Workgroup: T2TRG Research Group
Internet-Draft:
draft-irtf-t2trg-taxonomy-manufacturer-anchors-03
Published: 30 January 2024
Intended Status: Informational
Expires: 2 August 2024
Authors: M. Richardson
Sandelman Software Works

A Taxonomy of operational security considerations for manufacturer installed keys and Trust Anchors

Abstract

This document provides a taxonomy of methods used by manufacturers of silicon and devices to secure private keys and public trust anchors. This deals with two related activities: how trust anchors and private keys are installed into devices during manufacturing, and how the related manufacturer held private keys are secured against disclosure.

This document does not evaluate the different mechanisms, but rather just serves to name them in a consistent manner in order to aid in communication.

RFCEDITOR: please remove this paragraph. This work is occurring in https://github.com/mcr/idevid-security-considerations

Status of This Memo

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1. Introduction

An increasing number of protocols derive a significant part of their security by using trust anchors [RFC4949] that are installed by manufacturers. Disclosure of the list of trust anchors does not usually cause a problem, but changing them in any way does. This includes adding, replacing or deleting anchors.

The document [RFC6024] deals with how trust anchor stores are managed in the device which uses them. This document deals with how the PKI associated with such a trust anchor is managed.

Many protocols also leverage manufacturer installed identities. These identities are usually in the form of [ieee802-1AR] Initial Device Identity certificates (IDevID). The identity has two components: a private key that must remain under the strict control of a trusted part of the device, and a public part (the certificate), which (ignoring, for the moment, personal privacy concerns) may be freely disclosed.

There also situations where identities are tied up in the provision of symmetric shared secrets. A common example is the SIM card ([_3GPP.51.011]): it now comes as a virtual SIM, which could in theory be factory provisioned. The provision of an initial, per-device default password also falls into the category of symmetric shared secret.

It is further not unusual for many devices (particularly smartphones) to also have one or more group identity keys. This is used, for instance, in [fidotechnote] to make claims about being a particular model of phone (see [I-D.richardson-rats-usecases]). The key pair that does this is loaded into large batches of phones for privacy reasons.

The trust anchors are used for a variety of purposes. Trust anchors are used to verify:

- the signature on a software update (as per [I-D.ietf-suit-architecture]),
- a TLS Server Certificate, such as when setting up an HTTPS connection,
- the [RFC8366] format voucher that provides proof of an ownership change.

Device identity keys are used when performing enrollment requests (in [RFC8995], and in some uses of [I-D.ietf-emu-eap-noob]. The device identity certificate is also used to sign Evidence by an Attesting Environment (see [I-D.ietf-rats-architecture]).

These security artifacts are used to anchor other chains of information: an EAT Claim as to the version of software/firmware running on a device ([I-D.birkholz-suit-coswid-manifest]), an EAT claim about legitimate network activity (via [I-D.birkholz-rats-mud], or embedded in the IDevID in [RFC8520]).

Known software versions lead directly to vendor/distributor signed Software Bill of Materials (SBOM), such as those described by [I-D.ietf-sacm-coswid] and the NTIA/SBOM work [ntiasbom] and CISQ/OMG SBOM work underway [cisqsbom].

In order to manage risks and assess vulnerabilities in a Supply Chain, it is necessary to determine a degree of trustworthiness in each device. A device may mislead audit systems as to its provenance, about its software load or even about what kind of device it is (see [RFC7168] for a humorous example).

In order to properly assess the security of a Supply Chain it is necessary to understand the kinds and severity of the threats which a device has been designed to resist. To do this, it is necessary to understand the ways in which the different trust anchors and identities are initially provisioned, are protected, and are updated.

To do this, this document details the different trust anchors (TrAnc) and identities (IDs) found in typical devices. The privacy and integrity of the TrAncs and IDs is often provided by a different, superior artifact. This relationship is examined.

While many might desire to assign numerical values to different mitigation techniques in order to be able to rank them, this document does not attempt to do that, as there are too many other (mostly human) factors that would come into play. Such an effort is more properly in the purview of a formal ISO9001 process such as ISO14001.

1.1. Terminology

This document is not a standards track document, and it does not make use of formal requirements language.

This section will be expanded to include needed terminology as required.

The words Trust Anchor are contracted to TrAnc rather than TA, in order not to confuse with [RFC9397]'s "Trusted Application".

This document defines a number of hyphenated terms, and they are summarized here:

device-generated: a private or symmetric key which is generated on the device

infrastructure-generated: a private or symmetric key which is generated by some system, likely located at the factory that built the device

mechanically-installed: when a key or certificate is programmed into non-volatile storage by an out-of-band mechanism such as JTAG [JTAG]

mechanically-transferred: when a key or certificate is transferred into a system via private interface, such as serial console, JTAG managed mailbox, or other physically private interface

network-transferred: when a key or certificate is transferred into a system using a network interface which would be available after the device has shipped. This applies even if the network is physically attached using a bed-of-nails [BedOfNails].

device/infrastructure-co-generated: when a private or symmetric key is derived from a secret previously synchronized between the silicon vendor and the factory using a common algorithm.

