

# **Enhancing Trust and Resource Allocation in Telecommunications Cloud**

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### **Abstract**

Network Functions Virtualization (NFV) has brought the telecommunications industry multiple benefits; however, it has also introduced many new security issues. This thesis tackles security issues related to NFV trust and defines trust as confidence in the integrity of the software and hardware in a system. Existing NFV trust solutions have added trust to the NFV infrastructure with boot time measurements, placement of Virtualized Network Functions (VNFs) on trusted infrastructure and integrity checks of a small set of VNF operations.

This thesis implements the introduced trust elements from existing solutions and proposes several extensions. These extensions enable trust in the NFV management software with run time measurements, introduces a new method for building VNF trust, extends the number of trusted VNF operations and increases the user auditability of trust decisions.

The proposed extensions are designed, implemented and evaluated in a trusted NFV cloud environment. Although the proposed extensions create a more trusted cloud, they come at a steep performance cost to VNF operations. However, the most impacted VNF operations only affect the cloud provider and not the telecommunications consumer.

This thesis offers a valuable contribution to NFV clouds where increased trust is more important than maximized performance or where VNF operations are rarely performed.

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**Keywords** Trusted Computing, Network Function Virtualization, Cloud Computing, Telecommunications

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## Preface

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Otaniemi, September 2018

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## Abbreviations

**ACM** Authenticated Code Module.

**AK** Attestation Key.

**API** Application Programming Interface.

**BIOS** Basic Input/Output System.

**CRTM** Core Root of Trust for Measurement.

**DRTM** Dynamic Root of Trust Measurement.

**EK** Endorsement Key.

**EMS** Element Management System.

**ENISA** The European Union Agency for Network and Information Security.

**ETSI** The European Telecommunications Standards Institute.

**IaaS** Infrastructure as a Service.

**IMA** Integrity Measurement Architecture.

**Intel CIT** Intel Cloud Integrity Technology.

**Intel TXT** Intel Trusted Execution Technology.

**LCP** Launch Control Policy.

**MANO** Management and Orchestration.

**NF** Network Function.

**NFV** Network Functions Virtualisation.

**NFVI** NFV Infrastructure.

**NFVIaaS** NFV Infrastructure as a Service.

**NIST** National Institute of Standards and Technology.

**OPNFV** Open Platform for NFV.

**OS** Operating System.

**OSS/BSS** Operations Support Systems and Business Support Systems.

**PCR** Platform Configuration Register.

**PKI** Public Key Infrastructure.

**RA** Remote Attestation.

**RabbitMQ** Rabbit Message Queue.

**REST** Representational State Transfer.

**SELinux** Security-Enhanced Linux.

**SRTM** Static Root of Trust Measurement.

**TCG** Trusted Computing Group.

**TEE** Trusted Execution Environment.

**TPM** Trusted Platform Module.

**TSecO** Trusted Security Orchestrator.

**VIM** Virtualised Infrastructure Manager.

**VM** Virtual Machine.

**VNF** Virtualised Network Function.

**VNFaaS** Virtual Network Function as a Service.

**VNFM** VNF Manager.

# 1 Introduction

Telecommunications is transforming, and an increasing amount of services are being moved into the cloud. This transformation has numerous benefits, including scalability, reduced costs and increased service quality [31, 61].

The transformation is enabled by **Network Functions Virtualisation (NFV)**, which is defined by the **European Telecommunications Standards Institute (ETSI)** [8]. NFV allows **network functions (NFs)** to be deployed in the form of software, referred to as **Virtualised Network Functions (VNFs)**. These VNFs can be deployed as one or more **virtual machines (VMs)** and decouple NFs from hardware. This decoupling removes the old reliance on specialized hardware, as VNFs can run on any general purpose server. Removing dependency on specialized NF hardware improves telecommunications capital efficiencies and reduces the number of different hardware architectures [8]. Additionally, the softwarization of NFs enables quicker deployment and increases the flexibility in starting, stopping and moving NFs, while keeping their original functionality [8].

In an NFV cloud, multiple vendors can develop the different cloud components, including hardware resources, VNFs and management software [8]. This brings many benefits to development and deployment; however, it raises some trust issues as the whole hardware and software stack is no longer controlled by a single vendor [32]. Therefore, as VNFs can run mission critical functions, it is important to establish and maintain a high trust level in the underlying infrastructure, the VNFs and in the cloud management.

