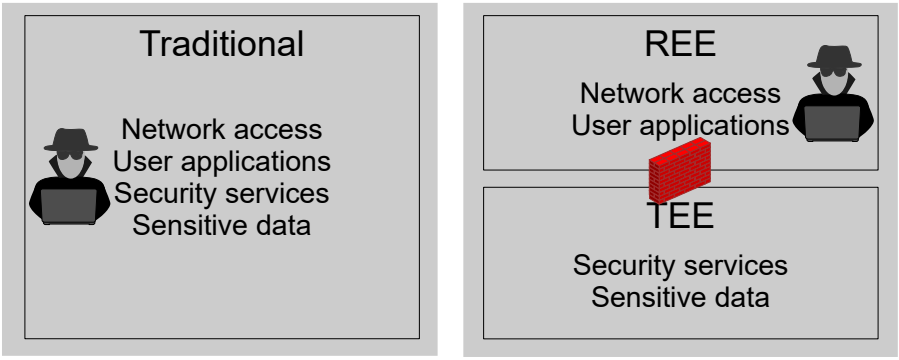


Figure 2.1: Comparison between a traditional architecture and an architecture separating the REE and TEE. This illustrates the motivation of a TEE.

Arm TrustZone One such TEE is Arm's TrustZone [18, 19]. It partitions all software and hardware resources of the containing system into the Normal World (NW) and the Secure World (SW), as shown in Figure 2.2. The secure monitor is triggered by the dedicated instruction Secure Monitor Call (SMC), which then manages the context switches between the NW and the SW. While the SW can access the resources of the SW and the NW, the NW is restricted to its own assigned resources. Since Arm is the dominant processor architecture for Internet of Things (IoT) devices with a market share of 86 % as of 2022 [20], many of the approaches in this field of research use Arm TrustZone [21].

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

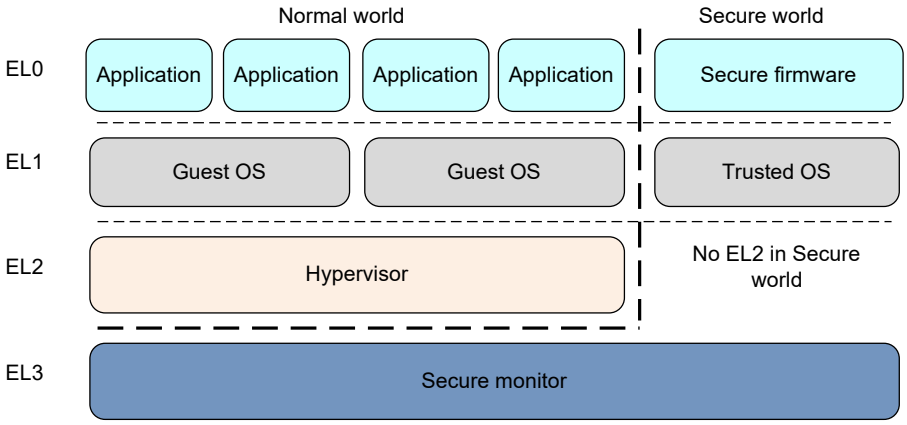


Figure 2.2: The architecture of Arm TrustZone for AArch64 [22]. The exception levels (EL) indicate the privilege levels; the higher, the more privileges.

2.2 Remote Attestation

According to NIST SP 1800–19B [23], 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."

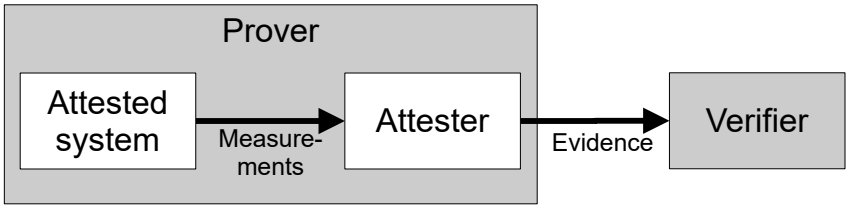


Figure 2.3: Data flow of attestation data for a remote attestation [24].

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 [25, 26]. Figure 2.3 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 Root of Trust for Measurements (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 in the attester by getting to know its manufacturer and the security properties that it guarantees. Consequently, the verifier can trust the statements the attester conducts about the attested system.

Remote attestation commonly consists of two steps [27]. (i) The attestation, and (ii) establishing a secure channel. In this work, we focus on the first step.

A remote attestation procedure can be divided into two categories—implicit and explicit attestation [28]. In implicit attestation, the prover's state is implicitly inferred from the prover having control over a signing key, which is only possible if it is in a known state. That is, the sole ability to create the evidence defines the properties of trustworthiness. With explicit attestation, the device's state is explicitly described in the evidence. The solution we propose carries out an explicit attestation.

2.3 Trusted Platform Module

The Trusted Computing Group (TCG)[2] published the first TPM specification (v1.1) in August 2000 [29], and the most current specification to date (v2.0 Revision 01.59) 19 years later in November 2019 [9]. 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. Table 2.1 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 [9], some alternative names behind them in brackets, as they are sometimes referred to, and the intended use-case of the hierarchies [30].

- **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 used as a cryptographic coprocessor. Keys in this hierarchy are discarded when the TPM is restarted.

The hierarchies are separated to provide actors granular access to the TPM. For example, a privacy administrator can only have access to the endorsement hierarchy,

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

while the end user only has access to the owner hierarchy. They possess different behaviors as well. The Null hierarchy cannot be restricted. The Platform hierarchy is initialized with an empty password on each restart of the TPM and is intended to be locked by the early boot code by setting a password only known to the early boot code.

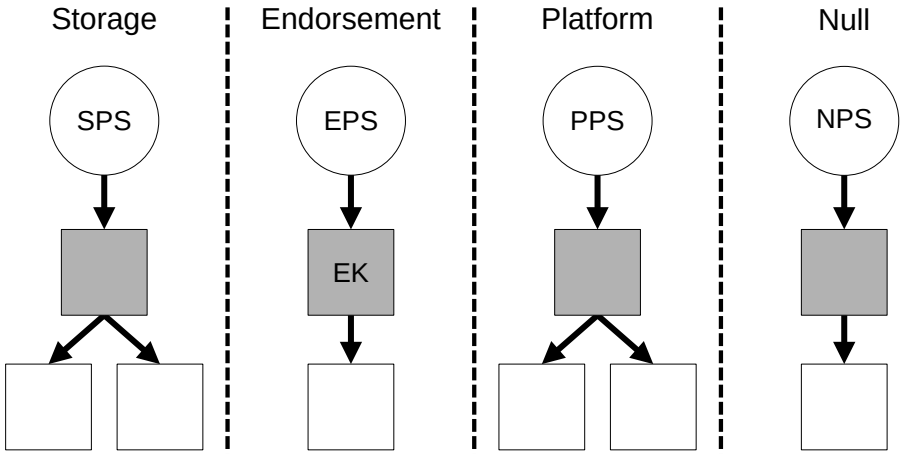


Figure 2.4: The source of entropy of the keys generated in a TPM for each hierarchy. Circle: primary seed, e.g., the storage primary seed (SPS); gray rectangle: primary key, e.g., the endorsement key (EK); white rectangle: ordinary key.

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 Figure 2.4. 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 its type 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 [9]. This prevents an attacker from asking the TPM to sign an artificially constructed quote for signing keys. Analogously, restricted encryption keys can only be used to encrypt data generated by the TPM, e.g., other keys created on the TPM.

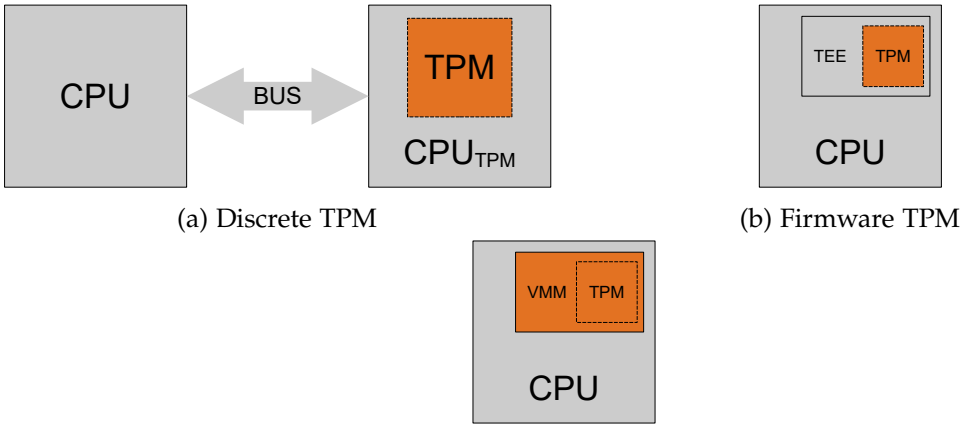
The Platform Configuration Registers (PCRs) are the fundament for the remote system attestation. They are one-way registers in which values can never be explicitly written but only extended; this operation is known as *hash extend* [30]. Its design prohibits the removal of extensions, which would cause 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 [31], with the first eight representing the firmware boot process and the higher ones representing

the OS or applications [32]. The fixed length of the PCR values is essential for the memory-constrained nature of TPMs [30].

The PCR value at index i can only be modified, i.e., extended, by adding together the currently contained hash value and the new hash, as depicted in Equation 2.1 [9]. 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 [31] 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 [33–35]. Although the SHA-1 uses in TPM 1.2 were analyzed to be not affected [36], cryptographic algorithms only become weaker over time [30]. 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 [37] 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 TPMs—discrete TPMs, firmware TPMs, and virtual TPMs—as illustrated in Figure 2.5. They all offer the same functionality but have different security guarantees and performance characteristics, as explained in the following sections.

2.3.1 Discrete TPM

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

TPM specifications [9, 31] 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 Firmware TPM

fTPMs [38, 39] are executed in the environment of the host CPU. In other words, they share hardware resources such as memory and execution units with other software, while dTPMs do not. A typical environment for fTPMs are TEEs isolating them from the REE, which means that even the OS in the REE cannot arbitrarily access the memory of the fTPM but must adhere to the fTPM's and TEE's provided interfaces.

The trend is moving towards fTPMs, which can also be seen by the increasing efforts to bring them to the RISC-V processor family [40]. Typical implementations are the Intel® Platform Trust Technology (Intel PTT) [41], and AMD's Secure Processor (AMD-SP), with the latter being an Arm-based coprocessor on the die with TrustZone [42].

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 only accessible by the TEE [43]. Last, fTPMs depend on more components for their security than single-component dTPMs, e.g., the hardware-provided isolation between the REE and the TEE, and the boot chain.

