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Authors: H. Birkholz
Fraunhofer SIT
D. Thaler
Microsoft
M. Richardson
Sandelman Software Works
N. Smith
Intel
W. Pan
Huawei Technologies

Remote Attestation Procedures Architecture

Abstract

In network protocol exchanges, it is often the case that one entity (a Relying Party) requires evidence about a remote peer to assess the peer's trustworthiness, and a way to appraise such evidence. The evidence is typically a set of claims about its software and hardware platform. This document describes an architecture for such remote attestation procedures (RATS).

Note to Readers

Discussion of this document takes place on the RATS Working Group mailing list (rats@ietf.org), which is archived at https://mailarchive.ietf.org/arch/browse/rats/.

Source for this draft and an issue tracker can be found at https://github.com/ietf-rats-wg/architecture.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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1. Introduction

In Remote Attestation Procedures (RATS), one peer (the "Attester") produces believable information about itself - Evidence - to enable a remote peer (the "Relying Party") to decide whether to consider that Attester a trustworthy peer or not. RATS are facilitated by an additional vital party, the Verifier.

The Verifier appraises Evidence via Appraisal Policies and creates the Attestation Results to support Relying Parties in their decision process. This documents defines a flexible architecture consisting of attestation roles and their interactions via conceptual messages. Additionally, this document defines a universal set of terms that can be mapped to various existing and emerging Remote Attestation Procedures. Common topological models and the data flows associated with them, such as the "Passport Model" and the "Background-Check Model" are illustrated. The purpose is to define useful terminology for attestation and enable readers to map their solution architecture to the canonical attestation architecture provided here. Having a common terminology that provides well-understood meanings for common themes such as roles, device composition, topological models, and appraisal is vital for semantic interoperability across solutions and platforms involving multiple vendors and providers.

Amongst other things, this document is about trust and trustworthiness. Trust is a choice one makes about another system. Trustworthiness is a quality about the other system that can be used in making one's decision to trust it or not. This is subtle

difference and being familiar with the difference is crucial for using this document. Additionally, the concepts of freshness and trust relationships with respect to RATS are elaborated on to enable implementers in order to choose appropriate solutions to compose their Remote Attestation Procedures.

2. Terminology

This document uses the following terms.

Appraisal Policy for Evidence: A set of rules that informs how a Verifier evaluates the validity of information about an Attester. Compare /security policy/ in [RFC4949]

Appraisal Policy for Attestation Results: A set of rules that direct how a Relying Party uses the Attestation Results regarding an Attester generated by the Verifiers. Compare /security policy/ in [RFC4949]

Attestation Result: The output generated by a Verifier, typically including information about an Attester, where the Verifier vouches for the validity of the results

Attester: A role performed by an entity (typically a device) whose Evidence must be appraised in order to infer the extent to which the Attester is considered trustworthy, such as when deciding whether it is authorized to perform some operation

Claim: A piece of asserted information, often in the form of a name/value pair. (Compare /claim/ in [RFC7519])

Endorsement: A secure statement that some entity (typically a manufacturer) vouches for the integrity of an Attester's signing capability

Endorser: An entity (typically a manufacturer) whose Endorsements help Verifiers appraise the authenticity of Evidence

Evidence: A set of information about an Attester that is to be appraised by a Verifier. Evidence may include configuration data, measurements, telemetry, or inferences.

Relying Party: A role performed by an entity that depends on the validity of information about an Attester, for purposes of reliably applying application specific actions. Compare /relying party/ in [RFC4949]

Relying Party Owner: An entity (typically an administrator), that is authorized to configure Appraisal Policy for Attestation Results in a Relying Party

Verifier:
A role performed by an entity that appraises the validity of Evidence about an Attester and produces Attestation Results to be used by a Relying Party

Verifier Owner: An entity (typically an administrator), that is authorized to configure Appraisal Policy for Evidence in a Verifier

3. Reference Use Cases

This section covers a number of representative use cases for remote attestation, independent of specific solutions. The purpose is to provide motivation for various aspects of the architecture presented in this draft. Many other use cases exist, and this document does not intend to have a complete list, only to have a set of use cases that collectively cover all the functionality required in the architecture.

Each use case includes a description followed by a summary of the Attester and a Relying Party roles.

3.1. Network Endpoint Assessment

Network operators want a trustworthy report that includes identity and version of information of the hardware and software on the machines attached to their network, for purposes such as inventory, audit, anomaly detection, record maintenance and/or trending reports (logging). The network operator may also want a policy by which full access is only granted to devices that meet some definition of hygiene, and so wants to get claims about such information and verify their validity. Remote attestation is desired to prevent vulnerable or compromised devices from getting access to the network and potentially harming others.

Typically, solutions start with a specific component (called a "Root of Trust") that provides device identity and protected storage for measurements. The system components perform a series of measurements that may be signed by the Root of Trust, considered as Evidence about the hardware, firmware, BIOS, software, etc. that is running.

Attester: A device desiring access to a network

Relying Party: A network infrastructure device such as a router, switch, or access point

3.2. Confidential Machine Learning (ML) Model Protection

A device manufacturer wants to protect its intellectual property. This is primarily the ML model it developed and runs in the devices

purchased by its customers. The goals for the protection include preventing attackers, potentially the customer themselves, from seeing the details of the model.

This typically works by having some protected environment in the device go through a remote attestation with some manufacturer service that can assess its trustworthiness. If remote attestation succeeds, then the manufacturer service releases either the model, or a key to decrypt a model the Attester already has in encrypted form, to the requester.

Attester: A device desiring to run an ML model to do inferencing

Relying Party: A server or service holding ML models it desires to protect

3.3. Confidential Data Retrieval

This is a generalization of the ML model use case above, where the data can be any highly confidential data, such as health data about customers, payroll data about employees, future business plans, etc. An assessment of system state is made against a set of policies to evaluate the state of a system using attestations for the system requesting data. Attestation is desired to prevent leaking data to compromised devices.

Attester: An entity desiring to retrieve confidential data

Relying Party: An entity that holds confidential data for retrieval by other entities

3.4. Critical Infrastructure Control

In this use case, potentially dangerous physical equipment (e.g., power grid, traffic control, hazardous chemical processing, etc.) is connected to a network. The organization managing such infrastructure needs to ensure that only authorized code and users can control such processes, and they are protected from malware or other adversaries. When a protocol operation can affect some critical system, the device attached to the critical equipment thus wants some assurance that the requester has not been compromised. As such, remote attestation can be used to only accept commands from requesters that are within policy.

Attester: A device or application wishing to control physical equipment

Relying Party: A device or application connected to potentially dangerous physical equipment (hazardous chemical processing, traffic control, power grid, etc.)

3.5. Trusted Execution Environment (TEE) Provisioning

A "Trusted Application Manager (TAM)" server is responsible for managing the applications running in the TEE of a client device. To do this, the TAM wants to assess the state of a TEE, or of applications in the TEE, of a client device. The TEE conducts a remote attestation procedure with the TAM, which can then decide whether the TEE is already in compliance with the TAM's latest policy, or if the TAM needs to uninstall, update, or install approved applications in the TEE to bring it back into compliance with the TAM's policy.

Attester: A device with a trusted execution environment capable of running trusted applications that can be updated

Relying Party: A Trusted Application Manager

3.6. Hardware Watchdog

One significant problem is malware that holds a device hostage and does not allow it to reboot to prevent updates from being applied. This is a significant problem, because it allows a fleet of devices to be held hostage for ransom.

In the case, the Relying Party is the watchdog timer in the TPM/ secure enclave itself, as described in [TCGarch] section 43.3. The Attestation Results are returned to the device, and provided to the enclave.

If the watchdog does not receive regular, and fresh, Attestation Results as to the systems' health, then it forces a reboot.

Attester: The device that is desired to keep from being held hostage for a long period of time

Relying Party: A remote server that will securely grant the Attester permission to continue operating (i.e., not reboot) for a period of time

3.7. FIDO Biometric Authentication

In the Fast IDentity Online (FIDO) protocol [WebAuthN], [CTAP], the device in the user's hand authenticates the human user, whether by biometrics (such as fingerprints), or by PIN and password. FIDO authentication puts a large amount of trust in the device compared to typical password authentication because it is the device that verifies the biometric, PIN and password inputs from the user, not the server. For the Relying Party to know that the authentication is trustworthy, the Relying Party needs to know that the Authenticator

part of the device is trustworthy. The FIDO protocol employs remote attestation for this.

The FIDO protocol supports several remote attestation protocols and a mechanism by which new ones can be registered and added. Remote attestation defined by RATS is thus a candidate for use in the FIDO protocol.

Other biometric authentication protocols such as the Chinese IFAA standard and WeChat Pay as well as Google Pay make use of attestation in one form or another.

Attester: Every FIDO Authenticator contains an Attester.

Relying Party: Any web site, mobile application back end or service that does biometric authentication.

4. Architectural Overview

Figure 1 depicts the data that flows between different roles, independent of protocol or use case.