This thesis defines trust as confidence in the integrity of hardware and software throughout their life cycles. With this definition of trust, this thesis aims to accomplish one of the high level goals of the NFV specification, which is the integrity protection of hardware and software [11].

## 1.1 Problem Statement

Although integrity protection is considered in the NFV specification [11], it is not fully developed in any existing implementation or research. Integrity protection in NFV is made difficult due to the amount of vendors [32], the number of elements and the dynamic nature of a cloud [7]. To combat these difficulties, integrity protection should be non-tamperable, flexible and auditable.

The most common device for storing non-tamperable measurements in an NFV cloud is the **Trusted Platform Module (TPM)** [8]. This is a cryptographic coprocessor designed by the **Trusted Computing Group (TCG)**<sup>1</sup> to be a hardware anchor on

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<sup>1</sup><https://trustedcomputinggroup.org/>

which secure systems can be built [5]. This device provides safe storage for boot time measurements of components such as the BIOS, bootloader and kernel. TPM boot time measurements in NFV infrastructure have been used in research [35, 48, 52] and in implementations [34, 37, 60]. However, current implementations allow for little flexibility in changing the expected measurement values and has limited user auditability of measurements.

To enable a trusted NFV cloud, the trust built in the underlying infrastructure has to be extended to include NFV cloud management and VNFs. Boot time measurements are not sufficient, as these elements run after boot time. Early attempts have been made to secure the trust of cloud management with run time measurements stored in the TPM [7, 36]; however, these attempts were only theoretical. Extending the trust into VNFs has been done in research [3, 45, 62, 63] and in implementations [34, 37, 60]. Despite the extensive research, implementations of VNF trust cover only workload placement and a very limited set of life cycle operations, such as VNF start up and suspend. Moreover, they offer minimal trust checks of the VNF supply chain and have limited user auditability of both the VNF movement and measurements.

## 1.2 Contributions

This thesis contributes to trusted NFV by proposing, implementing and evaluating the following set of trust extensions.

- Extend cloud infrastructure measurements into run time and measure the critical files for cloud management.
- Extend VNF life cycle trust to cover VNF image supply chain and a bigger set of VNF operations, including migration.
- Extend the auditability of the NFV cloud by adding an audit trail of measurements and VNF operations.

These extensions are implemented in a state-of-the-art trusted NFV cloud. In addition to the proposed extensions, the implementation includes improvements made in earlier trusted cloud implementations, such as trust policies [60].

The extensions are evaluated for trust added both on an NFV architectural level and for a specific NFV use case. The chosen use case is the ETSI defined NFV Infrastructure as a Service (NFVIaaS) [9].

### 1.3 Scope

This thesis aims to construct and maintain trust in a **NFV** cloud. It does not aim to prevent unwanted changes in **NFV**, instead it detects and handles them. Security issues beyond integrity measurements, such as access control and secure communication, are not in the scope of this thesis.

### 1.4 Publications

This thesis has contributed to two original research publications.

The first publication created a testbed for trusted telecommunications systems in a safety critical environment [54]. The trusted **VNF** solution from this thesis was a part of this testbed and research.

The second publication aimed to combine remote attestation and root cause analysis in an **NFV** cloud [53]. The trusted **NFV** cloud implemented in this thesis contributed to the **NFV** cloud testbed and remote attestation experimentation of the publication.

### 1.5 Structure of the Thesis

Although the thesis is structured linearly, the chapters are connected as pairs. First, Chapters 2 and 3 review existing knowledge. Then, Chapters 4 and 5 present the thesis contributions. Finally, Chapters 6 and 7 evaluate the contributions and conclude the thesis. Figure 1 shows the flow of this thesis. The remainder of this section briefly introduces each chapter.

Chapter 2 presents **NFV**, reviews the trusted **NFVIaaS** use case and introduces trusted computing.

Chapter 3 explains the challenges of creating a trusted **NFV** cloud; describes existing implementations and research; extends trusted **NFVIaaS** with the existing trust implementations and reveals the limitations in existing trust solutions.

Chapter 4 introduces the proposed trusted cloud extensions and clarifies how these solve the limitations in previous solutions.