In addition, Section 4.1.1 introduces three primary private key generation techniques named *arbitrarily* after three vegetables (avocado, bamboo, and carrot) and two secondary ones named after two fruits (salak and sapodilla). The two secondary ones refer to methods where a secure element is involved, and mnemonically start with the same letter: S.

2. Applicability Model

There is a wide variety of devices to which this analysis can apply. (See [I-D.bormann-lwig-7228bis].) This document will use a J-group processor as a sample. This class is sufficiently large to experience complex issues among multiple CPUs, packages and operating systems, but at the same time, small enough that this class is often deployed in single-purpose IoT-like uses. Devices in this class often have Secure Enclaves (such as the "Grapeboard"), and can include silicon manufacturer controlled processors in the boot process (the Raspberry PI boots under control of the GPU).

Almost all larger systems (servers, laptops, desktops) include a Baseboard Management Controller (BMC), which ranges from a M-Group Class 3 MCU, to a J-Group Class 10 CPU (see, for instance [openbmc] which uses a Linux kernel and system inside the BMC). As the BMC usually has complete access to the main CPU's memory, I/O hardware and disk, the boot path security of such a system needs to be understood first as being about the security of the BMC.

2.1. A reference manufacturing/boot process

In order to provide for immutability and privacy of the critical TrAnc and IDs, many CPU manufacturers will provide for some kind of private memory area which is only accessible when the CPU is in certain privileged states. See the Terminology section of [RFC9397], notably TEE, REE, and TAM, and also section 4, Architecture.

The private memory that is important is usually non-volatile and rather small. It may be located inside the CPU silicon die, or it may be located externally. If the memory is external, then it is usually encrypted by a hardware mechanism on the CPU, with only the key kept inside the CPU.

The entire mechanism may be external to the CPU in the form of a hardware-TPM module, or it may be entirely internal to the CPU in the form of a firmware-TPM. It may use a custom interface to the rest of the system, or it may implement the TPM 1.2 or TPM 2.0 specifications. Those details are important to performing a full evaluation, but do not matter much to this model (see initial-enclave-location below).

During the manufacturing process, once the components have been soldered to the board, the system is usually put through a system-level test. This is often done as a "bed-of-nails" test [BedOfNails], where the board has key points attached mechanically to a test system. A [JTAG] process tests the System Under Test, and then initializes some firmware into the still empty flash storage.

It is now common for a factory test image to be loaded first: this image will include code to initialize the private memory key described above, and will include a first-stage bootloader and some kind of (primitive) Trusted Application Manager (TAM). (The TAM is a piece of software that lives within the trusted execution environment.)

Embedded in the stage one bootloader will be a Trust Anchor that is able to verify the second-stage bootloader image.

After the system has undergone testing, the factory test image is erased, leaving the first-stage bootloader. One or more second-stage bootloader images are installed. The production image may be installed at that time, or if the second-stage bootloader is able to install it over the network, it may be done that way instead.

There are many variations of the above process, and this section is not attempting to be prescriptive, but to be provide enough illustration to motivate subsequent terminology.

The process may be entirely automated, or it may be entirely driven by humans working in the factory, or a combination of the above.

These steps may all occur on an access-controlled assembly line, or the system boards may be shipped from one place to another (maybe another country) before undergoing testing.

Some systems are intended to be shipped in a tamper-proof state, but it is usually not desirable that bed-of-nails testing be possible without tampering, so the initialization process is usually done prior to rendering the system tamper-proof. An example of a one-way tamper-proof, weather resistant treatment might to mount the system board in a case and fill the case with resin.

Quality control testing may be done prior to as well as after the application of tamper-proofing, as systems which do not pass inspection may be reworked to fix flaws, and this should ideally be impossible once the system has been made tamper-proof.

3. Types of Trust Anchors

Trust Anchors (TrAnc) are fundamentally public keys with authorizations implicitly attached through the code that references them.

They are used to validate other digitally signed artifacts. Typically, these are chains of PKIX certificates leading to an End-Entity certificate (EE).

The chains are usually presented as part of an externally provided object, with the term "externally" to be understood as being as close as untrusted flash, to as far as objects retrieved over a network.

There is no requirement that there be any chain at all: the trust anchor can be used to validate a signature over a target object directly.

The trust anchors are often stored in the form of self-signed certificates. The self-signature does not offer any cryptographic assurance, but it does provide a form of error detection, providing verification against non-malicious forms of data corruption. If storage is at a premium (such as inside-CPU non-volatile storage) then only the public key itself need to be stored. For a 256-bit ECDSA key, this is 32 bytes of space.

When evaluating the degree of trust for each trust anchor there are four aspects that need to be determined:

- can the trust anchor be replaced or modified?
- can additional trust anchors be added?
- can trust anchors be removed?
- how is the private key associated with the trust anchor, maintained by the manufacturer, maintained?

The first three things are device specific properties of how the integrity of the trust anchor is maintained.