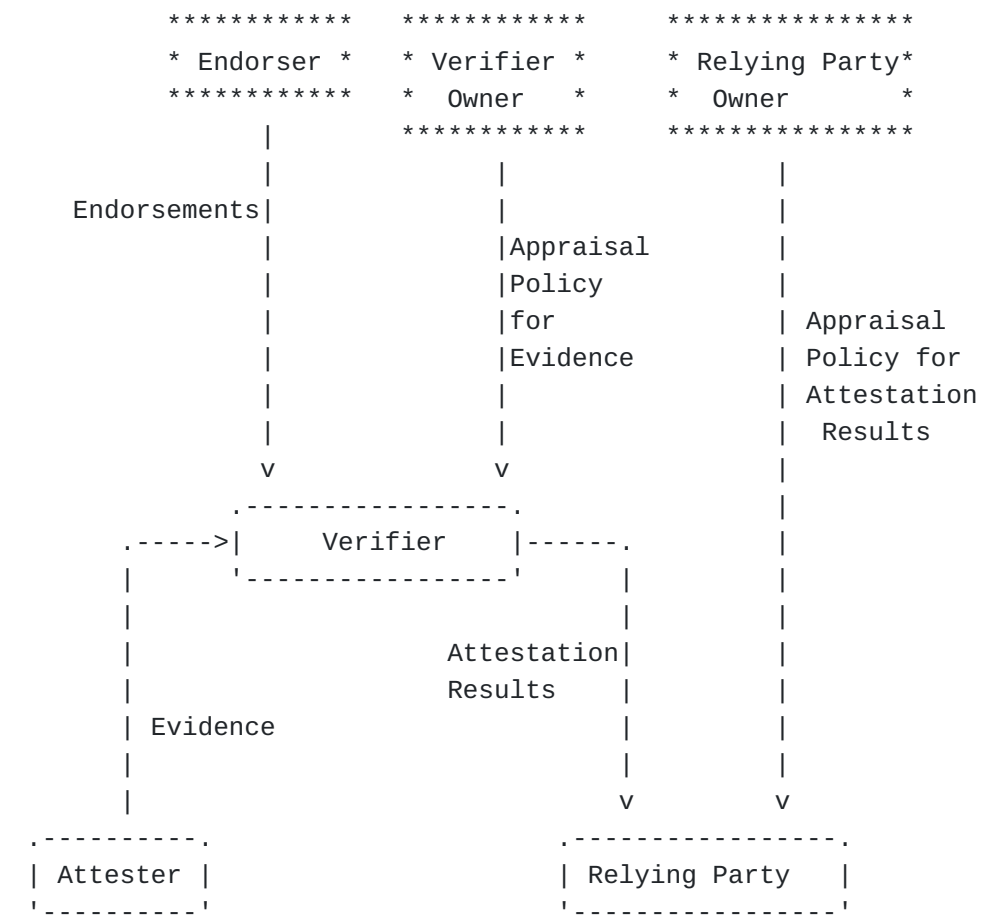

Figure 1: Conceptual Data Flow

An Attester creates Evidence that is conveyed to a Verifier.

The Verifier uses the Evidence, and any Endorsements from Endorsers, by applying an Appraisal Policy for Evidence to assess the trustworthiness of the Attester, and generates Attestation Results for use by Relying Parties. The Appraisal Policy for Evidence might be obtained from an Endorser along with the Endorsements, and/or might be obtained via some other mechanism such as being configured in the Verifier by the Verifier Owner.

The Relying Party uses Attestation Results by applying its own Appraisal Policy to make application-specific decisions such as authorization decisions. The Appraisal Policy for Attestation Results is configured in the Relying Party by the Relying Party Owner, and/or is programmed into the Relying Party.

4.1. Appraisal Policies

The Verifier, when appraising Evidence, or the Relying Party, when appraising Attestation Results, checks the values of some claims against constraints specified in its Appraisal Policy. Such constraints might involve a comparison for equality against a reference value, or a check for being in a range bounded by reference values, or membership in a set of reference values, or a check against values in other claims, or any other test.

Such reference values might be specified as part of the Appraisal Policy itself, or might be obtained from a separate source, such as an Endorsement, and then used by the Appraisal Policy.

The actual data format and semantics of any reference values are specific to claims and implementations. This architecture document does not define any general purpose format for them or general means for comparison.

4.2. Two Types of Environments of an Attester

An Attester consists of at least one Attesting Environment and at least one Target Environment. In some implementations, the Attesting and Target Environments might be combined. Other implementations might have multiple Attesting and Target Environments, such as in the examples described in more detail in Section 4.3 and Section 4.4. Other examples may exist, and the examples discussed could even be combined into even more complex implementations.

Claims are collected from Target Environments, as shown in Figure 2. That is, Attesting Environments collect the values and the information to be represented in Claims, by reading system registers and variables, calling into subsystems, taking measurements on code or memory and so on of the Target Environment. Attesting

Environments then format the claims appropriately, and typically use key material and cryptographic functions, such as signing or cipher algorithms, to create Evidence. There is no limit to or requirement on the places that an Attesting Environment can exist, but they typically are in Trusted Execution Environments (TEE), embedded Secure Elements (eSE), and BIOS firmware. An execution environment may not, by default, be capable of claims collection for a given Target Environment. Execution environments that are designed to be capable of claims collection are referred to in this document as Attesting Environments.

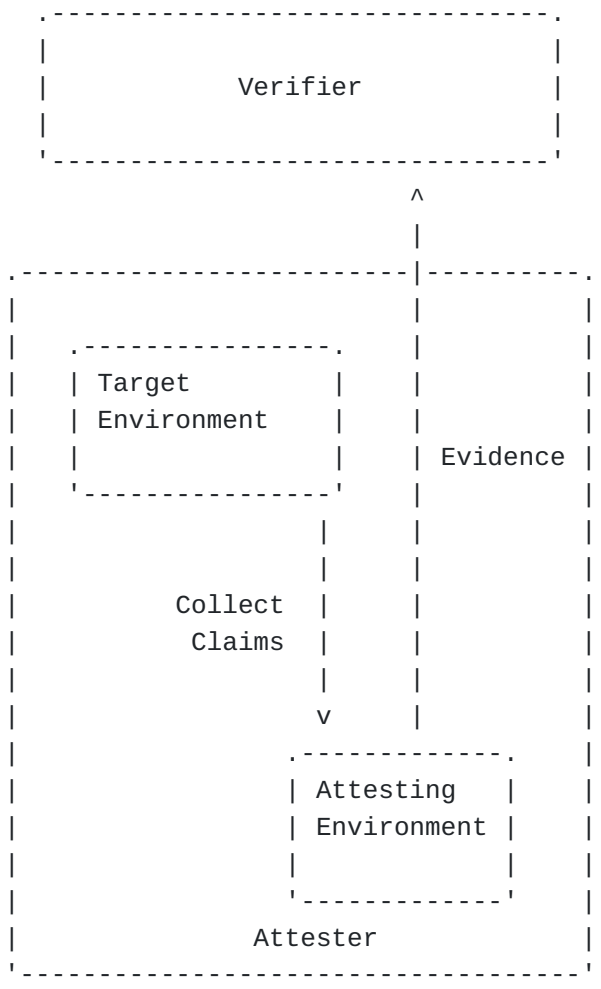

Figure 2: Two Types of Environments

4.3. Layered Attestation Environments

By definition, the Attester role creates Evidence. An Attester may consist of one or more nested or staged environments, adding complexity to the architectural structure. The unifying component is the Root of Trust and the nested, staged, or chained attestation Evidence produced. The nested or chained structure includes Claims,

collected by the Attester to aid in the assurance or believability of the attestation Evidence.

Figure 3 depicts an example of a device that includes (A) a BIOS stored in read-only memory in this example, (B) an updatable bootloader, and (C) an operating system kernel.

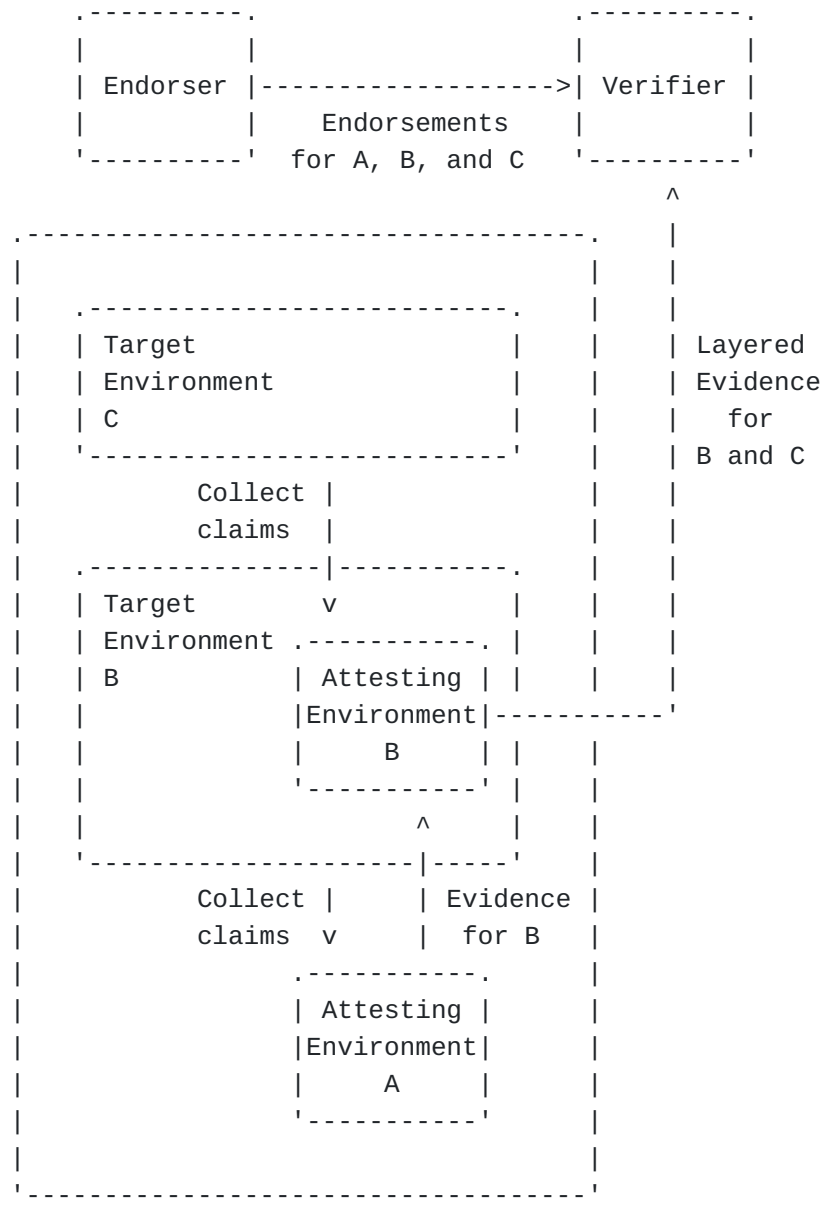

Figure 3: Layered Attester

Attesting Environment A, the read-only BIOS in this example, has to ensure the integrity of the bootloader (Target Environment B). There are potentially multiple kernels to boot, and the decision is up to the bootloader. Only a bootloader with intact integrity will make an appropriate decision. Therefore, these Claims have to be measured

securely. At this stage of the boot-cycle of the device, the Claims collected typically cannot be composed into Evidence.