Chapter 5 implements a state-of-the-art trusted **NFV** cloud with the added extensions.

Chapter 6 evaluates the results of the proposed extensions, extends trusted **NFVIaaS** with the thesis implementation and tests the implementation performance.

Chapter 7 concludes the thesis and proposes future work.

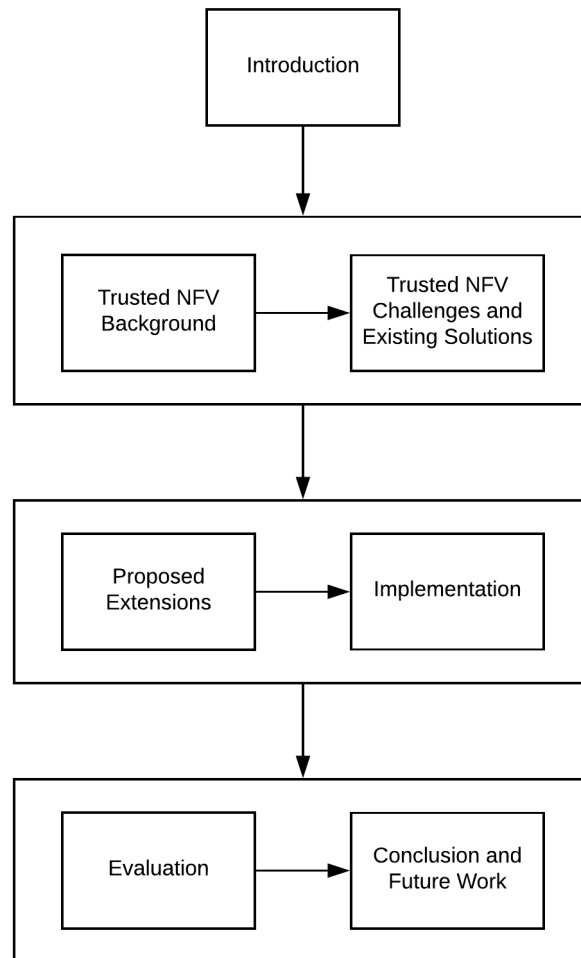


Figure 1: The flow and structure of this thesis



## 2 Trusted NFV Background

This Chapter presents the technologies needed for creating a trusted [NFV](#) cloud and introduces trusted [NFVIaaS](#). First, the Chapter introduces [NFV](#), [NFV](#) architecture and most common [NFV](#) implementation. Then, it reviews the trusted [NFVIaaS](#) use case in a base [NFV](#) implementation. Finally, the Chapter presents trusted computing and shows how it can be used to verify the integrity of a platform.

### 2.1 Network Function Virtualization

[Network Functions Virtualisation \(NFV\)](#) is a network architecture concept that allows for the cloudification of the telecommunications sector by the virtualization of network functions. The [NFV](#) architecture is specified by [the European Telecommunications Standards Institute \(ETSI\)](#) and describes the [NFV](#) functional blocks and their interfaces [8]. The architecture is on a reference level and does not specify any implementation.

The most common implementation is [open platform for NFV \(OPNFV\)](#) running on OpenStack. This use-case currently implements only a subset of the [ETSI NFV](#) architecture. The whole architecture and the [OPNFV](#) subset can be seen in [Figure 2](#).

#### 2.1.1 NFV Architecture

The [NFV](#) architecture is extensive and meant to cover a wide variety of telecommunications use-cases [10]. The following is a description of the [NFV](#) architectural blocks implemented in [OPNFV](#) on OpenStack and a brief introduction on the ones either partially or not implemented.

A [Virtualised Network Function \(VNF\)](#) is a virtual [network function \(NF\)](#) that does not depend on specialized hardware. [NFs](#) include Evolved Packet Core network elements, such as Mobility Management Entity and Packet Data Network Gateway, and conventional network functions, such as Dynamic Host Configuration Protocol servers. The functional behaviour of a [NF](#) is mostly independent of whether the [NF](#) is virtualized or traditional. A [VNF](#) can be composed of multiple internal components and these components can be deployed over multiple [VMs](#) [8].