However, since they require only a TEE, which is mostly already available at currently used processors, they are cheaper for manufacturers as they need less extra hardware. In addition, TPM processors are weak [38, 44]. Raj et al. [38] and Cheng et al. [45] independently conclude that firmware TPMs executed on main processors are generally much faster than dTPMs. fTPMs 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 [46, 47].

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 VMs [48]. They can be realized purely in software [48] or backed by dTPMs [49]. A characteristic feature of virtual resources is their migration capabilities, i.e., they can be suspended and later continued on another machine. vTPMs do not 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 [50–52] 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 to verify the boot components' digital signatures, ensuring their authenticity. Alternatively, merely the hashes of the components can be measured and compared with benign reference values, ensuring integrity and not authenticity. The first boot component stored in ROM must be trusted without verification, forming the root of trust. Nonetheless, plain Secure Boot does not prevent downgrade attacks since only the authenticity, not the concrete versions of boot components, are verified [53].

In contrast, Measured Boot conducts precise measurements of the booted software for retrospective evaluations [54]. 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 Section 2.3, 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 initially proposed by Microsoft as part of their Robust IoT (RIoT) architecture [55]. In 2017, the DICE specification was published by TCG [56], 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 [28]. 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 measures the subsequent component before handing over the execution. 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) [57, 58]. The union of all security-relevant components of a device form its Trusted Computing Base (TCB). Their individual identities are called TCB Component Identifier (TCI), 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. Some configurations are not part of the binary usually provided in well-known formats such as `json` or `xml`. They must be measured with the corresponding binary file or represented by two separate TCIs.

The DICE layer is the first to be booted. Its specification [59] states three hardware requirements. The DICE layer

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

These requirements can be justified intuitively. (1) The UDS must be read-only and unique to the device to provide a basis for long-term identification and derivation of the device's 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. For example, this lock mechanism can be realized with eFuses [59]. (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 the manufacturer provided.

While the UDS is exclusive to the DICE layer, each later component retrieves a Compound Device Identifier (CDI) from its predecessor. Each layer's CDI 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 CDIs of all subsequent components, as implied by Equation 2.2.

Just as the DICE layer must ensure 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 (Equation 2.3) or an alias key pair (Equation 2.4).

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

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

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

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

The result of a boot process using DICE is a certificate chain, which can be seen in Figure 2.6 and Equation 2.5. Each certificate represents a layer by embedding its TCI. 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 self-signed root is the certificate of the DICE manufacturer. It is either stored on the device or retrieved from the manufacturer, e.g., via its website.

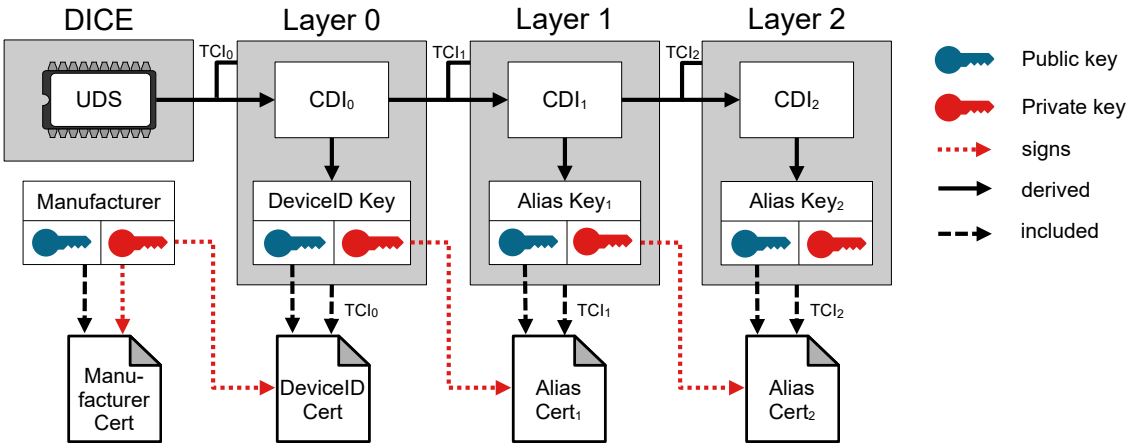


Figure 2.6: The generation of the CDIs and the certificates for each layer in a DICE architecture. The diagram could be continued for an arbitrary number of layers.

The following is the DeviceID certificate, generated and signed by the manufacturer during provisioning. It links the DICE implementation to its manufacturer, which is essential to retrieve the guarantees it conducts 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 keeps and protects 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 $n-1$.

In Figure 2.6, the CDIs 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.

The prover forwards this DICE certificate chain to the verifier for remote attestation. 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 TCIs part of the certificates. Finally, they can decide whether this TCI list is trustworthy.

To our knowledge, DICE is so far considered secure apart from physical attacks; only implementation problems can bear security problems [57, 60].

3 Related Work

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

3.1 Attacks on TPMs

Generally, attacks on TPMs 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*.

Discrete TPM The *TPM Reset Attack* on TPM 1.1 is described independently in [61, 62] conducting state decoupling. It requires minimal hardware, precisely only a wire connecting the reset line of the LPC bus [63] 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 PCRs to special hardware modes that are no longer accessible in the later boot process [64].

Winter and Dietrich [65] circumvent this counter measurement with an attack on dTPMs 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 initially sent with. In addition, they introduce a new approach to 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 instead of real hardware, Winter mentions in his master's thesis that initial tests indicate that these attacks also apply to TPM 2.0 [66]. To the best of our knowledge, this is the only statement done about these attacks for TPM 2.0.

Firmware TPM As seen in the previous section, the bus between a CPU and a dTPM is a typical attack vector on dTPMs 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 fTPMs.

Moghimi et al. [67] 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. [68] 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 PCRs 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 [9]. Some implementations reset the TPM, which resets its PCRs. 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 PCRs can be reset. The authors fixed this issue upstream with a software patch.

Jacob et al. [69] target proprietary AMD fTPMs by attacking their TEE, namely the AMD Secure Processor (AMD-SP). By that, they can expose the entire internal state of the fTPM bypassing any authentication mechanisms. To do so, they leak the secret key from the BIOS flash chip used to derive the encryption and signature keys for the fTPMs non-volatile data. They achieve this by using a voltage fault injection that bypasses the authenticity check in the host's boot process. It allows them to boot their crafted firmware component that leaks the required information.

Cohen from the Google Cloud Security team also targets AMD's fTPM running with the AMD-SP [70]. 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 complete 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 fTPMs 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. [71] is similar to DICE. Their only hardware requirement is a ROM containing a secret key only 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 in 2014 [72]. Since then, the lack of an update 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 [73]. 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 TCIs do. Due to the nature of attestation based on symmetric cryptography, the verifier and the prover must have shared secrets. Depending on the desired flexibility of the verifier, the UDS, the CDI, or the alias key has to be shared. If the alias key is leaked, trust in the system breaks and is unrecoverable since the same key is generated on each boot, provided no changes have been made.

DICE+ proposed by Jia et al. [74] solves this by equipping the prover with a monotonic counter, which is incremented on each reboot. The prover shares its UDS and the initial value of its counter with the verifier during provisioning in an out-of-band manner. The counter influences the alias key, which alters the attestation result after each reboot. 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 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 incapable of asymmetric cryptography, we target 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. [75] propose an attestation system with DICE without TEE. While we combine DICE with the TPM infrastructure, they mix 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 [76]. Their design is orthogonal to ours because they do not integrate data binding to software identities.

3.3 DICE implementation

Jäger, Petri, and Fuchs [77] describe how the remote attestation procedure described in the DICE specification can be implemented by discussing possible options. Thereby, they complement our work by evaluating how to implement DICE. Jäger and Petri continue their work later [60] because they observed a limitation in their initial implementation, allowing them to jump into DICE code, possibly leaking the UDS. Lorych and Jäger carried on exploring the design space of DICE later on [78]. As with SMART, all these publications aim not to attest an fTPM and do not describe how to combine the infrastructure of DICE and fTPMs.

Tao et al. [53] propose a formally verified DICE implementation called DICE*. They focus on the software side of the first DICE layer and are agnostic to the hardware used. Therefore, it can be used together with the hardware designs from the previously listed works.

Bravi, Sisinni, and Lioy [75] explain how DICE can be implemented with the novel RISC-V technology Physical Memory Protection (PMP).

3.4 Software TPMs implementation

Firmware TPM The official TCG reference implementation of the TPM 2.0 specification is provided by Microsoft.[1] Raj et al. [38] 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. Their analysis calls for hardware entropy for a secure fTPM implementation, but does not elaborate on how this can be achieved.

Gross et al. [79] 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 fTPMs, 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 an hTPM since there is no dTPM, and the overall design is simpler.

In contrast, Kim and Kim [80] 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 using the significantly better performance in fTPM mode due to modern CPU features. In addition, due to the availability of the dTPM, it is 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.

Virtual TPM The initially proposed design of virtual TPMs requires the operating system and the hypervisor to be trusted [48].

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

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

Wang et al. [81] 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 in the individual enclaves and SGX itself, enabling the host operating system and hypervisor to be untrusted.

Pecholt and Wessel [16] 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 [82] eliminate the need to manually establish 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

In the following, we describe the design with which we aim to handle the previously stated questions and problems.

4.1 Terminology

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

In the original DICE release from Microsoft [55], the identifier of a component is called the Firmware identifier (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 [83] defines an X.509 extension that contains the TCIs. They continue to be referred to as FWIDs in the machine-readable formal definition of this extension, while everywhere else, they are referred to as TCIs. In personal correspondence with TCG, we learned this is due to backward compatibility. The old term FWID is retained whenever it is used in something alive in the long-term, like formal definitions, and the new term TCI in assets that can be updated more quickly, such as the specification text. Therefore, we will use the term TCI in this theoretical chapter, and in the implementation chapter (Chapter 5), we will use the term FWID. 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 Figure 4.1. As you might notice, it is similar to our overview picture of DICE (Figure 2.6). This is expected since our system leverages DICE as our static RTM (S-RTM). Static in this context means it uses the trusted state that a device always has at the same point, hereafter switching on, for further measurements. This contrasts to a dynamic RTM (D-RTM), which can do this at any time, e.g., Intel SGX.