After the boot sequence is started, the BIOS conducts the most important and defining feature of layered attestation, which is that the successfully measured Target Environment B now becomes (or contains) an Attesting Environment for the next layer. This procedure in Layered Attestation is sometimes called "staging". It is important that the new Attesting Environment B not be able to alter any Claims about its own Target Environment B. This can be ensured having those Claims be either signed by Attesting Environment A or stored in an untamperable manner by Attesting Environment A.

Continuing with this example, the bootloader's Attesting Environment B is now in charge of collecting Claims about Target Environment C, which in this example is the kernel to be booted. The final Evidence thus contains two sets of Claims: one set about the bootloader as measured and signed by the BIOS, plus a set of Claims about the kernel as measured and signed by the bootloader.

This example could be extended further by making the kernel become another Attesting Environment for an application as another Target Environment. This would result in a third set of Claims in the Evidence pertaining to that application.

The essence of this example is a cascade of staged environments. Each environment has the responsibility of measuring the next environment before the next environment is started. In general, the number of layers may vary by device or implementation, and an Attesting Environment might even have multiple Target Environments that it measures, rather than only one as shown in Figure 3.

4.4. Composite Device

A Composite Device is an entity composed of multiple sub-entities such that its trustworthiness has to be determined by the appraisal of all these sub-entities.

Each sub-entity has at least one Attesting Environment collecting the claims from at least one Target Environment, then this sub-entity generates Evidence about its trustworthiness. Therefore each sub-entity can be called an Attester. Among all the Attesters, there may be only some which have the ability to communicate with the Verifier while others do not.

For example, a carrier-grade router consists of a chassis and multiple slots. The trustworthiness of the router depends on all its slots' trustworthiness. Each slot has an Attesting Environment such as a TEE collecting the claims of its boot process, after which it

generates Evidence from the claims. Among these slots, only a main slot can communicate with the Verifier while other slots cannot. But other slots can communicate with the main slot by the links between them inside the router. So the main slot collects the Evidence of other slots, produces the final Evidence of the whole router and conveys the final Evidence to the Verifier. Therefore the router is a Composite Device, each slot is an Attester, and the main slot is the lead Attester.

Another example is a multi-chassis router composed of multiple single carrier-grade routers. The multi-chassis router provides higher throughput by interconnecting multiple routers and can be logically treated as one router for simpler management. A multi-chassis router provides a management point that connects to the Verifier. Other routers are only connected to the main router by the network cables, and therefore they are managed and appraised via this main router's help. So, in this case, the multi-chassis router is the Composite Device, each router is an Attester and the main router is the lead Attester.

Figure 4 depicts the conceptual data flow for a Composite Device.

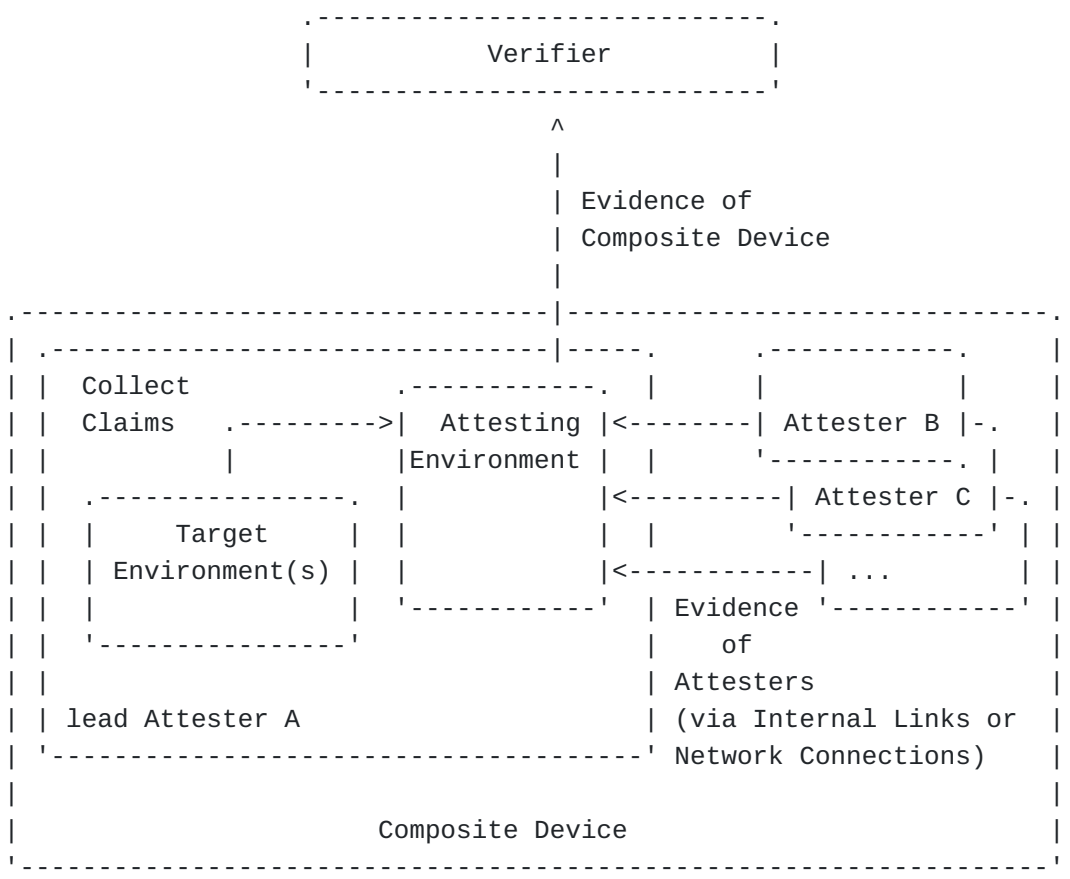

Figure 4: Conceptual Data Flow for a Composite Device

In the Composite Device, each Attester generates its own Evidence by its Attesting Environment(s) collecting the claims from its Target Environment(s). The lead Attester collects the Evidence of all other Attesters and then generates the Evidence of the whole Composite Attester.

An entity can take on multiple RATS roles (e.g., Attester, Verifier, Relying Party, etc.) at the same time. The combination of roles can be arbitrary. For example, in this Composite Device scenario, the entity inside the lead Attester can also take on the role of a Verifier, and the outside entity of Verifier can take on the role of a Relying Party. After collecting the Evidence of other Attesters, this inside Verifier uses Endorsements and Appraisal Policies (obtained the same way as any other Verifier) in the verification process to generate Attestation Results. The inside Verifier then conveys the Attestation Results of other Attesters, whether in the same conveyance protocol as the Evidence or not, to the outside Verifier.

In this situation, the trust model described in Section 7 is also suitable for this inside Verifier.

5. Topological Models

Figure 1 shows a basic model for communication between an Attester, a Verifier, and a Relying Party. The Attester conveys its Evidence to the Verifier for appraisal, and the Relying Party gets the Attestation Result from the Verifier. There are multiple other possible models. This section includes some reference models. This is not intended to be a restrictive list, and other variations may exist.

5.1. Passport Model

The passport model is so named because of its resemblance to how nations issue passports to their citizens. The nature of the Evidence that an individual needs to provide to its local authority is specific to the country involved. The citizen retains control of the resulting passport document and presents it to other entities when it needs to assert a citizenship or identity claim, such as an airport immigration desk. The passport is considered sufficient because it vouches for the citizenship and identity claims, and it is issued by a trusted authority. Thus, in this immigration desk analogy, the passport issuing agency is a Verifier, the passport is an Attestation Result, and the immigration desk is a Relying Party.

In this model, an Attester conveys Evidence to a Verifier, which compares the Evidence against its Appraisal Policy. The Verifier then gives back an Attestation Result. If the Attestation Result was

a successful one, the Attester can then present the Attestation Result to a Relying Party, which then compares the Attestation Result against its own Appraisal Policy.

There are three ways in which the process may fail. First, the Verifier may refuse to issue the Attestation Result due to some error in processing, or some missing input to the Verifier. The second way in which the process may fail is when the Attestation Result is examined by the Relying Party, and based upon the Appraisal Policy, the result does not pass the policy. The third way is when the Verifier is unreachable.

Since the resource access protocol between the Attester and Relying Party includes an Attestation Result, in this model the details of that protocol constrain the serialization format of the Attestation Result. The format of the Evidence on the other hand is only constrained by the Attester-Verifier remote attestation protocol.

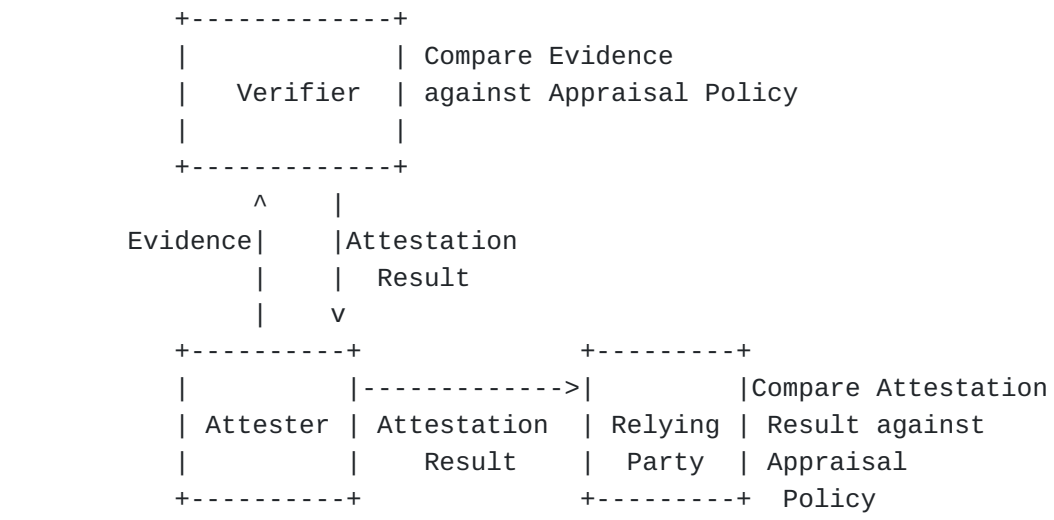

Figure 5: Passport Model

5.2. Background-Check Model

The background-check model is so named because of the resemblance of how employers and volunteer organizations perform background checks. When a prospective employee provides claims about education or previous experience, the employer will contact the respective institutions or former employers to validate the claim. Volunteer organizations often perform police background checks on volunteers in order to determine the volunteer's trustworthiness. Thus, in this analogy, a prospective volunteer is an Attester, the organization is the Relying Party, and a former employer or government agency that issues a report is a Verifier.