[NFV infrastructure \(NFVI\)](#) comprises all the hardware and software components on which [VNFs](#) are deployed, managed and executed. The infrastructure does not have to be in a single location. [NFVI](#) consists of hardware and virtual resources; however, from a [VNFs](#) perspective it looks like a single entity providing virtualized resources. The hardware resources of the [NFVI](#) provides processing, storage and

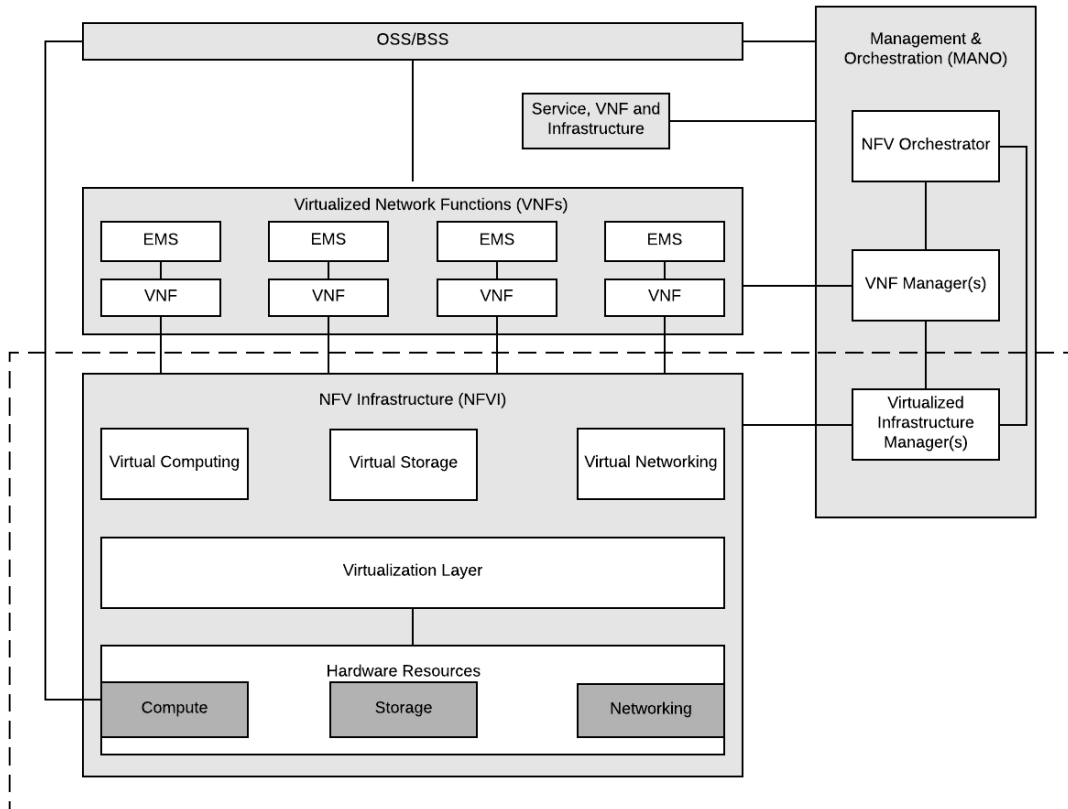


Figure 2: ETSI NFV architecture with OPNFV subset in dotted box [8, 14, 23]

connectivity to **VNFs**. **NFVI** hardware is assumed to be commercial-of-the-shelf hardware and not purpose-built hardware. The hardware resources are made available to **VNFs** through a virtualization layer. This virtualization layer provides **VNFs** with the virtualized resources they need while abstracting away the hardware logic and location [8].

One or more **Virtualised Infrastructure Managers (VIMs)** compose the control and management of a **VNF**'s interaction with computing, storage, network and virtualization. A **VIM** manages the resources of the **NFVI** and allocates them to **VNFs** and **VMs** as needed. Furthermore, it handles the control functions of a **NFVI**, including the visibility, inventory and fault-handling [8].

Some functional blocks are not completely implemented in **OPNFV** on OpenStack. These blocks are the **Element Management System (EMS)**, which manages the functionality of one or more **VNFs**; the Orchestrator, which manages the orchestration of **NFVI** and software resources; the **VNF Managers**, which are responsible for **VNF** life cycle management; Service, **VNF** and Infrastructure descriptions and **Operations Support Systems and Business Support Systems (OSS/BSS)** [8].