The fourth property has nothing to do with the device, but has to do with the reputation and care of the entity that maintains the private key.

Different anchors have different authorizations associated with them.

These are:

3.1. Secured First Boot Trust Anchor

This anchor is part of the first-stage boot loader, and it is used to validate a second-stage bootloader which may be stored in external flash. This is called the initial software trust anchor.

3.2. Software Update Trust Anchor

This anchor is used to validate the main application (or operating system) load for the device.

It can be stored in a number of places. First, it may be identical to the Secure Boot Trust Anchor.

Second, it may be stored in the second-stage bootloader, and therefore its integrity is protected by the Secured First Boot Trust Anchor.

Third, it may be stored in the application code itself, where the application validates updates to the application directly (update in place), or via a double-buffer arrangement. The initial (factory) load of the application code initializes the trust arrangement.

In this situation the application code is not in a secured boot situation, as the second-stage bootloader does not validate the application/operating system before starting it, but it may still provide measured boot mechanism.

3.3. Trusted Application Manager anchor

This anchor is the secure key for the [RFC9397] Trusted Application Manager (TAM). Code which is signed by this anchor will be given execution privileges as described by the manifest which accompanies the code. This privilege may include updating anchors.

3.4. Public WebPKI anchors

These anchors are used to verify HTTPS certificates from web sites. These anchors are typically distributed as part of desktop browsers, and via desktop operating systems.

The exact set of these anchors is not precisely defined: it is usually determined by the browser vendor (e.g., Mozilla, Google, Apple, Safari, Microsoft), or the operating system vendor (e.g., Apple, Google, Microsoft, Ubuntu). In most cases these vendors look to the CA/Browser Forum [CABFORUM] for inclusion criteria.

3.5. DNSSEC root

This anchor is part of the DNS Security extensions. It provides an anchor for securing DNS lookups. Secure DNS lookups may be important in order to get access to software updates. This anchor is now scheduled to change approximately every 3 years, with the new key announced several years before it is used, making it possible to embed keys that will be valid for up to five years.

This trust anchor is typically part of the application/operating system code and is usually updated by the manufacturer when they do updates. However, a system that is connected to the Internet may update the DNSSEC anchor itself through the mechanism described in [RFC5011].

There are concerns that there may be a chicken and egg situation for devices that have remained in a powered off state (or disconnected from the Internet) for some period of years. That upon being reconnected, that the device would be unable to do DNSSEC validation. This failure would result in them being unable to obtain operating system updates that would then include the updates to the DNSSEC key.

3.6. Private/Cloud PKI anchors

It is common for many IoT and network appliances to have links to vendor provided services. For instance, the IoT device that calls home for control purposes, or the network appliance that needs to validate a license key before it can operate. (This may be identical to, or distinct from a Software Update anchor. In particular, the device might call home over HTTPS to learn if there is a software update that needs to be done, but the update is signed by another key)

Such vendor services can be provided with public certificates, but often the update policies such public anchors precludes their use in many operational environments. Instead a private PKI anchor is included. This can be in the form a multi-level PKI (as described in Section 5.1), or degenerate to a level-1 PKI: a self-signed certificate. A level-1 PKI is very simple to create and operate, and there are innumerable situations where there is just a call to "curl" with the "--pinnedpubkey" option has been used.

3.7. Onboarding and other Enrollment anchors

[RFC8995], [RFC8572] and [RFC8366] specifies a mechanism for onboarding of new devices. The voucher archifact is transfered to the device by different means, and the device must verify the signature on it. This requires a trust anchor to be built-in to the device, and some kind of private PKI be maintained by the vendor (or it's authorized designate). [I-D.anima-masa-considerations] provides some advice on choices in PKI design for a MASA. The taxomony presented in this document apply to describing how this PKI has been designed.

3.8. Onboarded network-local anchors

[RFC7030], [RFC8995] and [I-D.ietf-netconf-trust-anchors] provide mechanisms by which new trust anchors may be loaded by a device during an onboarding process. The trust anchors involved are typically local to an enterprise and are used to validate connections to other devices in the network. This typically includes connections to network management systems that may also load or modify other trust anchors in the system. [I-D.anima-masa-considerations] provides some advice in the BRSKI ([RFC8995]) case for appropriate PKI complexity for such local PKIs

3.9. What else?

what anchors are still missing?

4. Types of Identities

Identities are installed during manufacturing time for a variety of purposes.

Identities require some private component. Asymmetric identities (e.g., RSA, ECDSA, EdDSA systems) require a corresponding public component, usually in the form of a certificate signed by a trusted third party.

This certificate associates the identity with attributes.

The process of making this coordinated key pair and then installing it into the device is called identity provisioning.

4.1. Manufacturer installed IDevID certificates

[ieee802-1AR] defines a category of certificates that are installed by the manufacturer which contain a device unique serial number.

A number of protocols depend upon this certificate.