In this model, an Attester conveys Evidence to a Relying Party, which simply passes it on to a Verifier. The Verifier then compares the Evidence against its Appraisal Policy, and returns an Attestation Result to the Relying Party. The Relying Party then compares the Attestation Result against its own appraisal policy.

The resource access protocol between the Attester and Relying Party includes Evidence rather than an Attestation Result, but that Evidence is not processed by the Relying Party. Since the Evidence is merely forwarded on to a trusted Verifier, any serialization format can be used for Evidence because the Relying Party does not need a parser for it. The only requirement is that the Evidence can be *encapsulated in* the format required by the resource access protocol between the Attester and Relying Party.

However, like in the Passport model, an Attestation Result is still consumed by the Relying Party and so the serialization format of the Attestation Result is still important. If the Relying Party is a constrained node whose purpose is to serve a given type resource using a standard resource access protocol, it already needs the parser(s) required by that existing protocol. Hence, the ability to let the Relying Party obtain an Attestation Result in the same serialization format allows minimizing the code footprint and attack surface area of the Relying Party, especially if the Relying Party is a constrained node.

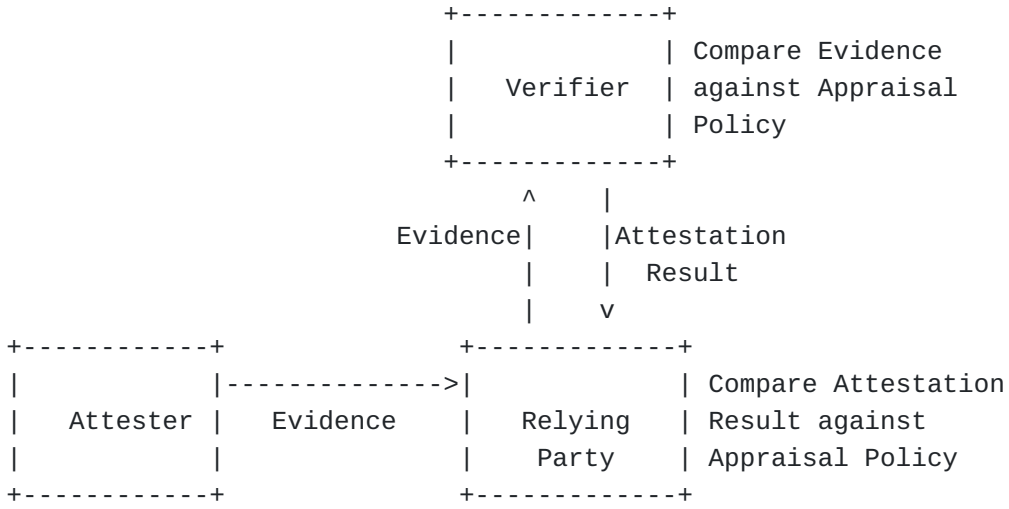

Figure 6: Background-Check Model

5.3. Combinations

One variation of the background-check model is where the Relying Party and the Verifier are on the same machine, performing both

functions together. In this case, there is no need for a protocol between the two.

It is also worth pointing out that the choice of model is generally up to the Relying Party. The same device may need to create Evidence for different Relying Parties and/or different use cases. For instance, it would provide Evidence to a network infrastructure device to gain access to the network, and to a server holding confidential data to gain access to that data. As such, both models may simultaneously be in use by the same device.

Figure 7 shows another example of a combination where Relying Party 1 uses the passport model, whereas Relying Party 2 uses an extension of the background-check model. Specifically, in addition to the basic functionality shown in Figure 6, Relying Party 2 actually provides the Attestation Result back to the Attester, allowing the Attester to use it with other Relying Parties. This is the model that the Trusted Application Manager plans to support in the TEEP architecture [I-D.ietf-teep-architecture].

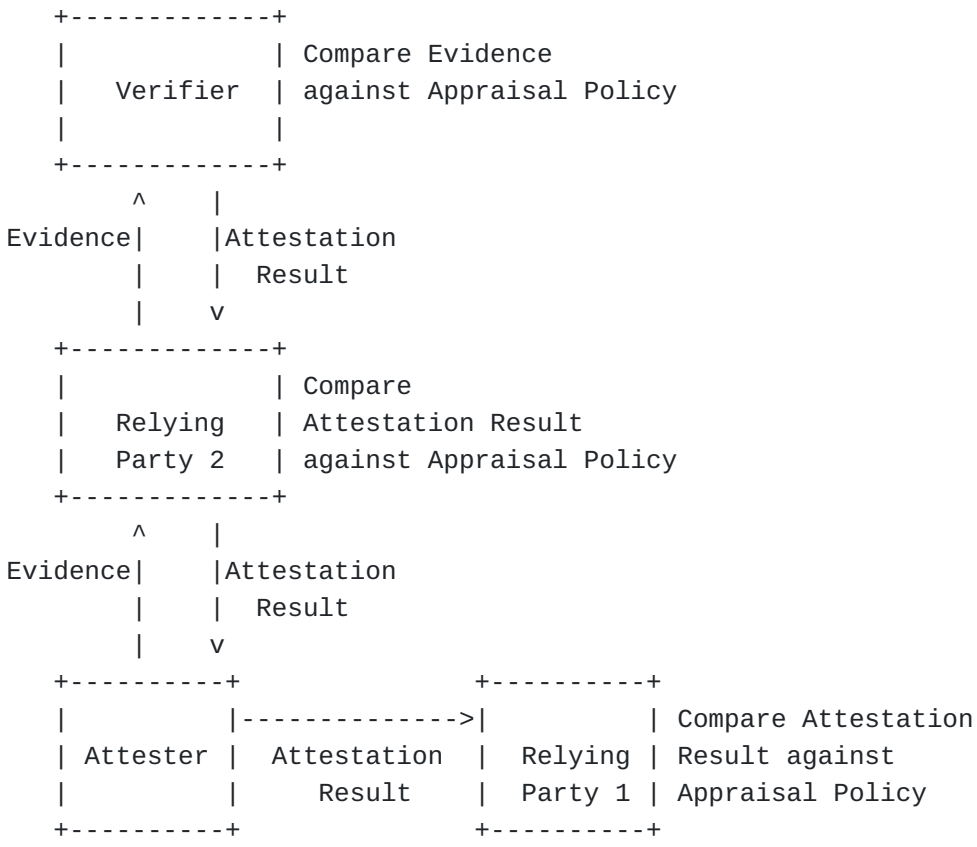

Figure 7: Example Combination

6. Roles and Entities

An entity in the RATS architecture includes at least one of the roles defined in this document. An entity can aggregate more than one role into itself. These collapsed roles combine the duties of multiple roles.

In these cases, interaction between these roles do not necessarily use the Internet Protocol. They can be using a loopback device or other IP-based communication between separate environments, but they do not have to. Alternative channels to convey conceptual messages include function calls, sockets, GPIO interfaces, local busses, or hypervisor calls. This type of conveyance is typically found in Composite Devices. Most importantly, these conveyance methods are out-of-scope of RATS, but they are presumed to exist in order to convey conceptual messages appropriately between roles.

For example, an entity that both connects to a wide-area network and to a system bus is taking on both the Attester and Verifier roles. As a system bus entity, a Verifier consumes Evidence from other devices connected to the system bus that implement Attester roles. As a wide-area network connected entity, it may implement an Attester role. The entity, as a system bus Verifier, may choose to fully isolate its role as a wide-area network Attester.

In essence, an entity that combines more than one role creates and consumes the corresponding conceptual messages as defined in this document.

7. Trust Model

7.1. Relying Party

The scope of this document is scenarios for which a Relying Party trusts a Verifier that can appraise the trustworthiness of information about an Attester. Such trust might come by the Relying Party trusting the Verifier (or its public key) directly, or might come by trusting an entity (e.g., a Certificate Authority) that is in the Verifier's certificate chain.

The Relying Party might implicitly trust a Verifier, such as in a Verifier/Relying Party combination where the Verifier and Relying Party roles are combined. Or, for a stronger level of security, the Relying Party might require that the Verifier first provide information about itself that the Relying Party can use to assess the trustworthiness of the Verifier before accepting its Attestation Results.

For example, one explicit way for a Relying Party "A" to establish such trust in a Verifier "B", would be for B to first act as an

Attester where A acts as a combined Verifier/Relying Party. If A then accepts B as trustworthy, it can choose to accept B as a Verifier for other Attesters.

Similarly, the Relying Party also needs to trust the Relying Party Owner for providing its Appraisal Policy for Attestation Results, and in some scenarios the Relying Party might even require that the Relying Party Owner go through a remote attestation procedure with it before the Relying Party will accept an updated policy. This can be done similarly to how a Relying Party could establish trust in a Verifier as discussed above.

7.2. Attester

In some scenarios, Evidence might contain sensitive information such as Personally Identifiable Information. Thus, an Attester must trust entities to which it conveys Evidence, to not reveal sensitive data to unauthorized parties. The Verifier might share this information with other authorized parties, according to rules that it controls. In the background-check model, this Evidence may also be revealed to Relying Party(s).

In some cases where Evidence contains sensitive information, an Attester might even require that a Verifier first go through a remote attestation procedure with it before the Attester will send the sensitive Evidence. This can be done by having the Attester first act as a Verifier/Relying Party, and the Verifier act as its own Attester, as discussed above.

7.3. Relying Party Owner

The Relying Party Owner might also require that the Relying Party first act as an Attester, providing Evidence that the Owner can appraise, before the Owner would give the Relying Party an updated policy that might contain sensitive information. In such a case, mutual attestation might be needed, in which case typically one side's Evidence must be considered safe to share with an untrusted entity, in order to bootstrap the sequence.