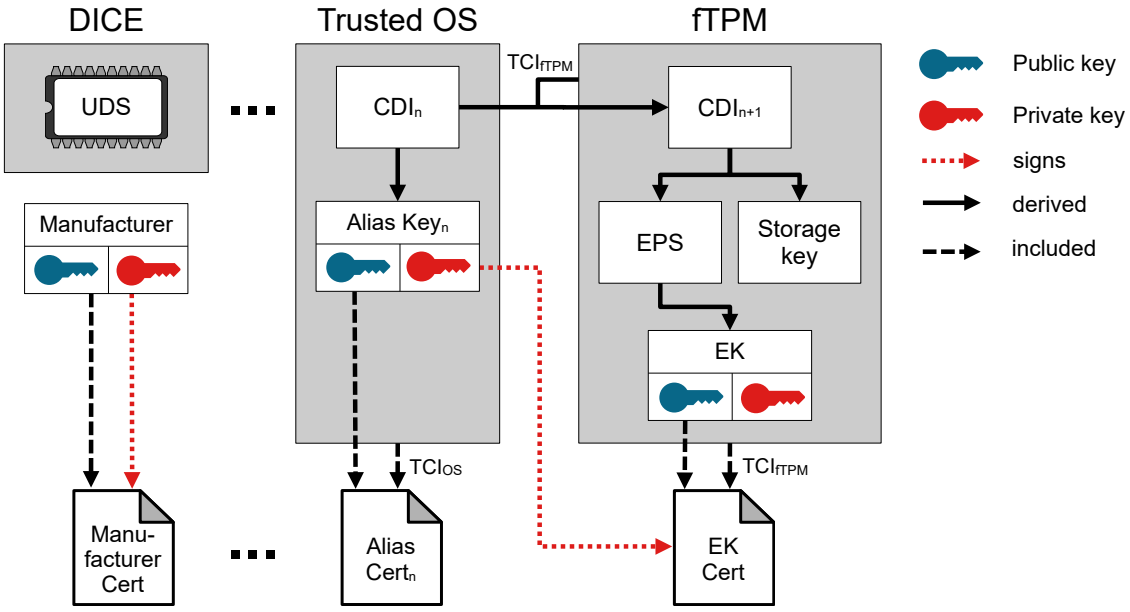


Figure 4.1: The architecture of our system.

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 operating system running in EL1 in the secure world, as seen in Figure 2.2. Like any other DICE component, the fTPM receives its secret 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

A TPM-compliant component can store persistent data, such as key material or other secrets. fTPMs can leverage the storage functionality of the underlying trusted OS. Even though, depending on the implementation, the data is thereby already encrypted before it is sent to the storage device, this only binds the data to the TEE, 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 (Figure 4.2). 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's storage must never be accessible to another TPM.

An attacker could thereby easily trigger a data loss. This must be avoided by integrat-

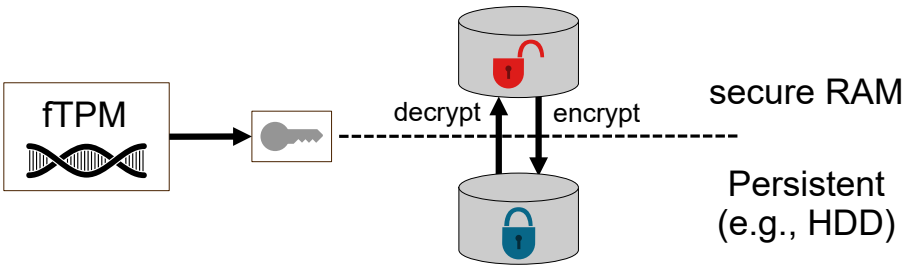


Figure 4.2: The fTPM's storage is protected by a key derived from its identity.

ing good practices with working with a TPM, including having secrets stored elsewhere. Microsoft recommends backing up all secrets stored on the TPM before clearing it [84], which can be generalized to the backup of the fTPM data where data loss causes severe damage.

Establishing the storage key prevents an attacker from accessing an fTPM's data by downgrading the fTPM. For example, suppose an attacker wants to access data stored in a particular fTPM and can exploit a vulnerability of an earlier version of that fTPM. In that case, replacing the fTPM with its old version is impossible, as neither the attacker nor the fTPM itself can decrypt the previous data.

However, it does not protect against the isolated downgrade of the fTPM itself or solely its data. As previously described, the data is reset when the fTPM is downgraded. 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 [85, 86]. For this reason, an RPMB partition is part of Microsoft's hardware requirements for an fTPM [38].

Only the TEE can write *to* the RPMB (authenticated write), and it can also ensure that received data 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 from 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 Endorsement Primary Seed (EPS) is generated based on the CDI. The TPM uses this seed to generate the primary Endorsement Key (EK). A primary key in the sense of the TPM means that it has no parent key but a parent seed, here the EPS. The indirection of generating the EK from the EPS via the CDI instead of directly from the CDI is introduced because the code of fTPMs is typically hardcoded to use the EPS during EK generation. We want our system to require as few modifications to TPM code as possible. The TPM must remove its CDI 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 DICE for this, which is hardware-based. Its DeviceID key, as the name suggests, represents the device identity. Note that the DeviceID contains the identity of layer 0 of the boot chain, i.e., the first mutable code. This can also be seen in Equation 2.3. For this reason, the DICE specification suggests keeping the first mutable code as small as possible so that it remains constant throughout the life of the device [28].

The EK is a restricted encryption key by default. 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 the privacy of the prover, it has the advantage of not requiring a third party Certificate Authority (CA). Section 4.7 provides more details and an extension to our system introducing privacy.

4.3 The identity of a firmware TPM

DICE offers two identities for each component—the TCI and the CDI. As shown in Equation 2.2, the CDI of a component changes when (i) the identity of the hardware changes, i.e., the UDS, (ii) the identity of a preceding component changes, or (iii) the component itself changes. In contrast, the TCI is the identity of a single component, considered in isolation, usually the hash of its binary, 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 containing the same software component. Note that a component's TCI is part of its CDI, as shown in Figure 4.3.

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 is that once a previous component has changed, whether it has gone into a benign or malicious state is unknown. If malicious, it could change the firmware TPM and access its sensitive material, such as private keys. Although the verifier later recognizes this during remote attestation, sensitive data could still be leaked. If the

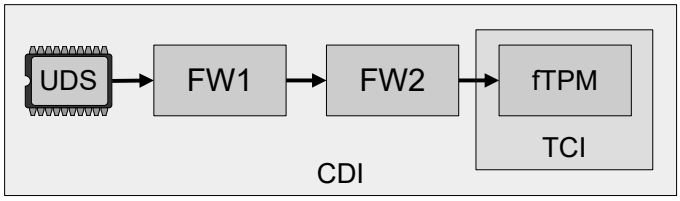


Figure 4.3: The CDI and the TCI from the perspective of an fTPM component with preceding firmware (FW). The UDS provides the hardware's identity.

identity of the fTPM also encapsulates everything before 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. This behavior should also be reflected in the EK so that the storage key and the EK change together or do 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 afterward. 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 in 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 must also be considered untrusted. This behavior is also represented mathematically in Equation 4.1. Therefore, trusting the fTPM requires trusting all underlying firmware components.

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

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

- We generally do not trust the component's manufacturer and, therefore, do not trust the component.
- The component is up-to-date, and there are no known vulnerabilities; 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 replaying the certificate chain. But we must promote the *some* to *the machine I communicate with*. This is solved in subsequent protocols where the verifier challenges the prover to control EKpriv corresponding to the EKpub of the EK certificate, for example, by verifying the subsequently retrieved quote. Although this is not explicitly part of our proposed solution, we describe it for better understanding and comprehensively explain the entire attestation process.

4.4.2 Verifier establishes trust to the prover's quote

For that, the verifier must know that the quote was signed with the restricted EKpriv corresponding to the EKpub in EKcert and that the fTPM controls EKpriv. The verifier also needs to trust that the fTPM did not leak EKpriv, as this would allow an attacker in its possession to replay the certificate chain and conduct the subsequent protocols. 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 that 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 must derive that the EK is restricted from the fTPM's TCI embedded in the EKcert. 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

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

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

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 an EK certificate. So, this certificate must fulfill the requirements for an Alias certificate from the DICE specification [87] and the EK certificate requirements from the TPM specification [88]. Therefore, we must ensure that these two specifications declare no conflicting requirements. DICE [87] 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 [89]. Generally, the EK certificate specification "does not preclude using other certificate extensions." The alias certificate specification leaves this undefined, i.e., it makes no statement about whether this is permitted or prohibited. However, it is irrelevant since the EK certificate specification does not define any X.509 extensions. The requirements for 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 does not have 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 Table 4.1. In summary, there are mostly no conflicts since both certificates expect the same value, both requirements can be satisfied with the same value, or only one of the certificates dictates a restriction for a specific field.

Table 4.1: Comparing the requirements for an Alias and EK certificate. The upper half contains basic certificate fields, and the lower half contains 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

The only conflict is in the subject name. An alias certificate must either identify the TCB class (general) or instance (specific); an EK certificate allows only a value uniquely identifying the TPM (specific) or empty otherwise. So, a general term like "fTPM" is prohibited by the EK certificate specification and an empty subject by the DICE specification. The only common denominator is a unique identifier. However, that is already part of the TCI embedded in our EK certificate. We favor the EK certificate specification here, leaving the subject name empty. This ensures that the EK certificate is also as expected for systems that do not know our solution and the TCI part of the certificate. Empty subject names also appear to be common practice in EK certificates, as this is the subject name chosen for all EK certificates we observed. Nevertheless, this should not be regarded as representable 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 [88]. The manufacturer is assumed to generate the EK certificate with 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 at 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 fTPM, 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 is. This cannot happen with the TCI 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 using 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 critical that fTPMs are updatable due to their history of showing vulnerabilities that have been patched consequently. Our fTPM can only be 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, it keeps representing the identity of the currently running fTPM.

The code of the fTPM is replaced during an update, which consequently retrieves

a new CDI and a new storage key. Therefore, the old data can no longer be accessed, leading to a manufacturer reset.

This mechanism is common practice as this is also described in the manuals for TPM upgrades by Lenovo [90] and Intel [91]. It is underpinned by the importance of pausing BitLocker before upgrading a TPM due to its upcoming data loss [92]. Thereby, BitLocker temporarily stores its encryption key in plaintext on the hard drive, restoring it after the TPM's update.

Apart from the associated data loss, 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 on what reveals the prover's identity when conducting a remote attestation and then suggest a modification to our architecture to integrate its privacy.

The verifier retrieves the certificate chain and a TPM quote in an ordinary remote attestation process with our system as described in Section 4.4. 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 containing subject keys representing the hardware's identity and the firmware components executed up to that point. 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 it is generated with a unique EKpriv. Consequently, all these keys must 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 are solved by introducing a new signing key—the Attestation Key (AK)—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 AKs 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 must also be certified to originate from an authentic TPM like the EK. In contrast to certifying EKs, manufacturers cannot be called upon to vouch for AKs. If AKcert references the issuing manufacturer, it is eventually disclosed to the verifier, revealing private information. Instead, we rely on a third-party CA, commonly called 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 evaluating the guarantees of the issuing manufacturer. 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 with 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 [9] 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.