### 2.1.2 OPNFV

OPNFV<sup>2</sup> is a Linux Foundation collaborative project created to facilitate the development of NFV. It is currently used in most NFV implementations [14, 23]. Participation in OPNFV is open to anyone and they aim to maintain an open source reference platform [10]. The OPNFV project is also used in commercial products and telecommunications vendors can demonstrate OPNFV readiness and availability by becoming OPNFV verified.

OPNFV depends on multiple upstream projects and does not aim to create OPNFV specific versions of these. These upstream projects include KVM, OpenDaylight, OpenAirInterface and OpenStack. With this philosophy, OPNFV can focus on NFV integration, testing and features built on top of other well established platforms and the interoperability of these platforms [55]. Early OPNFV releases, such as Arno, only support the subset of NFV architecture shown in Figure 2; however, future releases aim to add more upstream projects and cover the entire architecture [55].

## 2.2 OpenStack as a NFV Platform

OpenStack is a cloud operating system that controls pools of resources in a datacenter, such as computing and networking. These resources are presented through a web interface for management and user provisioning [21]. OpenStack provides OPNFV with the NFVI and Management and Orchestration (MANO) components of the ETSI NFV architecture [14], as marked in Figure 2. In addition, OpenStack can run VNFs as a set of VMs. In this thesis, a one-to-one relation between VNFs and VMs is assumed. This assumption is common in practical deployments [34, 59] and allows OpenStack to take on some of the responsibility of the VNF Manager (VNFM) block in NFV MANO.

Most of the telecom industry state that OpenStack is essential for current implementations of NFV [14, 23]. OPNFV and OpenStack are actively working to make OpenStack compliant to the NFV needs of network operators and new features are added twice per year in new OpenStack releases [14, 17]. This section and this thesis are based on the Pike release of OpenStack.

OpenStack is a collection of numerous service projects with different responsibilities. The Pike release of OpenStack officially supports 36 service projects [21]; however, most of the services are non-essential and installed based on feature needs, such as block storage or Docker support. This allows OpenStack to support a multitude of use-cases.

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<sup>2</sup><https://www.opnfv.org/>

### 2.2.1 NFVI

OpenStack provides the infrastructure for **NFV**, known as the **NFVI**. The infrastructure comprises compute nodes and a controller node [21]. Compute nodes run **VNF** workload while the controller runs the **MANO** functions of the **NFV** cloud. OpenStack **NFVI** consists of one or more off-the-shelf servers. The specification of the servers used in this thesis is found in appendix A.

OpenStack **NFVI** run the OpenStack Nova<sup>3</sup> and Neutron<sup>4</sup> services. Nova virtualizes the hardware resources of the servers and is capable of running **VNFs** while Neutron provides networking for the servers.

### 2.2.2 MANO

OpenStack provides **OPNFV** with **Management and Orchestration (MANO)** functionality. The OpenStack controller manages its own servers, thus serving as the **VIM** element of **NFV MANO**. Furthermore, the controller manages the running **VMs**, thereby providing parts the **VNFM** block. OpenStack **MANO** runs on one of the servers in its **NFVI** and a node can function as both a compute node and a controller node simultaneously.

OpenStack **MANO** uses the service projects Keystone<sup>5</sup>, Glance<sup>6</sup>, Nova, Neutron and Horizon<sup>7</sup>. Keystone provides identity, authentication and service discovery; Glance handles **VNF** images; Nova manages the scheduling of **VNFs**; Neutron provides networking and Horizon presents a web management interface.

## 2.3 OpenStack Internal Communication

Internal OpenStack communication between compute and controller nodes is handled by **Rabbit message queue (RabbitMQ)**<sup>8</sup>. In **RabbitMQ**, messages are sent out to various exchanges. Each of these exchanges can have multiple queues, and the queues can be directed at a topic, such as compute, or a topic on a specific host, such as the compute service running on hypervisor number 1. All queues can have any number of consumers, which share the load equally, and all nodes can be both consumer and publisher [33].