- [RFC8572] and [RFC8995] introduce mechanisms for new devices (called pledges) to be onboarded into a network without intervention from an expert operator. A number of derived protocols such as [I-D.ietf-anima-brski-async-enroll], [I-D.ietf-anima-constrained-voucher], [I-D.richardson-anima-voucher-delegation], [I-D.friel-anima-brski-cloud] extend this in a number of ways.

- [I-D.ietf-rats-architecture] depends upon a key provisioned into the Attesting Environment to sign Evidence.

- [I-D.ietf-suit-architecture] may depend upon a key provisioned into the device in order to decrypt software updates. Both symmetric and asymmetric keys are possible. In both cases, the decrypt operation depends upon the device having access to a private key provisioned in advance. The IDevID can be used for this if algorithm choices permit. ECDSA keys do not directly support encryption in the same way that RSA does, for instance, but the addition of ECIES can solve this. There may be other legal considerations why the IDevID might not be used, and a second key provisioned.

- TBD

4.1.1. Operational Considerations for Manufacturer IDevID Public Key generation

The OEM manufacturer has the responsibility to provision a key pair into each device as part of the manufacturing process. There are a variety of mechanisms to accomplish this, which this section details.

There are three fundamental ways to generate IDevID certificates for devices:

1. generating a private key on the device, creating a Certificate Signing Request (or equivalent), and then returning a certificate to the device.

2. generating a private key outside the device, signing the certificate, and the installing both into the device.

3. deriving the private key from a previously installed secret seed, that is shared with only the manufacturer.

There is additionally variations where the IDevID is provided as part of a Trusted Platform Module (TPM) or Secure Element (SE). The OEM vendor may purchase such devices from another vendor, and that vendor often offers provisioning of a key pair into the device as a service.

The document [I-D.moskowitz-ecdsa-pki] provides some practical instructions on setting up a reference implementation for ECDSA keys using a three-tier mechanism.

4.1.1.1. Avocado method: On-device private key generation

In this method, the device generates a private key on the device. This is done within some very secure aspect of the device, such as in a Trusted Execution Environment, and the resulting private key is then stored in a secure and permanent way. The permanency may extend beyond use of on-CPU flash, and could even involve blowing of one-time fuses.

Generating the key on-device has the advantage that the private key never leaves the device. The disadvantage is that the device may not have a verifiable random number generator. The use of pseudo-random number generator needs to be well seeded as explained in [RFC4086]. [factoringrsa] is an example of a successful attack on this scenario.

There are a number of options of how to get the public key from the device to the certification authority. As it is a public key, privacy is less of a concern, and the focus is on integrity. (However disclosing the public key may have impacts on trackability of the device)

So, transmission must be done in an integral manner, and must be securely associated with an assigned serial number. The serial number goes into the certificate, and the resulting certificate needs to be loaded into the manufacturer's asset database, and returned to the device to be stored as the IDevID certificate.

One way to do the transmission is during a factory Bed of Nails test (see [BedOfNails]) or JTAG Boundary Scan. When done via a physical connection like this, then this is referred to as a *avocado device-generated / mechanically-transferred* method.

There are other ways that could be used where a certificate signing request is sent over a special network channel when the device is powered up in the factory. This is referred to as the *avocado device-generated / network-transferred* method.

Regardless of how the certificate signing request is sent from the device to the factory, and how the certificate is returned to the device, a concern from production line managers is that the assembly line may have to wait for the certification authority to respond with the certificate. This is inherently a synchronous process, as the process can not start until the private key is generated and stored.

After the key generation, the device needs to set a flag such that it no longer will generate a new key, and will not accept a new IDevID via the factory network connection. This may be a software setting, or could be as dramatic as blowing a fuse.

Devices are typically constructed in a fashion such that the device is unable to ever disclose the private key via an external interface. This is usually done using a secure-enclave provided by the CPU architecture in combination with on-chip non-volatile memory.

The risk is that if an attacker with physical access is able to put the device back into an unconfigured mode, then the attacker may be able to substitute a new certificate into the device. It is difficult to construct a rationale for doing this as the attacker would not be able to forge a certificate from the manufacturers' CA. Other parties that rely on the IDevID would see the device as an imposter if another CA was used. However, if the goal is theft of the device itself (without regard to having access to firmware updates), then use of another manufacturer identity may be profitable. Stealing a very low value item, such as a light bulb makes very little sense. Stealing a medium value items, such as appliances, or high-value items such as cars, yachts or even airplanes would make sense. Replacing the manufacturer IDevID permits the attacker to also replace the authority to transfer ownership in protocols like [RFC8995].

4.1.1.2. Bamboo method: Off-device private key generation

In this method, a key pair is generated in the factory, outside of the device. The factory keeps the private key in a restricted area, but uses it to form a Certification Signing Request (CSR). The CSR is passed to the manufacturer's Certification Authority (CA), and a certificate is returned. Other meta-data is often also returned, such as a serial number.

Generating the key off-device has the advantage that the randomness of the private key can be better analyzed. As the private key is available to the manufacturing infrastructure, the authenticity of the public key is well known ahead of time.

The private key and certificate can be programmed into the device along with the initial bootloader firmware in a single step.