7.4. Verifier

The Verifier trusts (or more specifically, the Verifier's security policy is written in a way that configures the Verifier to trust) a manufacturer, or the manufacturer's hardware, so as to be able to appraise the trustworthiness of that manufacturer's devices. In solutions with weaker security, a Verifier might be configured to implicitly trust firmware or even software (e.g., a hypervisor). That is, it might appraise the trustworthiness of an application component, operating system component, or service under the assumption that information provided about it by the lower-layer

hypervisor or firmware is true. A stronger level of assurance of security comes when information can be vouched for by hardware or by ROM code, especially if such hardware is physically resistant to hardware tampering. The component that is implicitly trusted is often referred to as a Root of Trust.

A conveyance protocol that provides authentication and integrity protection can be used to convey unprotected Evidence, assuming the following properties exists:

1. The key material used to authenticate and integrity protect the conveyance channel is trusted by the Verifier to speak for the Attesting Environment(s) that collected claims about the Target Environment(s).

2. All unprotected Evidence that is conveyed is supplied exclusively by the Attesting Environment that has the key material that protects the conveyance channel

3. The Root of Trust protects both the conveyance channel key material and the Attesting Environment with equivalent strength protections.

7.5. Endorser and Verifier Owner

In some scenarios, the Endorser and Verifier Owner may need to trust the Verifier before giving the Endorsement and Appraisal Policy to it. This can be done similarly to how a Relying Party might establish trust in a Verifier as discussed above, and in such a case, mutual attestation might even be needed as discussed in Section 7.3.

8. Conceptual Messages

8.1. Evidence

Evidence is a set of claims about the target environment that reveal operational status, health, configuration or construction that have security relevance. Evidence is evaluated by a Verifier to establish its relevance, compliance, and timeliness. Claims need to be collected in a manner that is reliable. Evidence needs to be securely associated with the target environment so that the Verifier cannot be tricked into accepting claims originating from a different environment (that may be more trustworthy). Evidence also must be protected from man-in-the-middle attackers who may observe, change or misdirect Evidence as it travels from Attester to Verifier. The timeliness of Evidence can be captured using claims that pinpoint the time or interval when changes in operational status, health, and so forth occur.

8.2. Endorsements

An Endorsement is a secure statement that some entity (e.g., a manufacturer) vouches for the integrity of the device's signing capability. For example, if the signing capability is in hardware, then an Endorsement might be a manufacturer certificate that signs a public key whose corresponding private key is only known inside the device's hardware. Thus, when Evidence and such an Endorsement are used together, an appraisal procedure can be conducted based on Appraisal Policies that may not be specific to the device instance, but merely specific to the manufacturer providing the Endorsement. For example, an Appraisal Policy might simply check that devices from a given manufacturer have information matching a set of known-good reference values, or an Appraisal Policy might have a set of more complex logic on how to appraise the validity of information.

However, while an Appraisal Policy that treats all devices from a given manufacturer the same may be appropriate for some use cases, it would be inappropriate to use such an Appraisal Policy as the sole means of authorization for use cases that wish to constrain *which* compliant devices are considered authorized for some purpose. For example, an enterprise using remote attestation for Network Endpoint Assessment may not wish to let every healthy laptop from the same manufacturer onto the network, but instead only want to let devices that it legally owns onto the network. Thus, an Endorsement may be helpful information in authenticating information about a device, but is not necessarily sufficient to authorize access to resources which may need device-specific information such as a public key for the device or component or user on the device.

8.3. Attestation Results

Attestation Results are the input used by the Relying Party to decide the extent to which it will trust a particular Attester, and allow it to access some data or perform some operation. Attestation Results may be a Boolean simply indicating compliance or non-compliance with a Verifier's Appraisal Policy, or a rich set of Claims about the Attester, against which the Relying Party applies its Appraisal Policy for Attestation Results.

A result that indicates non-compliance can be used by an Attester (in the passport model) or a Relying Party (in the background-check model) to indicate that the Attester should not be treated as authorized and may be in need of remediation. In some cases, it may even indicate that the Evidence itself cannot be authenticated as being correct.

An Attestation Result that indicates compliance can be used by a Relying Party to make authorization decisions based on the Relying

Party's Appraisal Policy. The simplest such policy might be to simply authorize any party supplying a compliant Attestation Result signed by a trusted Verifier. A more complex policy might also entail comparing information provided in the result against known-good reference values, or applying more complex logic on such information.

Thus, Attestation Results often need to include detailed information about the Attester, for use by Relying Parties, much like physical passports and drivers licenses include personal information such as name and date of birth. Unlike Evidence, which is often very device- and vendor-specific, Attestation Results can be vendor-neutral if the Verifier has a way to generate vendor-agnostic information based on the appraisal of vendor-specific information in Evidence. This allows a Relying Party's Appraisal Policy to be simpler, potentially based on standard ways of expressing the information, while still allowing interoperability with heterogeneous devices.

Finally, whereas Evidence is signed by the device (or indirectly by a manufacturer, if Endorsements are used), Attestation Results are signed by a Verifier, allowing a Relying Party to only need a trust relationship with one entity, rather than a larger set of entities, for purposes of its Appraisal Policy.

9. Claims Encoding Formats

The following diagram illustrates a relationship to which remote attestation is desired to be added:

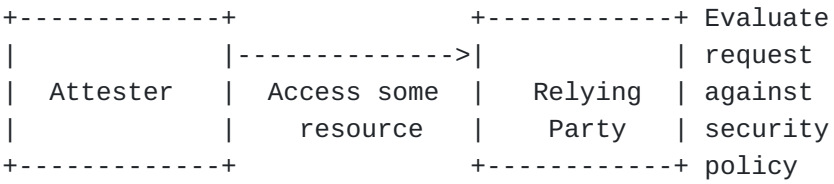

Figure 8: Typical Resource Access

In this diagram, the protocol between Attester and a Relying Party can be any new or existing protocol (e.g., HTTP(S), COAP(S), ROLIE [RFC8322], 802.1x, OPC UA, etc.), depending on the use case. Such protocols typically already have mechanisms for passing security information for purposes of authentication and authorization. Common formats include JWTs [RFC7519], CWTs [RFC8392], and X.509 certificates.

To enable remote attestation to be added to existing protocols, enabling a higher level of assurance against malware for example, it is important that information needed for appraising the Attester be usable with existing protocols that have constraints around what

formats they can transport. For example, OPC UA [OPCUA] (probably the most common protocol in industrial IoT environments) is defined to carry X.509 certificates and so security information must be embedded into an X.509 certificate to be passed in the protocol. Thus, remote attestation related information could be natively encoded in X.509 certificate extensions, or could be natively encoded in some other format (e.g., a CWT) which in turn is then encoded in an X.509 certificate extension.

Especially for constrained nodes, however, there is a desire to minimize the amount of parsing code needed in a Relying Party, in order to both minimize footprint and to minimize the attack surface area. So while it would be possible to embed a CWT inside a JWT, or a JWT inside an X.509 extension, etc., there is a desire to encode the information natively in the format that is natural for the Relying Party.

This motivates having a common "information model" that describes the set of remote attestation related information in an encoding-agnostic way, and allowing multiple encoding formats (CWT, JWT, X.509, etc.) that encode the same information into the claims format needed by the Relying Party.

The following diagram illustrates that Evidence and Attestation Results might each have multiple possible encoding formats, so that they can be conveyed by various existing protocols. It also motivates why the Verifier might also be responsible for accepting Evidence that encodes claims in one format, while issuing Attestation Results that encode claims in a different format.

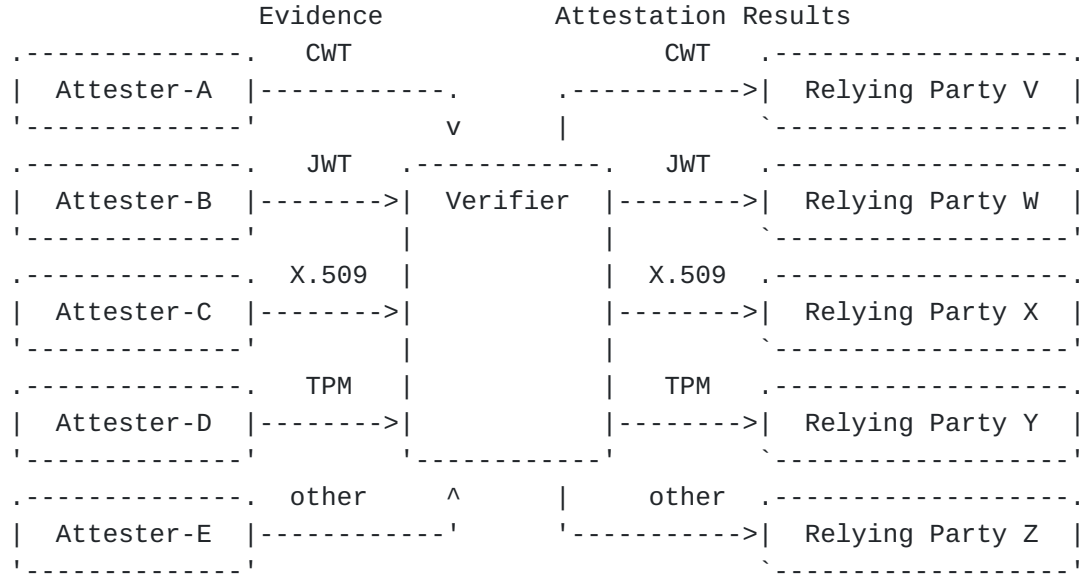

Figure 9: Multiple Attesters and Relying Parties with Different Formats

10. Freshness

A remote entity (Verifier or Relying Party) may need to learn the point in time (i.e., the "epoch") an Evidence or Attestation Result has been produced. This is essential in deciding whether the included Claims and their values can be considered fresh, meaning they still reflect the latest state of the Attester, and that any Attestation Result was generated using the latest Appraisal Policy for Evidence.