Figure 3 shows an example **RabbitMQ** flow, where the Nova scheduler is sending

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<sup>3</sup><https://docs.openstack.org/nova/pike/>

<sup>4</sup><https://docs.openstack.org/neutron/pike/>

<sup>5</sup><https://docs.openstack.org/keystone/pike/>

<sup>6</sup><https://docs.openstack.org/glance/pike/>

<sup>7</sup><https://docs.openstack.org/horizon/pike/>

<sup>8</sup><https://www.rabbitmq.com/>

messages to different Nova compute nodes.

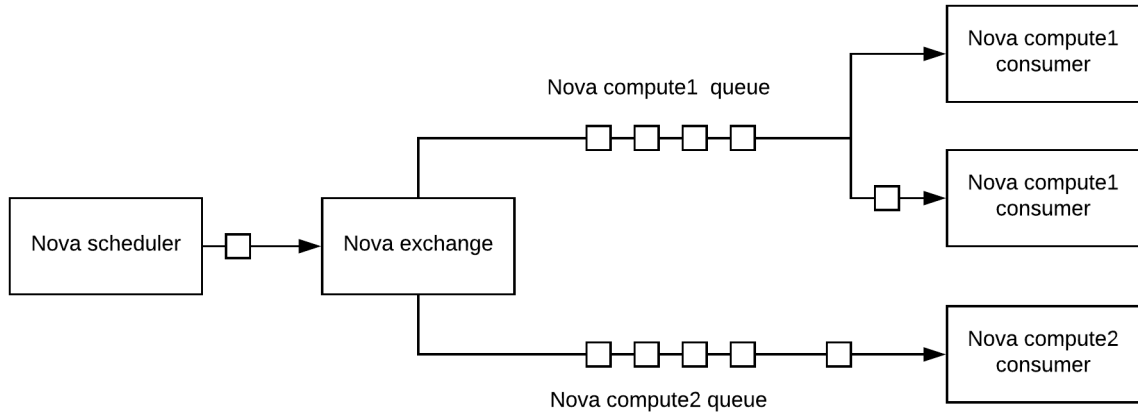


Figure 3: RabbitMQ example flow

## 2.4 OpenStack VNF Life Cycle

As [VNFs](#) do not depend on any specialized hardware, they can run on OpenStack as normal [VMs](#). OpenStack provides an [NFV](#) cloud with numerous cloud benefits by allowing the [VNFs](#) to be scheduled and operated in a scalable and flexible way [14, 23].

### 2.4.1 VNF Scheduling

In [VNF](#) scheduling, [VNFs](#) are placed on an available hypervisor by OpenStack [MANO](#). The hypervisor selection is done by evaluating a set of hypervisor filters that checks for sufficient computational resources, including the number of available CPUs and the amount of available RAM [21]. This placement process is a part of the start [VNF](#) operation, which is shown in Figure 4.

### 2.4.2 VNF Life Cycle Operations

In addition to running [VNFs](#), OpenStack can perform many [VNF](#) life cycle operations. These operations change the [VNF](#) state. A full [VNF](#) state diagram is included in Appendix B Figure B1.

This thesis focuses on three commonly used [VNF](#) operations.