As the private key can be known to the factory in advance of the device being ready for it, the certificate can also be generated in advance. This hides the latency to talk to the CA, and allows for the connectivity to the CA to be less reliable without shutting down the assembly line. A single write to the flash of the device can contain the entire firmware of the device, including configuration of trust anchors and private keys.

The major downside to generating the private key off-device is that it could be seen by the manufacturing infrastructure. It could be compromised by humans in the factory, or the equipment could be compromised. The use of this method increases the value of attacking the manufacturing infrastructure.

If private keys are generated by the manufacturing plant, and are immediately installed, but never stored, then the window in which an attacker can gain access to the private key is immensely reduced. But, the process then becomes more synchronous, negating much of the advantage of such a system.

As in the previous case, the transfer may be done via physical interfaces such as bed-of-nails, giving the *bamboo infrastructure-generated / mechanically-transferred* method.

There is also the possibility of having a *bamboo infrastructure-generated / network-transferred* key. There is a support for "server-generated" keys in [RFC7030], [RFC8894], and [RFC4210]. All methods strongly recommend encrypting the private key for transfer. This is difficult to comply with here as there is not yet any private key material in the device, so in many cases it will not be possible to encrypt the private key. Still, it may be acceptable if the device is connected directly by a wired network and unroutable addresses are used. This not really any less secure than a bed-of-nails interface.

4.1.1.3. Carrot method: Key setup based on secret seed

In this method, a random symmetric seed is generated by a supplier to the OEM. This is typically the manufacturer of the CPU, often a system on a chip (SOC). In this section there are two Original Equipment Manufacturer (OEM): the first is the familiar one that is responsible for the entire device (the device-OEM), and the second one is the silicon (the Silicon-OEM) vendor in which this symmetric seed key has been provisioned.

In this process, the Silicon-OEM provisions a unique secret into each device shipped. This is typically at least 256-bits in size.

This can be via fuses blown in a CPU's Trusted Execution Environment [RFC9397], a TPM, or a Secure Element that provisioned at it's fabrication time. In some cases, the secret is based upon a Physically Uncloneable Function [PUF].

This value is revealed to the OEM board manufacturer only via a secure channel. Upon first boot, the system (within a TEE, a TPM, or Secure Element) will generate a key pair using this seed to initialize a Pseudo-Random-Number-Generator (PRNG). The OEM, in a separate system, will initialize the same PRNG and, thus generate the same key pair. The OEM then derives the public key part, and signs it with their certification authority (CA) to turns it into a certificate. The private part is then destroyed by the OEM, ideally never stored or seen by anyone.

The certificate (being public information) is placed into a database, in some cases it is loaded by the device as its IDevID certificate, in other cases, it is retrieved during the onboarding process based upon a unique serial number asserted by the device.

In some ways, this method appears to have all of the downsides of the previous two methods: the device must correctly derive its own private key, and the OEM has access to the private key, making it also vulnerable. The device does not depend upon any internal source of random numbers to derive it's key.

The OEM does all of the private key manipulation in a secure place, probably offline, and need never involve the actual physical factory. The OEM can do this in a different country, even.

The security of the process rests upon the difficulty in extracting the seed provided by the Silicon-OEM. While the Silicon-OEM must operate a factory that is more secure, which has a much higher cost, the exposure for this facility can be much better controlled. The device-OEM's factory, which has many more components as input, including device testing, can operate at a much lower risk level.

Additionally, there are some other advantages to the OEM: The private keys and certificates may be calculated by the OEM asynchronously to the manufacturing process, either done in batches in advance of actual manufacturing, or on demand when an IDevID is requested.

There are additional downsides of this method for OEM: the cost is often higher, and may involve additional discrete parts. The security has been outsourced to the OEM-silicon fabrication system. The resulting seeds must be communicated to the OEM in batches, by heavily secured physical courier, and the device-OEM must store and care for these keys very carefully.

4.1.1.4. Salak method: on-device generation with Secure Element

In this method, a key-pair is generated by the device using an external security element. (It may be a discrete TPM, but the firmware TPM method is considered avocado).

The secure element provides additional assurance that the private key was properly generated. Secure elements are designed specifically so that private keys can not be extracted from the device, so even if the device is attacked in a sophisticated way, using hardware, the private key will not be disclosed.

4.1.1.5. Sapodilla method: Secure Element factory generation

In this method, a key-pair is generated by the Silicon-OEM in their factory. This method is essentially identical to the salak method, but it occurs in a different factory.

As a result the choice of which certification authority (CA) gets used may be very different. It is typical for the Silicon-OEM to operate a CA themselves. There are a few options: a) they may put IDevIDs into the device which are generic to the silicon-OEM provider, b) they may operate a CA on behalf of the device-OEM, c) they may even connect over a network to the device-OEM's CA.

The device-OEM receives the secure element devices in batches in a similiar way that they receive other parts. The secure elements are placed by the device-OEM's manufacturing plant into the devices.

Upon first boot the device-OEM's firmware can read the IDevID certificate that have been placed into the secure elements, and can ask the secure element to perform signing operations using the private key contained in the secure element. But, the private key can not be extracted.