Freshness is assessed based on a policy defined by the consuming entity, Verifier or Relying Party, that compares the estimated epoch against an "expiry" threshold defined locally to that policy. There is, however, always a race condition possible in that the state of the Attester, and the Appraisal Policy for Evidence, might change immediately after the Evidence or Attestation Result was generated. The goal is merely to narrow their recentness to something the Verifier (for Evidence) or Relying Party (for Attestation Result) is willing to accept. Freshness is a key component for enabling caching and reuse of both Evidence and Attestation Results, which is especially valuable in cases where their computation uses a substantial part of the resource budget (e.g., energy in constrained devices).

There are two common approaches for determining the epoch of an Evidence or Attestation Result.

The first approach is to rely on synchronized and trustworthy clocks, and include a signed timestamp (see [I-D.birkholz-rats-tuda]) along with the Claims in the Evidence or Attestation Result. Timestamps can be added on a per-Claim basis, to distinguish the time of creation of Evidence or Attestation Result from the time that a specific Claim was generated. The clock's trustworthiness typically requires additional Claims about the signer's time synchronization mechanism.

A second approach places the onus of timekeeping solely on the appraising entity, i.e., the Verifier (for Evidence), or the Relying Party (for Attestation Results), and might be suitable, for example, in case the Attester does not have a reliable clock or time synchronisation is otherwise impaired. In this approach, a non-predictable nonce is sent by the appraising entity, and the nonce is then signed and included along with the Claims in the Evidence or Attestation Result. After checking that the sent and received nonces are the same, the appraising entity knows that the Claims were signed after the nonce was generated. This allows associating a

"rough" epoch to the Evidence or Attestation Result. In this case the epoch is said to be rough because:

* The epoch applies to the entire claim set instead of a more granular association, and

* The time between the creation of Claims and the collection of Claims is indistinguishable.

Implicit and explicit timekeeping can be combined into hybrid mechanisms. For example, if clocks exist and are considered trustworthy but are not synchronized, a nonce-based exchange may be used to determine the (relative) time offset between the involved peers, followed by any number of timestamp based exchanges. In another setup where all Roles (Attesters, Verifiers and Relying Parties) share the same broadcast channel, the nonce-based approach may be used to anchor all parties to the same (relative) timeline, without requiring synchronized clocks, by having a central entity emit nonces at regular intervals and have the "current" nonce included in the produced Evidence or Attestation Result.

It is important to note that the actual values in Claims might have been generated long before the Claims are signed. If so, it is the signer's responsibility to ensure that the values are still correct when they are signed. For example, values generated at boot time might have been saved to secure storage until network connectivity is established to the remote Verifier and a nonce is obtained.

A more detailed discussion with examples appears in Section 16.

11. Privacy Considerations

The conveyance of Evidence and the resulting Attestation Results reveal a great deal of information about the internal state of a device as well as any users the device is associated with. In many cases, the whole point of the Attestation process is to provide reliable information about the type of the device and the firmware/software that the device is running. This information might be particularly interesting to many attackers. For example, knowing that a device is running a weak version of firmware provides a way to aim attacks better.

Many claims in Attestation Evidence and Attestation Results are potentially PII (Personally Identifying Information) depending on the end-to-end use case of the attestation. Attestation that goes up to include containers and applications may further reveal details about a specific system or user.

In some cases, an attacker may be able to make inferences about attestations from the results or timing of the processing. For

example, an attacker might be able to infer the value of specific claims if it knew that only certain values were accepted by the Relying Party.

Evidence and Attestation Results data structures are expected to support integrity protection encoding (e.g., COSE, JOSE, X.509) and optionally might support confidentiality protection (e.g., COSE, JOSE). Therefore, if confidentiality protection is omitted or unavailable, the protocols that convey Evidence or Attestation Results are responsible for detailing what kinds of information are disclosed, and to whom they are exposed.

Furthermore, because Evidence might contain sensitive information, Attesters are responsible for only sending such Evidence to trusted Verifiers. Some Attesters might want a stronger level of assurance of the trustworthiness of a Verifier before sending Evidence to it. In such cases, an Attester can first act as a Relying Party and ask for the Verifier's own Attestation Result, and appraising it just as a Relying Party would appraise an Attestation Result for any other purpose.

12. Security Considerations

12.1. Attester and Attestation Key Protection

Implementers need to pay close attention to the isolation and protection of the Attester and the factory processes for provisioning the Attestation Key Material. When either of these are compromised, the remote attestation becomes worthless because the attacker can forge Evidence.

Remote attestation applies to use cases with a range of security requirements, so the protections discussed here range from low to high security where low security may be only application or process isolation by the device's operating system and high security involves specialized hardware to defend against physical attacks on a chip.

12.1.1. On-Device Attester and Key Protection

It is assumed that the Attester is located in an isolated environment of a device like a process, a dedicated chip a TEE or such that collects the Claims, formats them and signs them with an Attestation Key. The Attester must be protected from unauthorized modification to ensure it behaves correctly. There must also be confidentiality so that the signing key is not captured and used elsewhere to forge evidence.

In many cases the user or owner of the device must not be able to modify or exfiltrate keys from the Attesting Environment of the

Attester. For example the owner or user of a mobile phone or FIDO authenticator is not trusted. The point of remote attestation is for the Relying Party to be able to trust the Attester even though they don't trust the user or owner.

Some of the measures for low level security include process or application isolation by a high-level operating system, and perhaps restricting access to root or system privilege. For extremely simple single-use devices that don't use a protected mode operating system, like a Bluetooth speaker, the isolation might only be the plastic housing for the device.

At medium level security, a special restricted operating environment like a Trusted Execution Environment (TEE) might be used. In this case, only security-oriented software has access to the Attester and key material.

For high level security, specialized hardware will likely be used providing protection against chip decapping attacks, power supply and clock glitching, faulting injection and RF and power side channel attacks.

12.1.2. Attestation Key Provisioning Processes

Attestation key provisioning is the process that occurs in the factory or elsewhere that establishes the signing key material on the device and the verification key material off the device. Sometimes this is referred to as "personalization".

One way to provision a key is to first generate it external to the device and then copy the key onto the device. In this case, confidentiality of the generator, as well as the path over which the key is provisioned, is necessary. This can be achieved in a number of ways.

Confidentiality can be achieved entirely with physical provisioning facility security involving no encryption at all. For low-security use cases, this might be simply locking doors and limiting personnel that can enter the facility. For high-security use cases, this might involve a special area of the facility accessible only to select security-trained personnel.

Cryptography can also be used to support confidentiality, but keys that are used to then provision attestation keys must somehow have been provisioned securely beforehand (a recursive problem).

In many cases both some physical security and some cryptography will be necessary and useful to establish confidentiality.

Another way to provision the key material is to generate it on the device and export the verification key. If public key cryptography is being used, then only integrity is necessary. Confidentiality is not necessary.

In all cases, the Attestation Key provisioning process must ensure that only attestation key material that is generated by a valid Endorser is established in Attesters and then configured correctly. For many use cases, this will involve physical security at the facility, to prevent unauthorized devices from being manufactured that may be counterfeit or incorrectly configured.

12.2. Integrity Protection

Any solution that conveys information used for security purposes, whether such information is in the form of Evidence, Attestation Results, Endorsements, or Appraisal Policy must support end-to-end integrity protection and replay attack prevention, and often also needs to support additional security properties, including:

- *end-to-end encryption,
- *denial of service protection,
- *authentication,
- *auditing,
- *fine grained access controls, and
- *logging.

Section 10 discusses ways in which freshness can be used in this architecture to protect against replay attacks.

To assess the security provided by a particular Appraisal Policy, it is important to understand the strength of the Root of Trust, e.g., whether it is mutable software, or firmware that is read-only after boot, or immutable hardware/ROM.

It is also important that the Appraisal Policy was itself obtained securely. As such, if Appraisal Policies for a Relying Party or for a Verifier can be configured via a network protocol, the ability to create Evidence about the integrity of the entity providing the Appraisal Policy needs to be considered.

The security of conveyed information may be applied at different layers, whether by a conveyance protocol, or an information encoding format. This architecture expects attestation messages (i.e., Evidence, Attestation Results, Endorsements and Policies) are end-

to-end protected based on the role interaction context. For example, if an Attester produces Evidence that is relayed through some other entity that doesn't implement the Attester or the intended Verifier roles, then the relaying entity should not expect to have access to the Evidence.

13. IANA Considerations

This document does not require any actions by IANA.

14. Acknowledgments

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15. Contributors

Thomas Hardjono created older versions of the terminology section in collaboration with Ned Smith. Eric Voit provided the conceptual separation between Attestation Provision Flows and Attestation Evidence Flows. Monty Wisemen created the content structure of the first three architecture drafts. Carsten Bormann provided many of the motivational building blocks with respect to the Internet Threat Model.

16. Appendix A: Time Considerations

The table below defines a number of relevant events, with an ID that is used in subsequent diagrams. The times of said events might be defined in terms of an absolute clock time such as Coordinated Universal Time, or might be defined relative to some other timestamp or timeticks counter.

ID	Event	Explanation of event
VG	Value generated	A value to appear in a Claim was created. In some cases, a value may have technically existed before an Attester became aware of it but the Attester might have no idea how long it has had that value. In such a case, the Value created time is the time at which the Claim containing the copy of the value was created.
HD	Handle distribution	A centrally generated identifier for time-bound recentness across a domain of devices is successfully distributed to Attesters.
NS	Nonce sent	A nonce not predictable to an Attester (recentness & uniqueness) is sent to an Attester.
NR	Nonce relayed	A nonce is relayed to an Attester by another entity.

ID	Event	Explanation of event
HR	Handle received	A handle distributed by a Handle Distributor was received.
EG	Evidence generation	An Attester creates Evidence from collected Claims.
ER	Evidence relayed	A Relying Party relays Evidence to a Verifier.
RG	Result generation	A Verifier appraises Evidence and generates an Attestation Result.
RR	Result relayed	A Relying Party relays an Attestation Result to a Relying Party.
RA	Result appraised	The Relying Party appraises Attestation Results.
OP	Operation performed	The Relying Party performs some operation requested by the Attester. For example, acting upon some message just received across a session created earlier at time(RA).
RX	Result expiry	An Attestation Result should no longer be accepted, according to the Verifier that generated it.