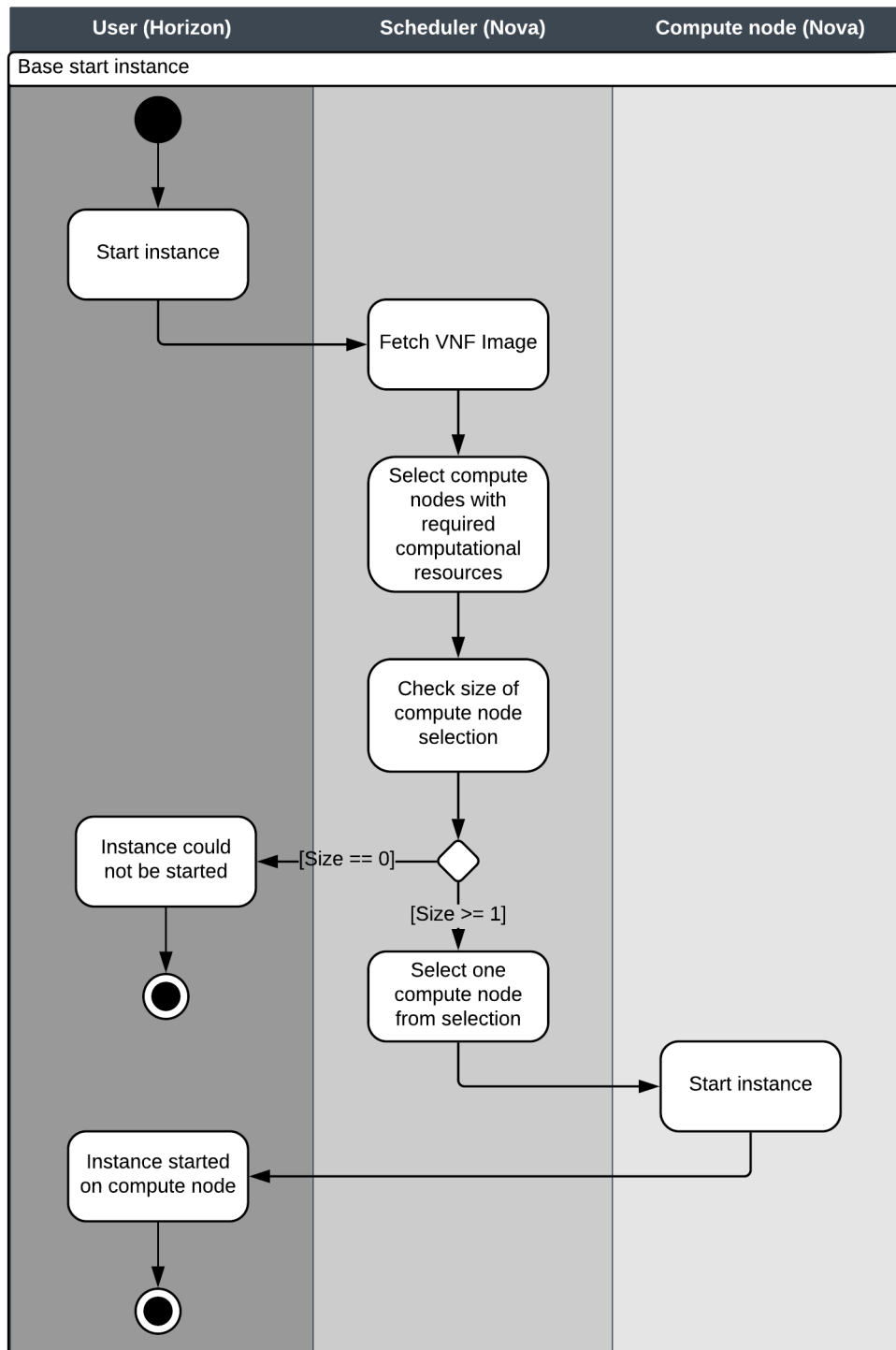


Figure 4: OpenStack start VNF instance

- Suspend, which stops the **VNF** instance and saves it to memory on the hypervisor.
- Resume, which loads a **VNF** instance from memory and starts it.
- Migrate, which stops a **VNF** instance and transfers it to a new hypervisor where it is started.

Figures 5, 6 and 7 show the steps of these three operations in OpenStack.

## 2.5 OpenStack NFV entities

To perform its part of **OPNFV**, OpenStack utilizes a set of **NFV** entities. The entities of an OpenStack **OPNFV** cloud are hardware elements, **VNF** images and **VNF** instances [21].

Hardware elements in OpenStack are commercial-off-the-shelf servers capable of running virtual workload. OpenStack hardware elements function as the **NFVI** layer of the **NFV** architecture. Additionally, one hardware element runs the **NFV MANO** layer. Other **NFV** hardware elements, such as routers [8], are not implemented in OpenStack nor in this thesis.

In OpenStack, **VNF** images form one half of the **NFV VNF** layer. **VNF** images are in OpenStack **VM** images. Although **VNFs** and **VMs** do not always have a one-to-one relation in **NFV** [8], it is a common simplification in practical deployments. This simplification is done in OpenStack [21], this thesis and existing trust solutions [34, 59]. **VNF** therefore equals **VM** in this thesis and extra **VNF** data is not considered.

The other half of the OpenStack **VNF** layer is formed by **VNF** instances. **VNF** instances are deployed **VNF** images and this deployment is done on one of the servers in OpenStack **NFVI**. **VNF** instances can perform many operations in OpenStack. The life cycle operations covered in this thesis were described in Section 2.4, while the full **VNF** state diagram can be found in Appendix B Figure B1.