Despite the increase convenience of this method, there may be a risk if the secure elements are stolen in transport. A thief could use them to generate signatures that would appear to be from device-OEM's devices. To deal with this, there is often a simple activation password that the device-OEM's firmware must provide to the secure element in order to activate it. This password is probably stored in the clear in the device-OEM's firmware: it can't be encrypted, because the source of decryption keys would be in the secure element.

5. Public Key Infrastructures (PKI)

[RFC5280] describes the format for certificates, and numerous mechanisms for doing enrollment have been defined (including: EST [RFC7030], CMP [RFC4210], SCEP [RFC8894]).

[RFC5280] provides mechanisms to deal with multi-level certification authorities, but it is not always clear what operating rules apply.

The certification authority (CA) that is central to [RFC5280]-style public key infrastructures can suffer three kinds of failures:

1. disclosure of a private key,

2. loss of a private key,

3. inappropriate signing of a certificate from an unauthorized source.

A PKI which discloses one or more private certification authority keys is no longer secure.

An attacker can create new identities, and forge certificates connecting existing identities to attacker controlled public/private keypairs. This can permit the attacker to impersonate any specific device.

There is an additional kind of failure when the CA is convinced to sign (or issue) a certificate which it is not authorized to do so. See for instance [ComodoGate]. This is an authorization failure, and while a significant event, it does not result in the CA having to be re-initialized from scratch.

This is distinguished from when a loss as described above renders the CA completely useless and likely requires a recall of all products that have ever had an IDevID issued from this CA.

If the PKI uses Certificate Revocation Lists (CRL)s, then an attacker that has access to the private key can also revoke existing identities.

In the other direction, a PKI which loses access to a private key can no longer function. This does not immediately result in a failure, as existing identities remain valid until their expiry time (notAfter). However, if CRLs or OCSP are in use, then the inability to sign a fresh CRL or OCSP response will result in all identities becoming invalid once the existing CRLs or OCSP statements expire.

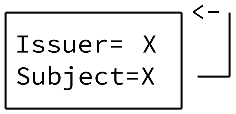
This section details some nomenclature about the structure of certification authorities.

5.1. Number of levels of certification authorities (pkilevel)

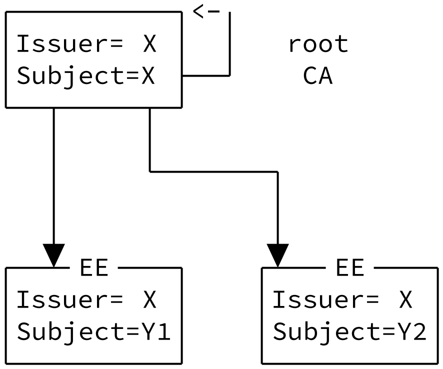
Section 6.1 of [RFC5280] provides a Basic Path Validation. In the formula, the certificates are arranged into a list.

The certification authority (CA) starts with a Trust Anchor (TrAnc). This is counted as the first level of the authority.

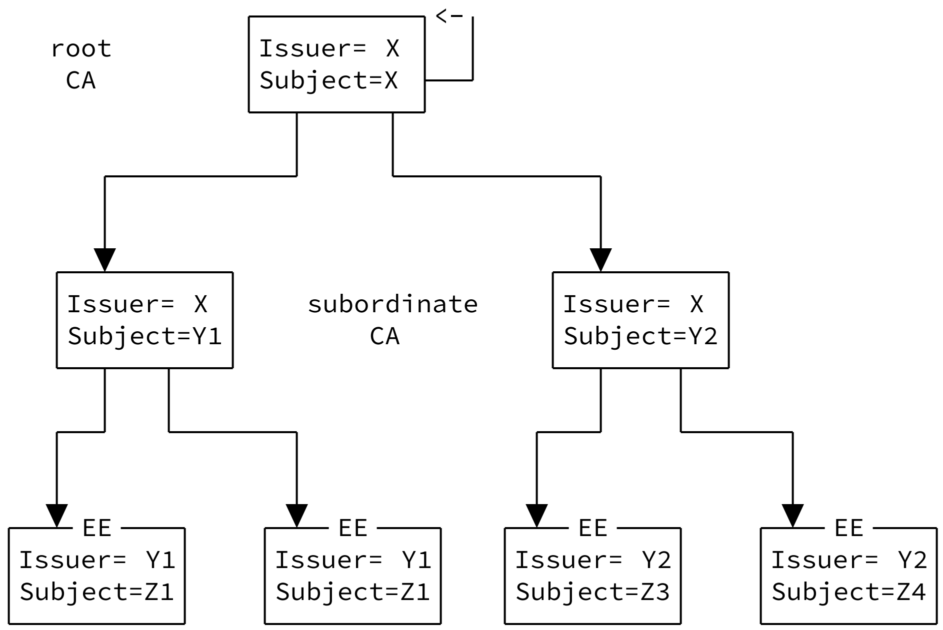
In the degenerate case of a self-signed certificate, then this a one level PKI.