Table 1

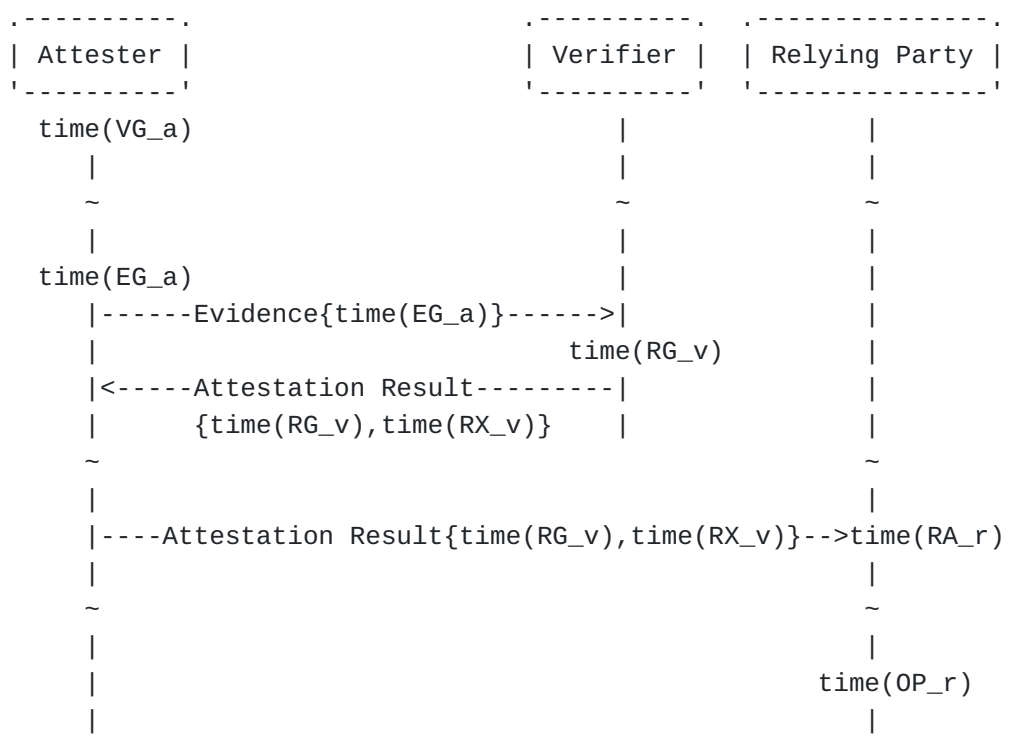
Using the table above, a number of hypothetical examples of how a solution might be built are illustrated below. a solution might be built. This list is not intended to be complete, but is just representative enough to highlight various timing considerations.

All times are relative to the local clocks, indicated by an "a" (Attester), "v" (Verifier), or "r" (Relying Party) suffix.

How and if clocks are synchronized depends upon the model.

16.1. Example 1: Timestamp-based Passport Model Example

The following example illustrates a hypothetical Passport Model solution that uses timestamps and requires roughly synchronized clocks between the Attester, Verifier, and Relying Party, which depends on using a secure clock synchronization mechanism. As a result, the receiver of a conceptual message containing a timestamp can directly compare it to its own clock and timestamps.



The Verifier can check whether the Evidence is fresh when appraising it at time(RG_v) by checking time(RG_v) - time(EG_a) < Threshold, where the Verifier's threshold is large enough to account for the maximum permitted clock skew between the Verifier and the Attester.

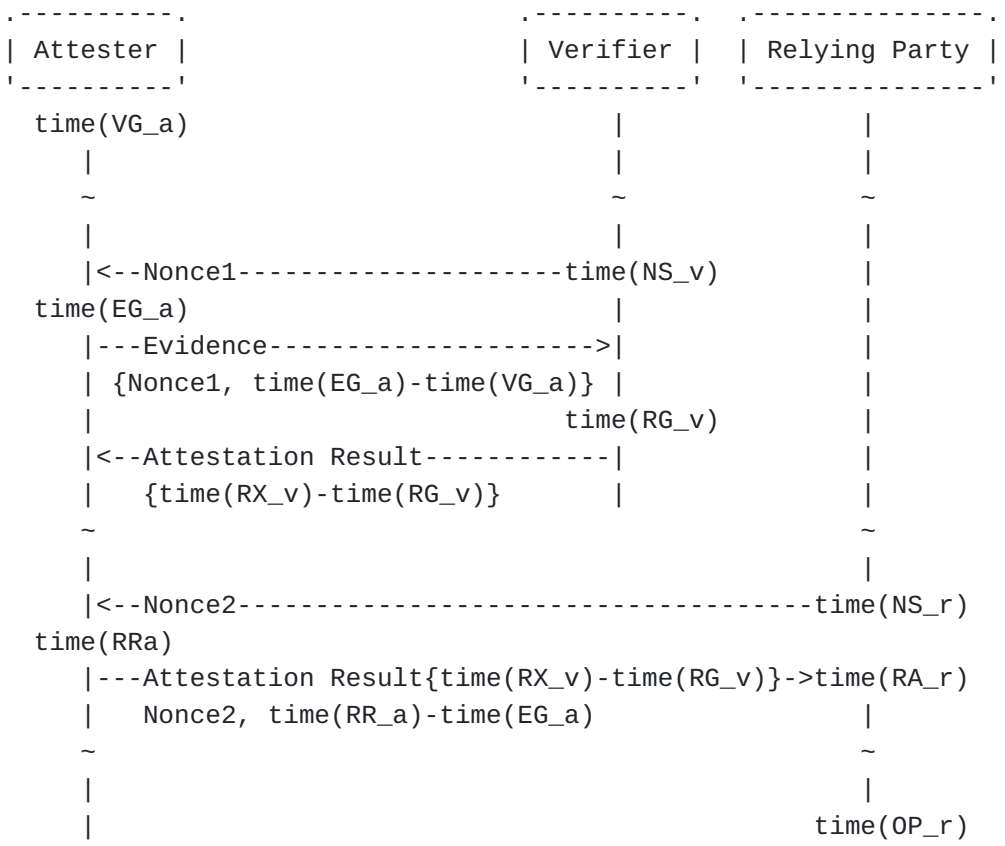
If time(VG_a) is also included in the Evidence along with the claim value generated at that time, and the Verifier decides that it can trust the time(VG_a) value, the Verifier can also determine whether the claim value is recent by checking time(RG_v) - time(VG_a) < Threshold, again where the threshold is large enough to account for the maximum permitted clock skew between the Verifier and the Attester.

The Relying Party can check whether the Attestation Result is fresh when appraising it at time(RA_r) by checking time(RA_r) - time(RG_v) < Threshold, where the Relying Party's threshold is large enough to account for the maximum permitted clock skew between the Relying Party and the Verifier. The result might then be used for some time (e.g., throughout the lifetime of a connection established at time(RA_r)). The Relying Party must be careful, however, to not allow continued use beyond the period for which it deems the Attestation Result to remain fresh enough. Thus, it might allow use (at time(OP_r)) as long as time(OP_r) - time(RG_v) < Threshold. However, if the Attestation Result contains an expiry time time(RX_v) then it could explicitly check time(OP_r) < time(RX_v).

16.2. Example 2: Nonce-based Passport Model Example

The following example illustrates a hypothetical Passport Model solution that uses nonces and thus does not require that any clocks are synchronized.

As a result, the receiver of a conceptual message containing a timestamp cannot directly compare it to its own clock or timestamps. Thus we use a suffix ("a" for Attester, "v" for Verifier, and "r" for Relying Party) on the IDs below indicating which clock generated them, since times from different clocks cannot be compared. Only the delta between two events from the sender can be used by the receiver.



In this example solution, the Verifier can check whether the Evidence is fresh at time(RG_v) by verifying that time(RG_v)-time(NS_v) < Threshold.

The Verifier cannot, however, simply rely on a Nonce to determine whether the value of a claim is recent, since the claim value might have been generated long before the nonce was sent by the Verifier. However, if the Verifier decides that the Attester can be trusted to correctly provide the delta time(EG_a)-time(VG_a), then it can determine recency by checking time(RG_v)-time(NS_v) + time(EG_a)-time(VG_a) < Threshold.

Similarly if, based on an Attestation Result from a Verifier it trusts, the Relying Party decides that the Attester can be trusted to correctly provide time deltas, then it can determine whether the Attestation Result is fresh by checking time(OP_r)-time(NS_r) + time(RR_a)-time(EG_a) < Threshold. Although the Nonce2 and time(RR_a)-time(EG_a) values cannot be inside the Attestation Result, they might be signed by the Attester such that the Attestation Result vouches for the Attester's signing capability.

The Relying Party must still be careful, however, to not allow continued use beyond the period for which it deems the Attestation Result to remain valid. Thus, if the Attestation Result sends a validity lifetime in terms of time(RX_v)-time(RG_v), then the Relying Party can check time(OP_r)-time(NS_r) < time(RX_v)-time(RG_v).

16.3. Example 3: Handle-based Passport Model Example

Handles are a third option to establish time-keeping next to nonces or timestamps. Handles are opaque data intended to be available to all RATS roles that interact with each other, such as the Attester or Verifier, in specified intervals. To enable this availability, handles are distributed centrally by the Handle Distributor role over the network. As any other role, the Handle Distributor role can be taken on by a dedicated entity or collapsed with other roles, such as a Verifier. The use of handles can compensate for a lack of clocks or other sources of time on entities taking on RATS roles. The only entity that requires access to a source of time is the entity taking on the role of Handle Distributor.

Handles are different from nonces as they can be used more than once and can be used by more than one entity at the same time. Handles are different from timestamps as they do not have to convey information about a point in time, but their reception creates that information. The reception of a handle is similar to the event that increments a relative tickcounter. Receipt of a new handle invalidates a previously received handle.