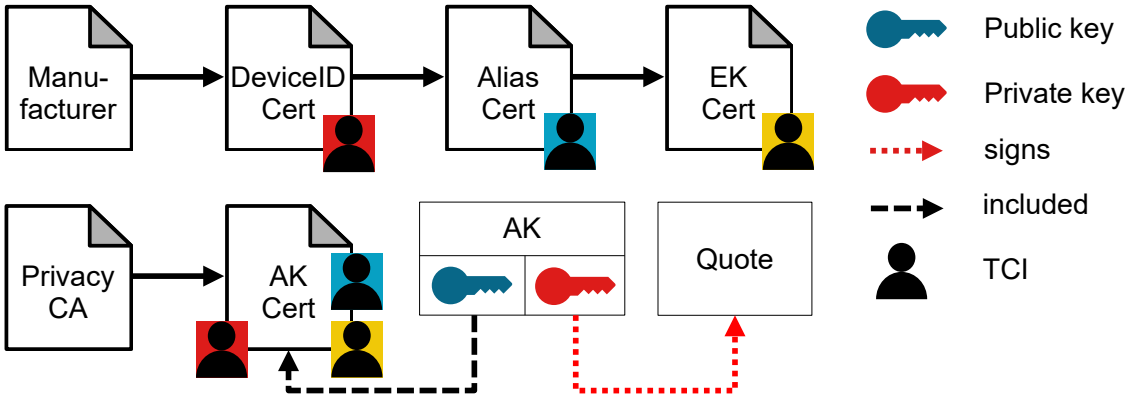


Figure 4.4: The adapted architecture integrating privacy.

We must also 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 that the AK was generated by an authentic TPM, hiding which exact TPM, even the manufacturer. The privacy CA also copies each TCI of the old certificate chain into the AK certificate, as depicted in Figure 4.4. The yielding private certificate chain is returned to the prover, who can forward it to a verifier without revealing its identity.

Whether the verifier trusts the firmware TPM is conducted in the same way as described in Subsection 4.4.1, with the only difference being that the TCIs are all embedded into a single certificate, i.e., the AK certificate. The verifier must also be able to trust the prover's quote as explained in Subsection 4.4.2. For that, the verifier must trust the AK certificate's issuer to verify that the AK is stored on an authentic TPM. The privacy CA does not need to check whether AK is restricted, which 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 verifier's statement 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 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 trustworthy prover based on the TCIs it provided. However, this makes the verifier dependent on another entity that decides whether or not the TCIs provided are trustworthy, which we consider undesirable.

We also want to highlight that AK does not need to be a child of 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 [9]. 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, the TPM obfuscates this data by adding random offsets to each value, which is desirable if privacy is a concern.

5 Implementation

As explained in Section 4.1, from now on, the term Firmware identifier (FWID) is used instead of the previously used term TCB Component Identifier (TCI). Also, keep in mind that while TEE and REE are technology-independent terms, we mainly use Secure World (SW) and Normal World (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 exceed 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

Figure 5.1 depicts the boot process. 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 FVP does not include it. Therefore, we assume its presence by mocking the first few certificates of the yielding certificate chain. Furthermore, it is independent hardware, so 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`

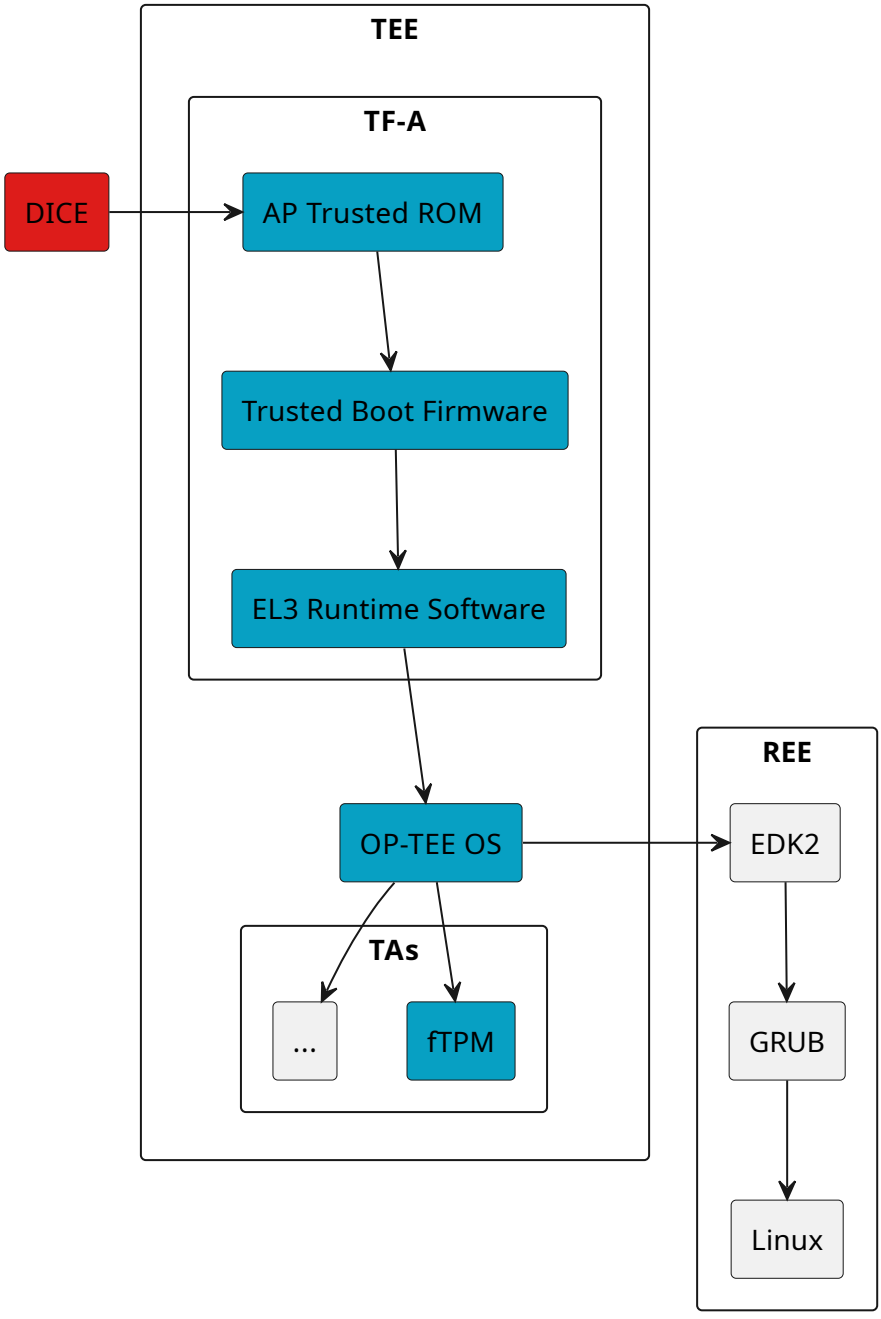


Figure 5.1: The boot chain of our system running in Arm's FVP. Blue: Represented by our yielding certificate chain. Red: Root of trust for verifier, and assumed to be present.

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 is running in the SW, as they never modify the execution environment of the processor. This design 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 that conducts the context switches between the SW and the NW. The TF-A documentation provides more complete and detailed information.[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 Trusted Applications (TAs).

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. Combining 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, which could lead to inconsistent states. This behavior also mirrors hardware TPMs, usually attached to the processor via serial buses like SPI. 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. We are not aware of any function provided by OP-TEE OS to register a TA to be started during the boot process. Instead, OP-TEE OS initializes TAs the first time something 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 [51] by Intel.

GRUB The GNU GRand Unified Bootloader[9] 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. 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 functionalities to be activated or deactivated at a granular level. Since the target machines are embedded devices with limited resources, the user should only activate needed functions. Therefore, we had to activate some functions.

The formulas that derive secrets directly from the CDI (Equation 5.1, Equation 5.2) use a keyed-hash message authentication code (HMAC) function. This is inspired by the CDI derivation proposed in the DICE hardware requirements specification [59]. It proposes two functions to combine information into a new secret—a hash function and an HMAC function. It also recommends the latter, which takes a little more time to execute but protects the CDI with twice the level of the hash function. This is backed by Jäger et al. [77], and NIST SP 800–57 [93]. 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, the MD5 function to retrieve a key with a sufficient size. Despite MD5 is considered broken, HMAC in conjunction with MD5 is not [94]. A fixed character string describing the purpose of the output secret seeds the HMAC functions.

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

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

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

We must retrieve the same EK as the TPM generates with `TPM2_CreatePrimary` packed 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 Figure 5.2. 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 to read the memory of the calling TA, i.e., the fTPM TA, which it processes into the FWID and eventually embeds in the EKcert. The attestation PTA hashes the constant memory pages of the calling TA, 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

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

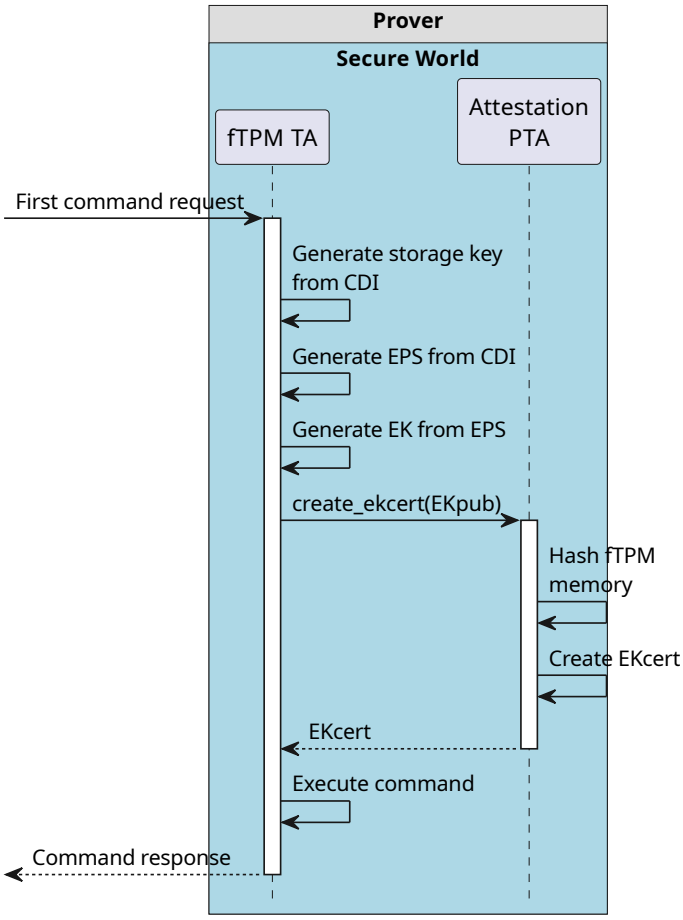


Figure 5.2: A UML sequence diagram describing the initialization of our firmware TPM.

mocked 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 measuring the fTPM is simply extracting the hash embedded in its TA binary header. A TA is an ELF binary wrapped in an OP-TEE-specific format, whose header contains a signature over all metadata and the payload, i.e., the ELF executable. While more straightforward and faster, it does not measure 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 [83]—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

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

since its last official release dates back to 2017, whereby its generated C code throws various warnings with a modern C compiler. While it allows multiple FWIDs to be embedded into an X.509 certificate, our implementation only stores one in each alias certificate. However, the privacy-focused architecture explained in Section 4.7 could leverage the possibility of storing multiple FWIDs in the extension. Each FWID consists of an identifier of the hash algorithm 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 mocked.