The private key associated with the Trust Anchor signs one or more certificates. When this first level authority trusts only End-Entity (EE) certificates, then this is a two level PKI.



When this first level authority signs subordinate certification authorities, and those certification authorities sign End-Entity certificates, then this is a three level PKI.



In general, when arranged as a tree, with the End-Entity certificates at the bottom, and the Trust Anchor at the top, then the level is where the deepest EE certificates are, counting from one.

It is quite common to have a three-level PKI, where the root (level one) of the CA is stored in a Hardware Security Module in a way that it cannot be continuously accessed ("offline"), while the level two subordinate CA can sign certificates at any time ("online").

5.2. Protection of CA private keys

The private key for the certification authorities must be protected from disclosure. The strongest protection is afforded by keeping them in a offline device, passing Certificate Signing Requests (CSRs) to the offline device by human process.

For examples of extreme measures, see [kskceremony]. There is however a wide spectrum of needs, as exampled in [rootkeyceremony]. The SAS70 audit standard is usually used as a basis for the Ceremony, see [keyceremony2].

This is inconvenient, and may involve latencies of days, possibly even weeks to months if the offline device is kept in a locked environment that requires multiple keys to be present.

There is therefore a tension between protection and convenience. Convenient and timely access to sign new artifacts is not something that is just nice to have. If access is inconvenient then it may cause delays for signing of new code releases, or it may incentivize technical staff to build in work arounds in order that they can get their job done faster. The compromise between situations is often mitigated by having some levels of the PKI be offline, and some levels of the PKI be online.

5.3. Preservation of CA and Trust Anchor private keys

A public key (or certificate) is installed into target device(s) as a trust anchor. Is it there in order to verify further artifacts, and it represents a significant investment. Trust anchors must not be easily replaced by attackers, and securing the trust anchor against such tampering may involve burning the trust anchor into unchangeable fuses inside a CPU.

Replacement of the anchor can involve a physical recall of every single device. It therefore important that the trust anchor is useable for the entire lifetime of every single one of the devices.

The previous section deals with attacks against the infrastructure: the attacker wants to get access to the private key material, or to convince the infrastructure to use the private key material to their bidding. Such an event, if undetected would be catastrosphic. But, when detected, would render almost every device useless (or potentially dangerous) until the anchor could be replaced.

There is a different situation, however, which would lead to a similiar result. If the legitimate owner of the trust anchor infrastructure loses access the private keys, then an equally catastrophic situation occurs.

There are many situations that could lead to this. The most typical situation would seem to be some kind of physical damage: a flood, a fire. Less obvious situations could occur if a human forgets a password, or if the human with the password(s) dies, or becomes incapacited.

Backups of critical material is routinely done. Storage of backups offsite deals with physical damage, and in many cases the organization maintains an entire set of equipment at another location.

The question then becomes: how are the backups unlocked, or activated. Why attack the primary site physically if an attacker can target the backup site, or the people whose job it is to activate the backup site?

Consider the situation where a hurricane or earthquake takes out all power and communications at an organizations' primary location, and it becomes necessary to activate the backup site. What does it take to do that?

Typically the secrets will be split using [shamir79] into multiple pieces, each piece being carried with a different trusted employee.

In [kskceremony], the pieces are stored on smartcards which are kept in a vault, and the trusted people carry keys to the vault.

One advantage of this mechanism is that if necessary, the doors to the vault can be drilled out. This takes some significant time and leaves significant evidence, so it can not be done quietly by an attacker. In the case of the DNSSEC Root, a failure of the vault to open actually required this to be done.

In other systems the digital pieces are carried on the person themselves, ideally encrypted with a password known only to that person.

[shamir79] allows for keys to be split up into n-components, where only some smaller number of them, k, need to be present to reconstruct the secret. This is known as a (k, n) threshold scheme.

5.3.1. Secret splitting, k-of-n

In this document, each of the people who hold a piece of the secret are referred to as Key Executives.

The choice of n, and the choice of k is therefore of critical concern. It seems unwise for an organizations to publish them, as it provides some evidence as to how many Key Executives would need to be coerced.

The identities of the n Key Executive should also be confidential. The list of who they are should probably be limited to the members of the board and executive. There does not seem to be any particular reason for the Key Executives to be members of the board, but having a long term relationship with the enterprise seems reasonable, and a clear understanding of when to use the piece.

The number k, which is the minimum number of people that would need to be coerced should also remain confidential.

A number that can be published is the difference between k and n, which represents the number of redundant Key Executives that exist.

An enterprise that has operations in multiple places may be better positioned to survive incidents that disrupt travel. For instance, an earthquake, tsunami, or pandemic not only has the possibility to kill Key Executives or the smartcard or USB key that they are stored on. [shamir79] suggests that n=2k-1, which implies that a simple majority of Key Executives are needed to reconstruct the secret, other values of k have some interesting advantages.

A value of k set to be less than a simple majority, where the Key Executives are split between two or more continents (with each continent having at least k Key Executives) would allow either continent to continue operations without the other group.