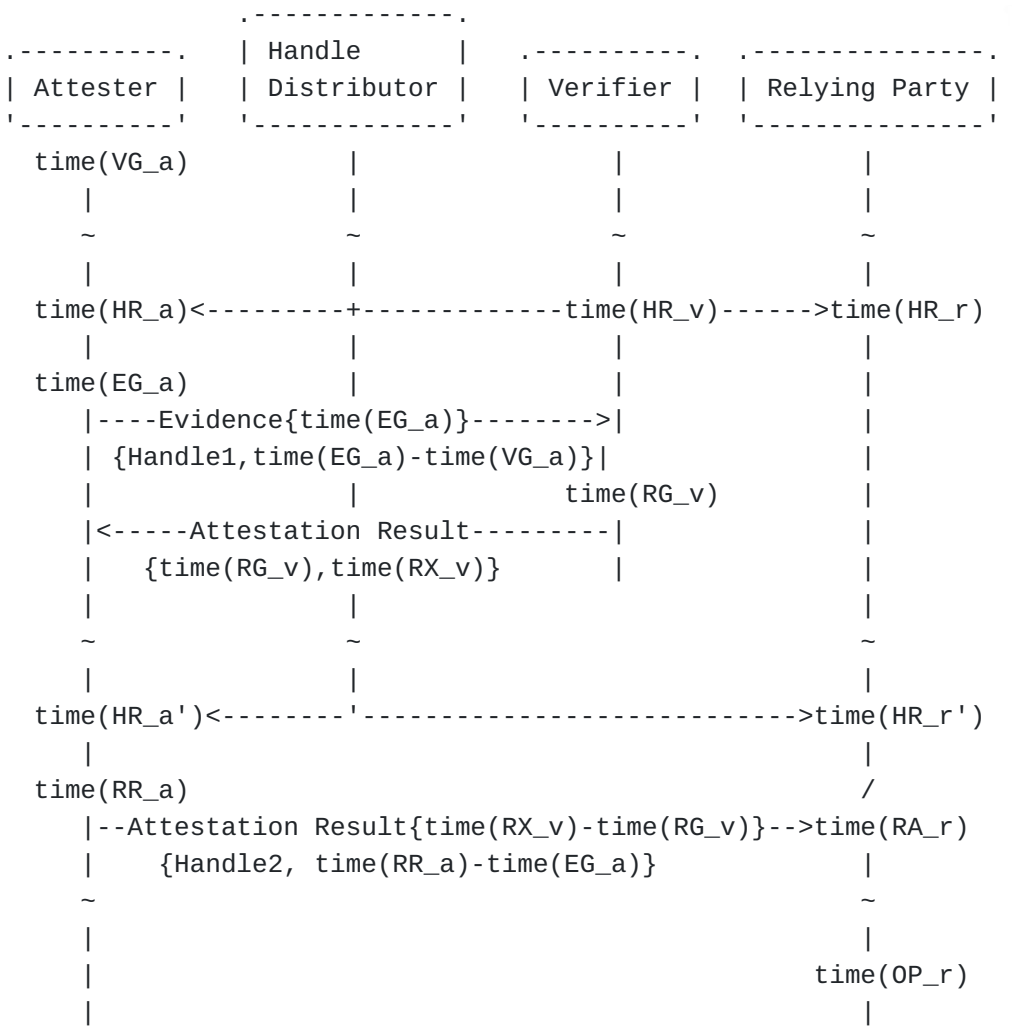
In this example, Evidence generation based on received handles always uses the current (most recent) handle. As handles are distributed over the network, all involved entities receive a fresh handle at roughly the same time. Due to distribution over the network, there is some jitter with respect to the time the Handle is received, time(HR), for each involved entity. To compensate for this jitter, there is a small period of overlap (a specified offset) in which both a current handle and corresponding former handle are valid in Evidence appraisal: validity-duration = time(HR'_v) + offset - time(HR_v). The offset is typically based on a network's round trip time. Analogously, the generation of valid Evidence is

only possible, if the age of the handle used is lower than the validity-duration: time(HR_v) - time(EG_a) < validity-duration.

From the point of view of a Verifier, the generation of valid Evidence is only possible, if the age of the handle used in the Evidence generation is younger than the duration of the distribution interval - "(time(HR'_v)-time(HR_v)) - (time(HR_a)-time(EG_a)) < validity-duration".

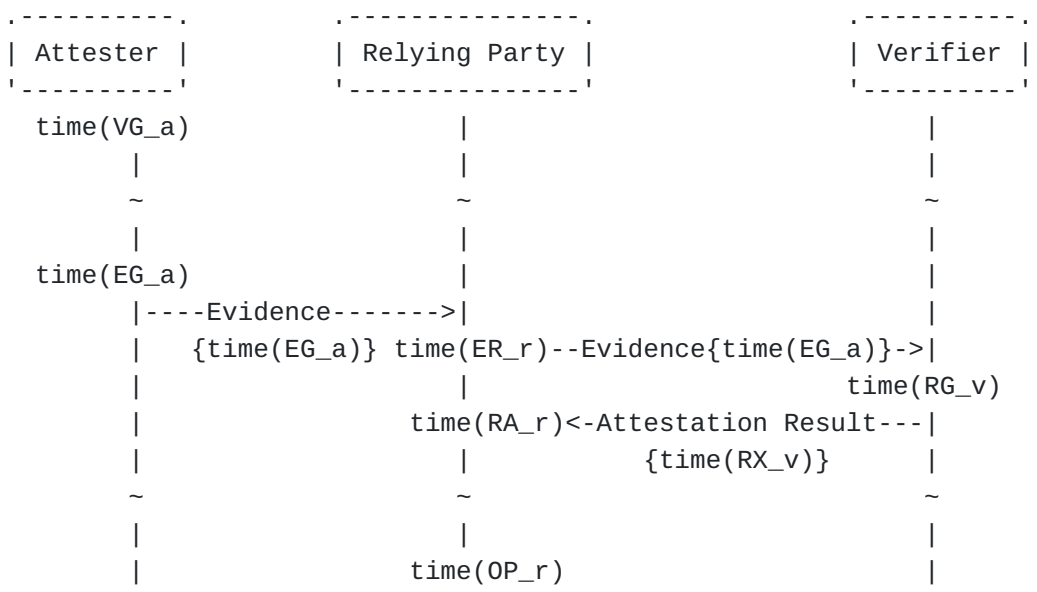
Due to the validity-duration of handles, multiple different pieces of Evidence can be generated based on the same handle. The resulting granularity (time resolution) of Evidence freshness is typically lower than the resolution of clock-based tickcounters.

The following example illustrates a hypothetical Background-Check Model solution that uses handles and requires a trustworthy time source available to the Handle Distributor role.



16.4. Example 4: Timestamp-based Background-Check Model Example

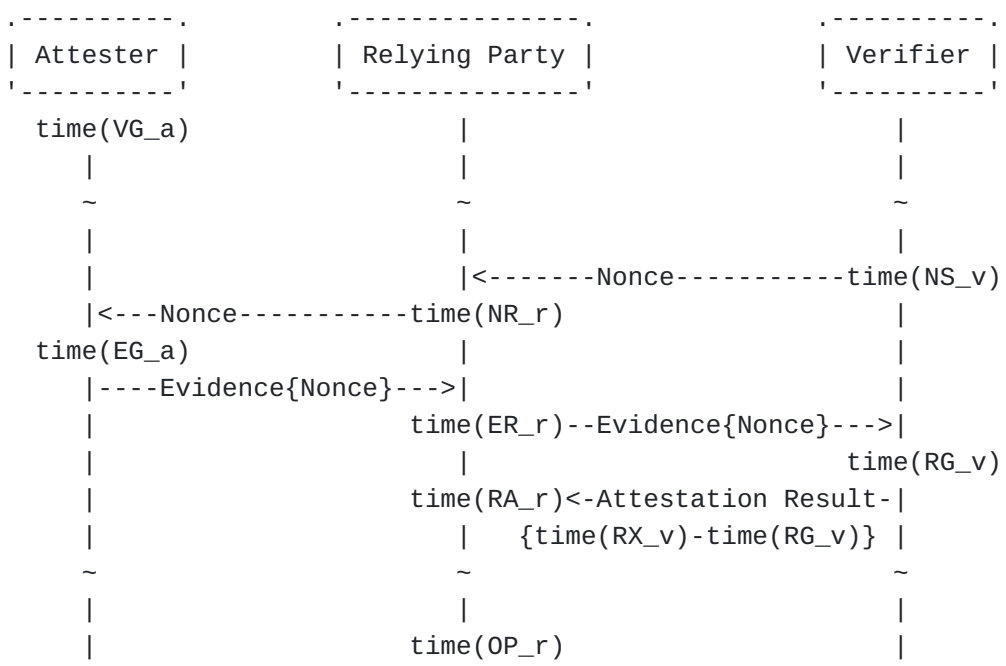
The following example illustrates a hypothetical Background-Check Model solution that uses timestamps and requires roughly synchronized clocks between the Attester, Verifier, and Relying Party.



The time considerations in this example are equivalent to those discussed under Example 1 above.

16.5. Example 5: Nonce-based Background-Check Model Example

The following example illustrates a hypothetical Background-Check Model solution that uses nonces and thus does not require that any clocks are synchronized. In this example solution, a nonce is generated by a Verifier at the request of a Relying Party, when the Relying Party needs to send one to an Attester.



The Verifier can check whether the Evidence is fresh, and whether a claim value is recent, the same as in Example 2 above.

However, unlike in Example 2, the Relying Party can use the Nonce to determine whether the Attestation Result is fresh, by verifying that time(OP_r)-time(NR_r) < Threshold.

The Relying Party must still be careful, however, to not allow continued use beyond the period for which it deems the Attestation Result to remain valid. Thus, if the Attestation Result sends a validity lifetime in terms of time(RX_v)-time(RG_v), then the Relying Party can check time(OP_r)-time(ER_r) < time(RX_v)-time(RG_v).

17. References

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Authors' Addresses

Henk Birkholz
Fraunhofer SIT
Rheinstrasse 75
64295 Darmstadt
Germany

Email: henk.birkholz@sit.fraunhofer.de

Dave Thaler
Microsoft
United States of America

Email: dthaler@microsoft.com

Michael Richardson
Sandelman Software Works
Canada

Email: mcr+ietf@sandelman.ca

Ned Smith
Intel Corporation
United States of America

Email: ned.smith@intel.com

Wei Pan
Huawei Technologies

Email: william.panwei@huawei.com