5.4 Firmware TPM attestation

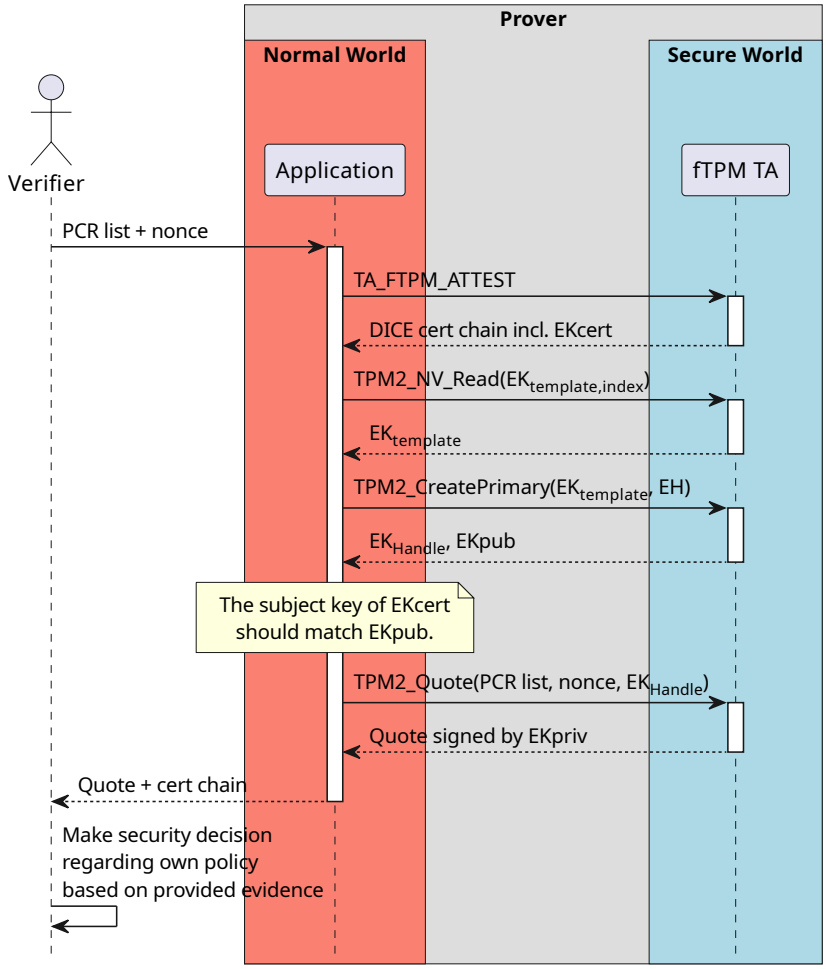


Figure 5.3: A UML sequence diagram describing the attestation of our firmware TPM.

We added a new TA command called `TA_FTPM_ATTEST` to the fTPM to obtain the

entire certificate chain from any application. Usually, the application that performs the prover part of the remote attestation issues this command. We want 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 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 Figure 5.3. Consequently, it receives the certificate chain created by DICE with the EKcert as the leaf certificate.

Afterward, 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 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 key has to be specified providing its entropy source, as the TPM uses the primary seed of the specified hierarchy 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. It does not return the private part of the EK, as this never leaves it in plaintext.

Eventually, the prover wants to create a quote to establish trust in the prover's system state in the NW and prove that it controls 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 now possesses the certificate chain and a quote. It transmits both to the verifier, which extracts the EKpub from EKcert, wherein it is the subject key. With that, it can verify the digital signature of the quote. The ability to create a quote with a fresh nonce proves the fTPM controls EKpriv. Therefore, the verifier can trust that the certificate chain has not been replayed and 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 quote's signature and ensure that the nonce in the quote matches the one that the verifier previously generated.

Note that the implementation just described assumes that the quote returned by

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

`TPM2_Quote` contains the values of the PCR registers. While this was the case with TPM 1.2, this changed with version 2.0. Instead, the resulting quote only contains a hash of the values of the requested PCR registers. The corresponding 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. The `tpm2_checkquote` tool performs this step. We have omitted it from the previous explanation and Figure 5.3 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 TPM generated the EPS [9], which is the case in our implementation as our fTPM derives it from the CDI.

5.5 Creating and storing our EK template and certificate

The EK is a primary key in the endorsement hierarchy, so the TPM derives it from the EPS and a key template. The template must be provided as part of the command `TPM2_CreatePrimary` to the TPM. The TPM can store an EK template that anyone can retrieve, which must be the one with which the EK part of its EKcert was created. This setup is necessary for the TPM to reproduce the EKpriv corresponding to the EKpub of EKcert to prove that the certificate corresponds to it.

A TPM can save an EK template but is not obligated to do so. Then, the default template defined by TCG is used, dictating the EK to be a restricted encryption key since it is privacy-sensitive and must be an RSA-2048 key [88]. As this fits most TPMs, the definition of the default template removes the burden of most TPMs 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.

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 this 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 [95] with SHA-256, and (iii) no inner symmetric key as required by the TPM specification [9] 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.

We added code to our fTPM, enabling it to reliably reproduce our custom EK template. After each manufacturer reset, e.g., caused by an identity change, the TPM regenerates this template to store it in the NV index `0x01c00004` as defined by the TPM EK specification for RSA-2048 EK templates [88]. We set the attributes for this NV index as defined by the TPM PC Client specification [31]. Thereby, the EK template in the NV index can only be written or deleted if a specific policy is fulfilled. However, the policy is empty

and can never be fulfilled, resulting in a non-deletable EK template. We also store the EKcert in the NV index `0x01c00002` as defined by the TCG EK Credential Profile [88] with the same attributes as the respective template so that it also cannot be deleted. The template and certificate are not sensitive material and are readable by anyone using the command `TPM2_NV_Read`. In the attestation phase, this is used by the application in the NW as depicted in Figure 5.3.

Nevertheless, our fTPM does not retrieve the EK template from the NV index during the initialization phase, where the fTPM generates EKpub to forward it to OP-TEE OS to generate the EKcert. Even though it could, this would entail an indirection via the NV storage, which is not measured. 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 the verifier needs to know to derive its trustworthiness.

5.6 Times in certificates and systems

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

Initially, we wanted to use the build time as the start of the validity period, as would be the case in an actual implementation. However, this turned out to be infeasible with FVP since a guest machine does not have internet access out of the box, and FVP also does not provide an option to use the host's time. While the host generates the mocked certificates, the FVP must continue the certificate chain and 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 approach 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 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 an expiration date, as specified by `9999-12-31 23:59:59` [96].

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 vital that it is after the start period of the certificates.

5.7 Implementing encrypted storage

The reference TPM's memory size is 16,896 bytes, split in an NV storage of 16,384 bytes, and an 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, small 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 into 512-byte blocks resulting in $16{,}896 \div 512 = 33$ blocks.

We consult the recommendations of the BSI [97] 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 to spare resources. Each block has one IV and tag, resulting in a storage overhead of 792 bytes as shown in Equation 5.4. The fTPM randomizes the IVs on every write event and is reset on any mismatch between the stored tag and the tag produced during decryption.

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

The data is loaded from the hard disk and decrypted only at startup time. It is written only during the 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 the impact on performance to be small.

5.8 Isolating storage of fTPM in OP-TEE

The data of the individual TAs must be saved somewhere permanently. The OP-TEE OS stores them in the REE file system and hence must protect it. 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.

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

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

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

Equation 5.5 shows that the TSK depends only on the SSK and the TA's UUID. As said, the SSK is the same for the whole device and hence for every TA, and the TA_{UUID} is public. A close look reveals that other TAs on the same device could use them to generate the fTPM's TSK to decrypt its FEKs protecting its private data. However, our

integration of an additional storage key prevents this, which encrypts the data with the fTPM's identity before sending it to the OP-TEE OS.

The TEE Management Framework 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 [98]. It allows grouping TAs into domains, whereby only TAs in the same domain can decrypt each other's data. However, as of the time of writing, OP-TEE OS does not implement this yet.

5.9 Technical obstacles

We had several resistances to overcome during the implementation, which are described here.

5.9.1 tpm2-tools

As mentioned, we use the `tpm2_checkquote` tool to verify the prover's quote on the verifier's side. However, this tool fails to perform a critical check to ensure that the quote was generated by the TPM and not externally. This poses a significant 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, formally proven secure over RSASSA-PKCS1-v1_5. RFC 8017 even requires RSASSA-PSS for new applications [99]. 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 defined NV index. We did not want to deviate from the standard nonce, a buffer of 256 bytes all set to 0. Therefore, we did not write a nonce to the NV index, only the EK template, which conforms to the TPM specification [88]. However, `tpm2_createek` expected a template *and* a nonce to be present. We wrote an empty nonce in the according NV index of the firmware TPM to circumvent this problem. Later, the maintainers of the `tpm2-tools` fixed it.[16] Then, it turned out that this tool had 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 problem and fixed it.[18]

[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`
[18] `https://github.com/OP-TEE/optee_os/issues/6111`

We tested 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 we activated the necessary functionality. It took extensive debugging efforts to find a workaround.[19]

The OP-TEE OS provides a libc library that implements only a subset of the C standard library. Its authors copy code of the newlib[20] to their libc 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 explicitly written 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 to merge the fix 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.

[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

In this chapter, we discuss our findings, limitations, and recommendations. Furthermore, we answer previously stated requirements and questions.

6.1 Evaluation

Here, we revisit and assess the security goals and requirements for an attestation process.

6.1.1 Security goals

First, we return to the security goals defined in the introduction (Section 1.4) and describe how we fulfill them.

SG-1: 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. If the trusted OS behaves correctly, the fTPM cannot access its private alias key, preventing it from faking its measurements or corresponding alias certificate. The verifier establishes trust in the trusted OS's behavior by examining its TCI. In fact, it needs to trust all TCIs of the preceding components for that. In general, each DICE layer must not have access to the private alias key of the preceding layer.

SG-2: Small root of trust We base our system's security on the DICE architecture's design and guarantees. 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 a single integer value representing a statistically unique value, we consider the root of trust small.

SG-3: 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 derive the FEK of any other TA within the same TEE. However, they cannot know the other TAs CDI since they cannot measure each other. Consequently, this prevents other TAs from generating our solution's fTPM's storage key. 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.

SG-4: 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.