This might be a very good way to manage a code signing or update signing key. Split it among development groups in three time zones (eight hours apart), such that any of those development groups can issue an emergency security patch. (Another way would be to have three End-Entity certificates that can sign code, and have each time zone sign their own code. That implies that there is at least a level two PKI around the code signing process, and that any bootloaders that need to verify the code being starting it are able to do PKI operations)

5.4. Supporting provisioned anchors in devices

IDevID-type Identity (or Birth) Certificates which are provisioned into devices need to be signed by a certification authority maintained by the manufacturer. During the period of manufacture of new product, the manufacturer needs to be be able to sign new Identity Certificates.

During the anticipated lifespan of the devices the manufacturer needs to maintain the ability for third parties to validate the Identity Certificates. If there are Certificate Revocation Lists (CRLs) involved, then they will need to re-signed during this period. Even for devices with a short active lifetime, the lifespan of the device could very long if devices are kept in a warehouse for many decades before being activated.

Trust anchors which are provisioned in the devices will have corresponding private keys maintained by the manufacturer. The trust anchors will often anchor a PKI which is going to be used for a particular purpose. There will be End-Entity (EE) certificates of this PKI which will be used to sign particular artifacts (such as software updates), or messages in communications protocols (such as TLS connections). The private keys associated with these EE certificates are not stored in the device, but are maintained by the manufacturer. These need even more care than the private keys stored in the devices, as compromise of the software update key compromises all of the devices, not just a single device.

6. Evaluation Questions

This section recaps the set of questions that may need to be answered. This document does not assign valuation to the answers.

6.1. Integrity and Privacy of on-device data

initial-enclave-location: Is the location of the initial software trust anchor internal to the CPU package? Some systems have a software verification public key which is built into the CPU package, while other systems store that initial key in a non-volatile device external to the CPU.

initial-enclave-integrity-key: If the first-stage bootloader is external to the CPU, and if it is integrity protected, where is the key used to check the integrity?

initial-enclave-privacy-key: If the first-stage data is external to the CPU, is it kept confidential by use of encryption?

first-stage-exposure: The number of people involved in the first stage initialization. An entirely automated system would have a number zero. A factory with three 8 hour shifts might have a number that is a multiple of three. A system with humans involved may be subject to bribery attacks, while a system with no humans may be subject to attacks on the system which are hard to notice.

first-second-stage-gap: how far and long does a board travel between being initialized with a first-stage bootloader to where it is locked down so that changes to the bootloader can no longer be made. For many situations, there is no distance at all as they occur in the same factory, but for other situations boards are manufactured and tested in one location, but are initialized elsewhere.

6.2. Integrity and Privacy of device identify infrastructure

For IDevID provisioning, which includes a private key and matching certificate installed into the device, the associated public key infrastructure that anchors this identity must be maintained by the manufacturer.

identity-pki-level: referring to Section 5.1, the level number at which End-Entity certificates are present.

identity-time-limits-per-subordinate: how long is each subordinate CA maintained before a new subordinate CA key is generated? There may be no time limit, only a device count limit.

identity-number-per-subordinate: how many identities are signed by a particular subordinate CA before it is retired? There may be no numeric limit, only a time limit.

identity-anchor-storage: how is the root CA key stored? An open description that might include whether an HSM is used, or not, or even the model of it.

identity-shared-split-extra: referring to Section 5.3.1, where a private key is split up into n-components, of which k are required to recover the key, this number is n-k. This is the number of spare shares. Publishing this provides a measure of how much redundancy is present while not actually revealing either k or n.

identity-shared-split-continents: the number of continents on which the private key can be recovered without travel by any of the secret share holders

6.3. Integrity and Privacy of included trust anchors

For each trust anchor (public key) stored in the device, there will be an associated PKI. For each of those PKI the following questions need to be answered.

pki-level: how deep is the EE that will be evaluated, based upon the criteria in Section 5.1

pki-algorithms: what kind of algorithms and key sizes can actively be used with the device.

pki-lifespan: what is the timespan for this anchor. Does it get replaced at some interval, and if so, by what means is this done?

pki-level-locked: (a Boolean) is the level where the EE cert will be found locked by the device, or can levels be added or deleted by the PKI operator without code changes to the device.

pki-breadth: how many different non-expired EE certificates is the PKI designed to manage?

pki-lock-policy: can any EE certificate be used with this trust anchor to sign? Or, is there some kind of policy OID or Subject restriction? Are specific subordinate CAs needed that lead to the EE?

pki-anchor-storage: how is the private key associated with this trust root stored? How many people are needed to recover it?

7. Privacy Considerations

many yet to be detailed

8. Security Considerations

This entire document is about security considerations.

9. IANA Considerations

This document makes no IANA requests.

10. Acknowledgements

Robert Martin of MITRE provided some guidance about citing the SBOM efforts. Carsten Borman provides many editorial suggestions.

11. Changelog

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Author's Address

Michael Richardson
Sandelman Software Works

Email: mcr+ietf@sandelman.ca