6.1.2 Attestation process requirements

TCG defines as part of their Trusted Attestation Protocol [100] the requirements for an attestation process to assure 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 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 decide on the prover's trustworthiness 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 consist of a hash and the corresponding hash algorithm identifier. Both are well-known concepts that are 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 the signing of attestation data, usually a quote. A TPM signs the quote with EKpriv corresponding to the EKpub in the EKcert. And EKpriv can only be created by a device with the TCIs represented by the previously obtained certificate chain and the according UDS, which is secret and unique for the respective prover.

6.2 Revisiting research questions

In the following, we briefly discuss our answers to the previously posed research questions from Section 1.2.

RQ-1: Identity of fTPM (Section 4.3) The first question asked is what constitutes the identity of an fTPM. We found that it is essential for its identity to include its entire underlying software stack because 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. The DICE's component-specific CDI represents this definition of identity.

RQ-2: DICE + TPM (Section 4.5) Next, we provide a design to combine the infrastructures of DICE and TPM. Here, the crucial point is where 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 TPMs. In short, the infrastructures meet and are combined at the step from the CDI (DICE) to the EPS (TPM).

RQ-3: Manage the fTPM's data securely (Subsection 4.2.1) Another important aspect to take care of is 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 choose to bind the data to an fTPM's identity, which only changes when the security properties of the fTPM change. As described in **RQ-1**, the fTPM's CDI represents this identity. Hence, we derive a storage key from it to protect the confidentiality and integrity of the fTPM's data.

RQ-4: Privacy (Section 4.7) Remote attestation without ensuring the privacy of the prover has the benefit of being straightforward and requiring only the expected parties—verifier and prover. Despite that, privacy can still be a higher prioritized criterion, such that we also explain an approach to integrate it into our solution. We introduce a proxy between the verifier and the prover—the privacy CA. The prover sends its certificate chain to the privacy CA, which then verifies that the fTPM is authentic by confirming that it roots in an authentic DICE implementation. It then bundles the chain's information, such as measurements, into a new certificate that preserves the prover's privacy by leaving information that reveals it. If the 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. Ultimately, the verifier can only derive that it communicates with *an* authentic TPM, but not *which*, and can still decide for itself whether it considers the fTPM to be trustworthy based on its measurements.

6.3 Implications of openly propagating system state

An attacker could use the TCIs to find the exact running software versions and match them to known vulnerabilities [24].

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 receiving the certificates. This can be circumvented by authenticating the verifier. However, this implies the prover only shares its attestation data with certain verifiers. This is a trade-off that the implementers of our solution must weigh up.

6.4 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 is 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.

6.4.1 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 as source code. The binary file must then be generated by the device provisioner itself. If its build environment does not support reproducible builds [101], there may be many binaries and, conversely, many TCIs that differ only in irrelevant details, e.g., embedded timestamps. This problem is unlikely to appear with closed-source software, as only a single distributor exists.

However, closed-source software restricts the criteria that can be used to decide whether a TCI is trustworthy. The trustworthiness of open-source software can be derived independently of its source code and exact change history if an older version is evaluated. With closed-source software, you must rely on its developers to communicate openly when security problems occur.

6.5 Hardware requirements

Besides the better performance, a significant advantage of fTPMs over dTPMs is that they involve fewer 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 fTPMs by Raj et al. from Microsoft [38], 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 additional hardware. An RPMB partition is required to protect the fTPM's storage from access outside the TEE and prevent rollback attacks. Our introduction of the storage key does not prevent rollback attacks on the fTPM's data or the fTPM itself. So, we also recommend using a trusted OS that implements secure storage on an RPMB partition, which involves the additional hardware requirement of an RPMB, which is unnecessary for dTPMs. However, storage has to be present anyway, and commonly used storage technologies in embedded devices support RPMB partitions, e.g., eMMC [85] and UFS [86].

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 [78], this is usually implemented in latches that 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 sufficient for the processor to support it without needing additional external hardware.

So, we are not canceling out the advantage of fewer additional hardware components over a dTPM; instead, we restrict the choice of processors and storage type.

6.6 Proving the fTPM runs in the TEE

The verifier must know that the fTPM runs within the TEE, 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. The verifier must not know the prover's hardware details since this might reveal its identity.

6.7 Caveats of attesting the fTPM's identity

The identity of a software component does not contain its current state. While the identity of 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 to the identity of the fTPM and not its state, implying we do not detect attacks that occur after the startup process during its runtime.

7 Conclusion

In the final chapter, we present some closing thoughts and indicate directions for future research based on our work.

7.1 Significance and closing thoughts

Trust to TPMs is established by identifying their manufacturer, which declares the guarantees of its implementation, such as the specification version followed. Trusting fTPMs implies trusting their entire preceding firmware. We started this work based on the observation that commodity fTPMs solve this by being part of a monolithic, proprietary environment where the entire firmware originates from the same manufacturer as the fTPM.

Our thesis aims to break this requirement and remotely attest the fTPM and its underlying firmware independently of their manufacturer. An fTPM cannot act as a hardware root of trust because, as the name suggests, it is a software component. In contrast, a dTPM can be a hardware root of trust. Our system closes this gap by adding an independent hardware root of trust to which trust can be remotely established, i.e., DICE, that measures the entire firmware up to the fTPM.

We believe this work is an essential step towards the independence of the manufacturer of the fTPM and its upstream firmware. Despite not considering this problem relevant for vendors like AMD and Intel, whose products are fully single-sourced, we believe this work is of value for open ecosystems, e.g., systems based on RISC-V. Recently, in 2021, an fTPM for RISC-V systems was described [40], and for the same, a DICE implementation was proposed in 2023 [75]. This indicates that this ecosystem will continue to evolve and take center stage.

In the spirit of Zero Trust, our system measures instead of assumes.

7.2 Future Work

Meaningful further work is implementing our solution on real hardware instead of in a simulation environment like FVP. This allows the interaction with the hardware to be verified, especially with an RPMB partition that requires hardware support. In addition, our solution's impact on the system's performance 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, future work is to concretize the description of

our implementation for TEE technologies other than Arm, e.g., Intel SGX. As described in Section 7.1, the recent research of fTPMs and DICE within the RISC-V ecosystem can also be synthesized with our design.

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

As mentioned in Section 4.2, RPMB's rollback protection only protects against attacks outside the TEE. We want 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 OS and not in the fTPM TA, as the trusted OS typically manages the metadata.

Furthermore, our solution does not protect against runtime attacks on the fTPM. In general, TAs 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 valuable extension of our solution.

Abbreviations

CA Certificate Authority

RTM Root of Trust for Measurements

S-RTM static RTM

D-RTM dynamic RTM

TPM Trusted Platform Module

fTPM firmware TPM

dTPM discrete TPM

TCG Trusted Computing Group

PCR Platform Configuration Register

EPS Endorsement Primary Seed

EK Endorsement Key

AK Attestation Key

DICE Device Identifier Composition Engine

TCB Trusted Computing Base

TCI TCB Component Identifier

FWID Firmware identifier

UDS Unique Device Secret

CDI Compound Device Identifier

TEE Trusted Execution Environment

REE Rich Execution Environment

NW Normal World

SW Secure World

TA Trusted Application

List of Figures

List of Tables

Bibliography

[1] T. Stremlau. "A Trusted Secure Ecosystem Begins With Self-Protection." In: *ISACA Journal* 4 (July 2021).

[2] S. Rose, O. Borchert, S. Mitchell, and S. Connelly. *Zero Trust Architecture*. Aug. 2020. DOI: 10.6028/nist.sp.800-207.

[3] President's Council of Advisors on Science and Technology. *Immediate opportunities for strengthening the nation's cybersecurity*. Nov. 2013.

[4] Microsoft. *Windows 11 Minimum Hardware Requirements*. June 2021. URL: https://learn.microsoft.com/en-us/windows-hardware/design/minimum/minimum-hardware-requirements-overview.

[5] D. Sims. *Valorant's anti-cheat system requires TPM 2.0 and secure boot on Windows 11*. Sept. 2021. URL: https://www.techspot.com/news/91138-valorant-anti-cheat-system-requires-tpm-20-secure.html.

[6] X. Ruan. "Trust Computing, Backed by the Intel Platform Trust Technology." In: *Platform Embedded Security Technology Revealed*. Apress, 2014, pp. 165–179. ISBN: 9781430265726. DOI: 10.1007/978-1-4302-6572-6_7.

[7] D. Dolev and A. Yao. "On the security of public key protocols." In: *IEEE Transactions on Information Theory* 29.2 (Mar. 1983), pp. 198–208. DOI: 10.1109/tit.1983.1056650.

[8] L. Singaravelu, C. Pu, H. Härtig, and C. Helmuth. "Reducing TCB complexity for security-sensitive applications: three case studies." In: *Proceedings of the 1st ACM SIGOPS/EuroSys European Conference on Computer Systems 2006*. EUROSYS06. ACM, Apr. 2006. DOI: 10.1145/1217935.1217951.

[9] Trusted Computing Group. *Trusted Platform Module Library Specification*. Family "2.0", Level 00, Revision 01.59. May 2019.

[10] T. A. Linden. "Operating System Structures to Support Security and Reliable Software." In: *ACM Computing Surveys* 8.4 (Dec. 1976), pp. 409–445. DOI: 10.1145/356678.356682.

[11] S. Bratus, P. C. Johnson, A. Ramaswamy, S. W. Smith, and M. E. Locasto. "The cake is a lie." In: *Proceedings of the 1st ACM workshop on Virtual machine security*. ACM, Nov. 2009. DOI: 10.1145/1655148.1655154.

[12] S. Nimgaonkar, S. Kotikela, and M. Gomathisankaran. "CTrust: A Framework for Secure and Trustworthy Application Execution in Cloud Computing." In: *2012 International Conference on Cyber Security*. IEEE, Dec. 2012. DOI: 10.1109/cybersecurity.2012.10.

[13] Z. Ning, J. Liao, F. Zhang, and W. Shi. "Preliminary Study of Trusted Execution Environments on Heterogeneous Edge Platforms." In: *2018 IEEE/ACM Symposium on Edge Computing (SEC)*. IEEE, Oct. 2018. DOI: 10.1109/sec.2018.00057.

[14] M. Sabt, M. Achemlal, and A. Bouabdallah. "Trusted Execution Environment: What It is, and What It is Not." In: *2015 IEEE Trustcom/BigDataSE/ISPA*. IEEE, Aug. 2015. DOI: 10.1109/trustcom.2015.357.

[15] GlobalPlatform. *TEE System Architecture Version 1.2*. Nov. 2018.

[16] J. Pecholt and S. Wessel. "CoCoTPM: Trusted Platform Modules for Virtual Machines in Confidential Computing Environments." In: *Proceedings of the 38th Annual Computer Security Applications Conference*. ACM, Dec. 2022. DOI: 10.1145/3564625.3564648.

[17] D. Lee. "Building Trusted Execution Environments." PhD thesis. EECS Department, University of California, Berkeley, May 2022. URL: http://www2.eecs.berkeley.edu/Pubs/TechRpts/2022/EECS-2022-96.html.

[18] ARM Limited. *ARM Security Technology - Building a Secure System using TrustZone Technology*. Issue C. 2009.

[19] B. Ngabonziza, D. Martin, A. Bailey, H. Cho, and S. Martin. "TrustZone Explained: Architectural Features and Use Cases." In: *2016 IEEE 2nd International Conference on Collaboration and Internet Computing (CIC)*. IEEE, Nov. 2016. DOI: 10.1109/cic.2016.065.

[20] Eclipse foundation. *IoT & Edge Developer Survey Report*. (Accessed July 2022). 2022. URL: https://outreach.eclipse.foundation/iot-edge-developer-2021.

[21] D. C. G. Valadares, N. C. Will, J. Caminha, M. B. Perkusich, A. Perkusich, and K. C. Gorgonio. "Systematic Literature Review on the Use of Trusted Execution Environments to Protect Cloud/Fog-Based Internet of Things Applications." In: *IEEE Access* 9 (2021), pp. 80953–80969. DOI: 10.1109/access.2021.3085524.

[22] Arm. *Security in an ARMv8 System*. 2017.

[23] M. Bartock, D. Dodson, M. Souppaya, D. Carroll, R. Masten, G. Scinta, P. Massis, H. Prafullchandra, J. Malnar, H. Singh, R. Ghandi, L. E. Storey, R. Yeluri, T. Shea, M. Dalton, R. Weber, K. Scarfone, A. Dukes, J. Haskins, C. Phoenix, and B. Swarts. *Trusted cloud:: security practice guide for VMware hybrid cloud infrastructure as a service (IaaS) environments*. Apr. 2022. DOI: 10.6028/nist.sp.1800-19.

[24] H. Birkholz, D. Thaler, M. Richardson, N. Smith, and W. Pan. *Remote ATtestation procedureS (RATS) Architecture*. RFC 9334. Jan. 2023. DOI: 10.17487/RFC9334. URL: https://www.rfc-editor.org/info/rfc9334.

[25] J. Ménétrey, C. Göttel, A. Khurshid, M. Pasin, P. Felber, V. Schiavoni, and S. Raza. "Attestation Mechanisms for Trusted Execution Environments Demystified." In: *Distributed Applications and Interoperable Systems*. Springer International Publishing, 2022, pp. 95–113. DOI: 10.1007/978-3-031-16092-9_7.

[26] G. Coker, J. Guttman, P. Loscocco, A. Herzog, J. Millen, B. O'Hanlon, J. Ramsdell, A. Segall, J. Sheehy, and B. Sniffen. "Principles of remote attestation." In: *International Journal of Information Security* 10.2 (Apr. 2011), pp. 63–81. DOI: 10.1007/s10207-011-0124-7.

[27] J. M. McCune, B. J. Parno, A. Perrig, M. K. Reiter, and H. Isozaki. "Flicker." In: *ACM SIGOPS Operating Systems Review* 42.4 (Apr. 2008), pp. 315–328. DOI: 10.1145/1357010.1352625.

[28] Trusted Computing Group. *DICE Layering Architecture*. Version 1.0 Revision 0.19. July 2020.

[29] Trusted Computing Group. *Trusted Computing Platform Alliance (TCPA) Main Specification Version 1.1b*. Feb. 2002.

[30] W. Arthur. *A Practical Guide to TPM 2.0 Using the New Trusted Platform Module in the New Age of Security. Using the New Trusted Platform Module in the New Age of Security*. Springer Nature, 2015, p. 392. ISBN: 9781430265849.

[31] Trusted Computing Group. *TCG PC Client Platform TPM Profile Specification for TPM 2.0*. Version 1.05 Revision 14. Sept. 2020.

[32] Trusted Computing Group. *TCG PC Client Platform Firmware Profile Specification*. Level 00 Version 1.06 Revision 52. Dec. 2023.

[33] V. Rijmen and E. Oswald. *Update on SHA-1*. Cryptology ePrint Archive, Paper 2005/010. https://eprint.iacr.org/2005/010. 2005. URL: https://eprint.iacr.org/2005/010.

[34] X. Wang, Y. L. Yin, and H. Yu. "Finding Collisions in the Full SHA-1." In: *Advances in Cryptology – CRYPTO 2005*. Springer Berlin Heidelberg, 2005, pp. 17–36. DOI: 10.1007/11535218_2.

[35] M. Stevens, E. Bursztein, P. Karpman, A. Albertini, and Y. Markov. "The First Collision for Full SHA-1." In: *Advances in Cryptology – CRYPTO 2017*. Springer International Publishing, 2017, pp. 570–596. DOI: 10.1007/978-3-319-63688-7_19.

[36] K. Goldman and S. Potter. *SHA-1 Uses in TPM v1.2*. Apr. 2010.

[37] Microsoft. *TPM recommendations*. Feb. 2023. URL: https://learn.microsoft.com/en-us/windows/security/information-protection/tpm/tpm-recommendations.

[38] H. Raj, S. Saroiu, A. Wolman, R. Aigner, J. Cox, P. England, C. Fenner, K. Kinshumann, J. Loeser, D. Mattoon, M. Nystrom, D. Robinson, R. Spiger, S. Thom, and D. Wooten. *fTPM: A Firmware-based TPM 2.0 Implementation*. Tech. rep. MSR-TR-2015-84. Nov. 2015. URL: https://www.microsoft.com/en-us/research/publication/ftpm-a-firmware-based-tpm-2-0-implementation/.

[39] H. Raj, S. Saroiu, A. Wolman, R. Aigner, J. Cox, P. England, C. Fenner, K. Kinshumann, J. Loeser, D. Mattoon, M. Nystrom, D. Robinson, R. Spiger, S. Thom, and D. Wooten. "fTPM: A Software-Only Implementation of a TPM Chip." In: *25th USENIX Security Symposium (USENIX Security 16)*. Austin, TX: USENIX Association, Aug. 2016, pp. 841–856. ISBN: 978-1-931971-32-4. URL: https://www.usenix.org/conference/usenixsecurity16/technical-sessions/presentation/raj.

[40] M. Boubakri, F. Chiatante, and B. Zouari. "Towards a firmware TPM on RISC-V." In: *2021 Design, Automation & Test in Europe Conference & Exhibition (DATE)*. IEEE, Feb. 2021. DOI: 10.23919/date51398.2021.9474152.

[41] S. Domas. *11th Gen Intel® Core™ Processor Security*. Tech. rep. Intel®, 2021.

[42] F. Khalid and A. Masood. "Hardware-Assisted Isolation Technologies: Security Architecture and Vulnerability Analysis." In: *2020 International Conference on Cyber Warfare and Security (ICCWS)*. IEEE, Oct. 2020. DOI: 10.1109/iccws48432.2020.9292371.

[43] Arm Limited. *Interaction between Measured Boot and an fTPM (PoC)*. URL: https://trustedfirmware-a.readthedocs.io/en/latest/design_documents/measured_boot_poc.html.

[44] W. Goh and C. K. Yeo. "Teaching an Old TPM New Tricks: Repurposing for Identity-Based Signatures." In: *IEEE Security & Privacy* 11.5 (Sept. 2013), pp. 28–35. DOI: 10.1109/msp.2013.53.

[45] J. L. Cheng, K. C. Chen, H. W. Zhang, W. Y. Chen, and D. Y. Wu. "Emulating Trusted Platform Module 2.0 on Raspberry Pi 2." In: *International Journal of Security, Privacy and Trust Management* 9.3 (Aug. 2020), pp. 1–11. DOI: 10.5121/ijsptm.2020.9301.

[46] J. Voas, N. Kshetri, and J. F. DeFranco. "Scarcity and Global Insecurity: The Semiconductor Shortage." In: *IT Professional* 23.5 (Sept. 2021), pp. 78–82. ISSN: 1941-045X. DOI: 10.1109/mitp.2021.3105248.

[47] H. Casper, A. Rexford, D. Riegel, A. Robinson, E. Martin, and M. Awwad. "The Impact of the Computer Chip Supply Shortage." In: Aug. 2021.

[48] S. Berger, R. Caceres, K. A. Goldman, R. Perez, R. Sailer, and L. van Doorn. "vTPM: Virtualizing the Trusted Platform Module." In: *15th USENIX Security Symposium (USENIX Security 06)*. Vancouver, B.C. Canada: USENIX Association, July 2006. URL: https://www.usenix.org/conference/15th-usenix-security-symposium/vtpm-virtualizing-trusted-platform-module.

[49] D. Liu, J. Lee, J. Jang, S. Nepal, and J. Zic. "A Cloud Architecture of Virtual Trusted Platform Modules." In: *2010 IEEE/IFIP International Conference on Embedded and Ubiquitous Computing*. IEEE, Dec. 2010. DOI: 10.1109/euc.2010.125.

[50] J. Hendricks and L. van Doorn. "Secure bootstrap is not enough." In: *Proceedings of the 11th workshop on ACM SIGOPS European workshop*. ACM, Sept. 2004. DOI: 10.1145/1133572.1133600.

[51] UEFI Forum, Inc. *Unified Extensible Firmware Interface (UEFI) Specification Version 2.10*. Aug. 2022.

[52] J. Frazelle. "Securing the boot process." In: *Communications of the ACM* 63.3 (Feb. 2020), pp. 38–42. DOI: 10.1145/3379512.

[53] Z. Tao, A. Rastogi, N. Gupta, K. Vaswani, and A. V. Thakur. "DICE*: A Formally Verified Implementation of DICE Measured Boot." In: *30th USENIX Security Symposium (USENIX Security 21)*. USENIX Association, Aug. 2021, pp. 1091–1107. ISBN: 978-1-939133-24-3. URL: https://www.usenix.org/conference/usenixsecurity21/presentation/tao.

[54] Trusted Computing Group. *TCG EFI Platform Specification*. Version 1.22 Revision 15. Jan. 2014.

[55] P. England, A. Marochko, D. Mattoon, R. Spiger, S. Thom, and D. Wooten. *RIoT - A Foundation for Trust in the Internet of Things*. Tech. rep. MSR-TR-2016-18. Apr. 2016. URL: https://www.microsoft.com/en-us/research/publication/riot-a-foundation-for-trust-in-the-internet-of-things/.

[56] Trusted Computing Group. *TCG ANNOUNCES DICE ARCHITECTURE FOR SECURITY AND PRIVACY IN IOT AND EMBEDDED DEVICES*. Sept. 2017. URL: https://trustedcomputinggroup.org/tcg-announces-dice-architecture-security-privacy-iot-embedded-devices/.

[57] S. Hristozov, M. Wettermann, and M. Huber. "A TOCTOU Attack on DICE Attestation." In: (2022). DOI: 10.48550/ARXIV.2201.11764.

[58] X. Carpent, K. Eldefrawy, N. Rattanavipanon, and G. Tsudik. "Temporal Consistency of Integrity-Ensuring Computations and Applications to Embedded Systems Security." In: *Proceedings of the 2018 on Asia Conference on Computer and Communications Security*. ACM, May 2018. DOI: 10.1145/3196494.3196526.

[59] Trusted Computing Group. *Hardware Requirements for a Device Identifier Composition Engine*. Level 00 Revision 78. Mar. 2018.

[60] L. Jäger and R. Petri. "DICE harder." In: *Proceedings of the 15th International Conference on Availability, Reliability and Security*. ACM, Aug. 2020. DOI: 10.1145/3407023.3407028.

[61] B. Kauer. "OSLO: Improving the Security of Trusted Computing." In: *16th USENIX Security Symposium (USENIX Security 07)*. Boston, MA: USENIX Association, Aug. 2007. URL: https://www.usenix.org/conference/16th-usenix-security-symposium/oslo-improving-security-trusted-computing.

[62] E. R. Sparks. "A Security Assessment of Trusted Platform Modules." In: *Dartmouth College Undergraduate Theses* (2007).

[63] Intel. *Intel® Low Pin Count (LPC)*. Aug. 2002. URL: https://www.intel.com/content/dam/www/program/design/us/en/documents/low-pin-count-interface-specification.pdf.

[64] S. Proskurin, M. Weiß, and G. Sigl. "seTPM: Towards Flexible Trusted Computing on Mobile Devices Based on GlobalPlatform Secure Elements." In: *Lecture Notes in Computer Science*. Springer International Publishing, 2016, pp. 57–74. ISBN: 9783319312712. DOI: 10.1007/978-3-319-31271-2_4.

[65] J. Winter and K. Dietrich. "A hijacker's guide to communication interfaces of the trusted platform module." In: *Computers & Mathematics with Applications* 65.5 (Mar. 2013), pp. 748–761. DOI: 10.1016/j.camwa.2012.06.018.

[66] J. Winter. "Trusted Computing And Local Hardware Attacks." MA thesis. Graz University of Technology, 2014.

[67] D. Moghimi, B. Sunar, T. Eisenbarth, and N. Heninger. *TPM-FAIL: TPM meets Timing and Lattice Attacks*. 2019. DOI: 10.48550/ARXIV.1911.05673.

[68] S. Han, W. Shin, J.-H. Park, and H. Kim. "A Bad Dream: Subverting Trusted Platform Module While You Are Sleeping." In: *27th USENIX Security Symposium (USENIX Security 18)*. Baltimore, MD: USENIX Association, Aug. 2018, pp. 1229–1246. ISBN: 978-1-939133-04-5. URL: https://www.usenix.org/conference/usenixsecurity18/presentation/han.

[69] H. N. Jacob, C. Werling, R. Buhren, and J.-P. Seifert. *faulTPM: Exposing AMD fTPMs' Deepest Secrets*. 2023. DOI: 10.48550/ARXIV.2304.14717.

[70] C. Cohen. *AMD-PSP: fTPM Remote Code Execution via crafted EK certificate*. Jan. 2018. URL: https://seclists.org/fulldisclosure/2018/Jan/12.

[71] K. Eldefrawy, A. Francillon, D. Perito, and G. Tsudik. "SMART: Secure and Minimal Architecture for (Establishing a Dynamic) Root of Trust." In: *NDSS 2012, 19th Annual Network and Distributed System Security Symposium, February 5-8, San Diego, USA*. Ed. by ISOC. © ISOC. Personal use of this material is permitted. The definitive version of this paper was published in NDSS 2012, 19th Annual Network and Distributed System Security Symposium, February 5-8, San Diego, USA and is available at : San Diego, 2012.

[72] Trusted Computing Group. *TPM 2.0 Mobile Reference Architecture*. Level 00 Revision 142. Dec. 2014.

[73] Trusted Computing Group. *Symmetric Identity Based Device Attestation*. Version 1.0 Revision 0.95. Jan. 2020.

[74] Y. Jia, B. Liu, W. Jiang, B. Wu, and C. Wang. "Poster: Enhancing Remote Healthiness Attestation for Constrained IoT Devices." In: *2020 IEEE 28th International Conference on Network Protocols (ICNP)*. IEEE, Oct. 2020. DOI: 10.1109/icnp49622.2020.9259373.

[75] E. Bravi, S. Sisinni, and A. Lioy. "Exploiting the DICE specification to ensure strong identity and integrity of IoT devices." In: *2023 8th International Conference on Smart and Sustainable Technologies (SpliTech)*. IEEE, June 2023. DOI: 10.23919/splitech58164.2023.10193517.

[76] E. Lear, R. Droms, and D. Romascanu. *Manufacturer Usage Description Specification*. RFC 8520. Mar. 2019. DOI: 10.17487/RFC8520. URL: https://www.rfc-editor.org/info/rfc8520.

[77] L. Jäger, R. Petri, and A. Fuchs. "Rolling DICE: Lightweight Remote Attestation for COTS IoT Hardware." In: *Proceedings of the 12th International Conference on Availability, Reliability and Security*. ARES '17. ACM, Aug. 2017. DOI: 10.1145/3098954.3103165.

[78] D. Lorych and L. Jäger. "Design Space Exploration of DICE." In: *Proceedings of the 17th International Conference on Availability, Reliability and Security*. ARES 2022. ACM, Aug. 2022. DOI: 10.1145/3538969.3543785.

[79] M. Gross, K. Hohentanner, S. Wiehler, and G. Sigl. "Enhancing the Security of FPGA-SoCs via the Usage of ARM TrustZone and a Hybrid-TPM." In: *ACM Transactions on Reconfigurable Technology and Systems* 15.1 (Nov. 2021), pp. 1–26. DOI: 10.1145/3472959.

[80] Y. Kim and E. Kim. "hTPM." In: *Proceedings of the 1st ACM Workshop on Cyber-Security Arms Race*. ACM, Nov. 2019. DOI: 10.1145/3338511.3357348.

[81] J. Wang, C. Fan, J. Wang, Y. Cheng, Y. Zhang, W. Zhang, P. Liu, and H. Hu. *SvTPM: A Secure and Efficient vTPM in the Cloud*. 2019. DOI: 10.48550/ARXIV.1905.08493.

[82] V. Narayanan, C. Carvalho, A. Ruocco, G. Almási, J. Bottomley, M. Ye, T. Feldman-Fitzthum, D. Buono, H. Franke, and A. Burtsev. *Remote attestation of SEV-SNP confidential VMs using e-vTPMs*. 2023. DOI: 10.48550/ARXIV.2303.16463.

[83] Trusted Computing Group. *DICE Attestation Architecture*. Version 1.00 Revision 0.23. Mar. 2021.

[84] Microsoft. *Troubleshoot the TPM*. Nov. 2023. URL: https://learn.microsoft.com/en-us/windows/security/hardware-security/tpm/initialize-and-configure-ownership-of-the-tpm.

[85] JEDEC SOLID STATE TECHNOLOGY ASSOCIATION. *JESD84-A441*. Mar. 2010.

[86] JEDEC SOLID STATE TECHNOLOGY ASSOCIATION. *JESD220F*. Aug. 2020.

[87] Trusted Computing Group. *DICE Certificate Profiles*. Version 1.0 Revision 0.01. July 2020.

[88] Trusted Computing Group. *TCG EK Credential Profile for TPM Family 2.0*. Version 2.5 Revision 2. Jan. 2022.

[89] S. O. Bradner. *Key words for use in RFCs to Indicate Requirement Levels*. RFC 2119. Mar. 1997. DOI: 10.17487/RFC2119. URL: https://www.rfc-editor.org/info/rfc2119.

[90] Lenovo. *TPM Firmware Update Utility*. URL: https://download.lenovo.com/pccbbs/mobiles/n1czt01w.txt.

[91] Intel Corporation. *Trusted Platform Module (TPM) Firmware Update Instructions*. 2018. URL: https://downloadmirror.intel.com/27513/eng/nuc5i5my-tpm-firmware-update.pdf.

[92] Microsoft. *Suspend BitLocker protection for non-Microsoft software updates*. Nov. 2021. URL: https://learn.microsoft.com/en-us/troubleshoot/windows-client/windows-security/suspend-bitlocker-protection-non-microsoft-updates.

[93] E. Barker. *Recommendation for key management:: part 1 - general*. May 2020. DOI: 10.6028/nist.sp.800-57pt1r5.

[94] M. Bellare. "New Proofs for NMAC and HMAC: Security Without Collision-Resistance." In: *Advances in Cryptology - CRYPTO 2006*. Springer Berlin Heidelberg, 2006, pp. 602–619. ISBN: 9783540374336. DOI: 10.1007/11818175_36.

[95] J. Jonsson and B. Kaliski. *Public-Key Cryptography Standards (PKCS) #1: RSA Cryptography Specifications Version 2.1*. RFC 3447. Feb. 2003. DOI: 10.17487/RFC3447. URL: https://www.rfc-editor.org/info/rfc3447.

[96] S. Boeyen, S. Santesson, T. Polk, R. Housley, S. Farrell, and D. Cooper. *Internet X.509 Public Key Infrastructure Certificate and Certificate Revocation List (CRL) Profile*. RFC 5280. May 2008. DOI: 10.17487/RFC5280. URL: https://www.rfc-editor.org/info/rfc5280.

[97] Bundesamt für Sicherheit in der Informationstechnik. *Cryptographic Mechanisms: Recommendations and Key Lengths*. BSI TR-02102-1. Jan. 2023.

[98] GlobalPlatform. *TEE Management Framework including ASN.1 Profile v1.1.2*. Nov. 2020.

[99] K. Moriarty, B. Kaliski, J. Jonsson, and A. Rusch. *PKCS #1: RSA Cryptography Specifications Version 2.2*. RFC 8017. Nov. 2016. DOI: 10.17487/RFC8017. URL: https://www.rfc-editor.org/info/rfc8017.

[100] Trusted Computing Group. *TCG Trusted Attestation Protocol (TAP) Information Model for TPM Families 1.2 and 2.0 and DICE Family 1.0*. Version 1.0 Revision 0.36. Sept. 2019.

[101] C. Lamb and S. Zacchiroli. "Reproducible Builds: Increasing the Integrity of Software Supply Chains." In: *IEEE Software* 39.2 (Mar. 2022), pp. 62–70. ISSN: 1937-4194. DOI: 10.1109/ms.2021.3073045.

[102] Open Compute Project. *Caliptra: A Datacenter System on a Chip (SOC) Root of Trust (RoT)*. Revision 1.0 Version 0.5. July 2022.