## 2.6 Trusted NFV Infrastructure as a Service

**NFV Infrastructure as a Service (NFVIaaS)** is an **ETSI** defined **NFV** use case [9], which in turn is a special case of the **National Institute of Standards and Technology (NIST)** defined **Infrastructure as a Service (IaaS)** [44]. While **IaaS** only needs to provide a pool of resources to a cloud tenant [44], **NFVIaaS** should also support the operational life cycle of the tenant **VNFs** [9]. This section will consider trust in **NFVIaaS** as provided by OpenStack.

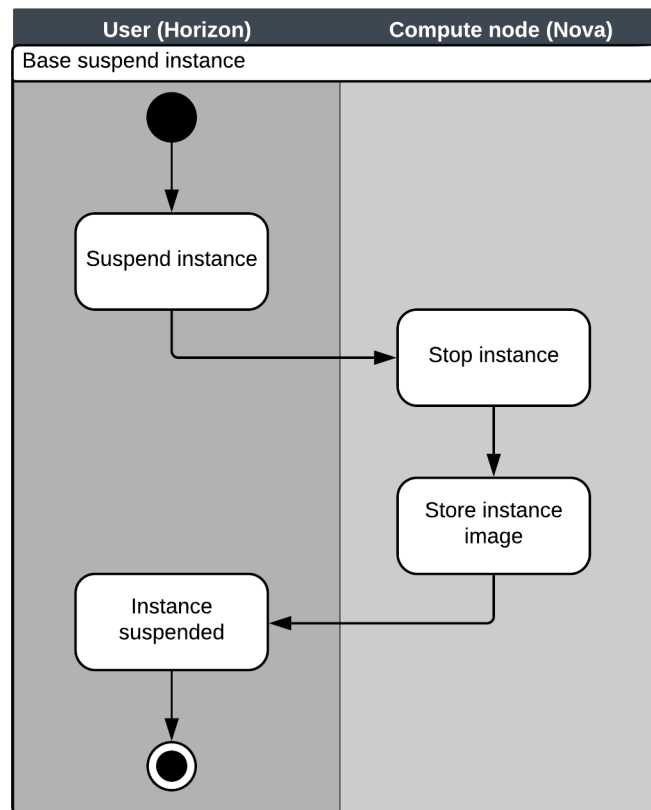


Figure 5: OpenStack suspend VNF instance



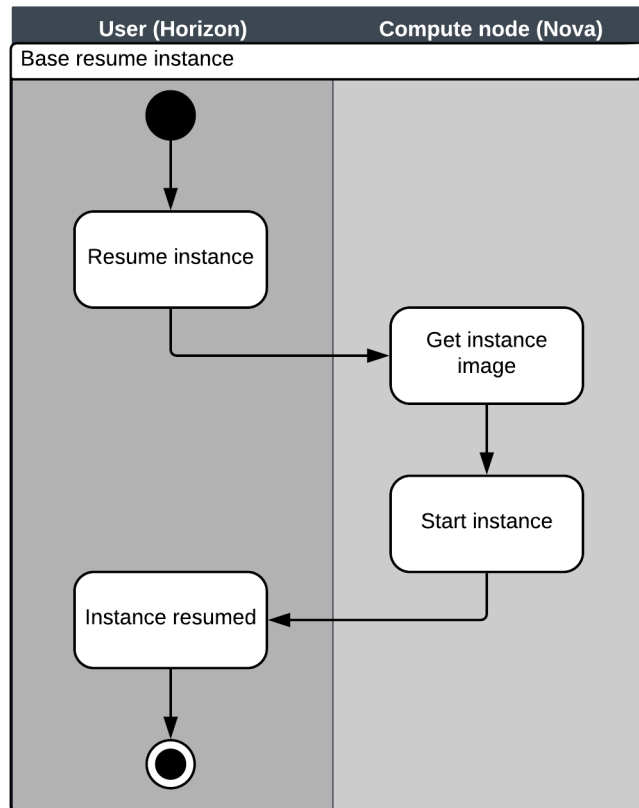


Figure 6: OpenStack resume VNF instance

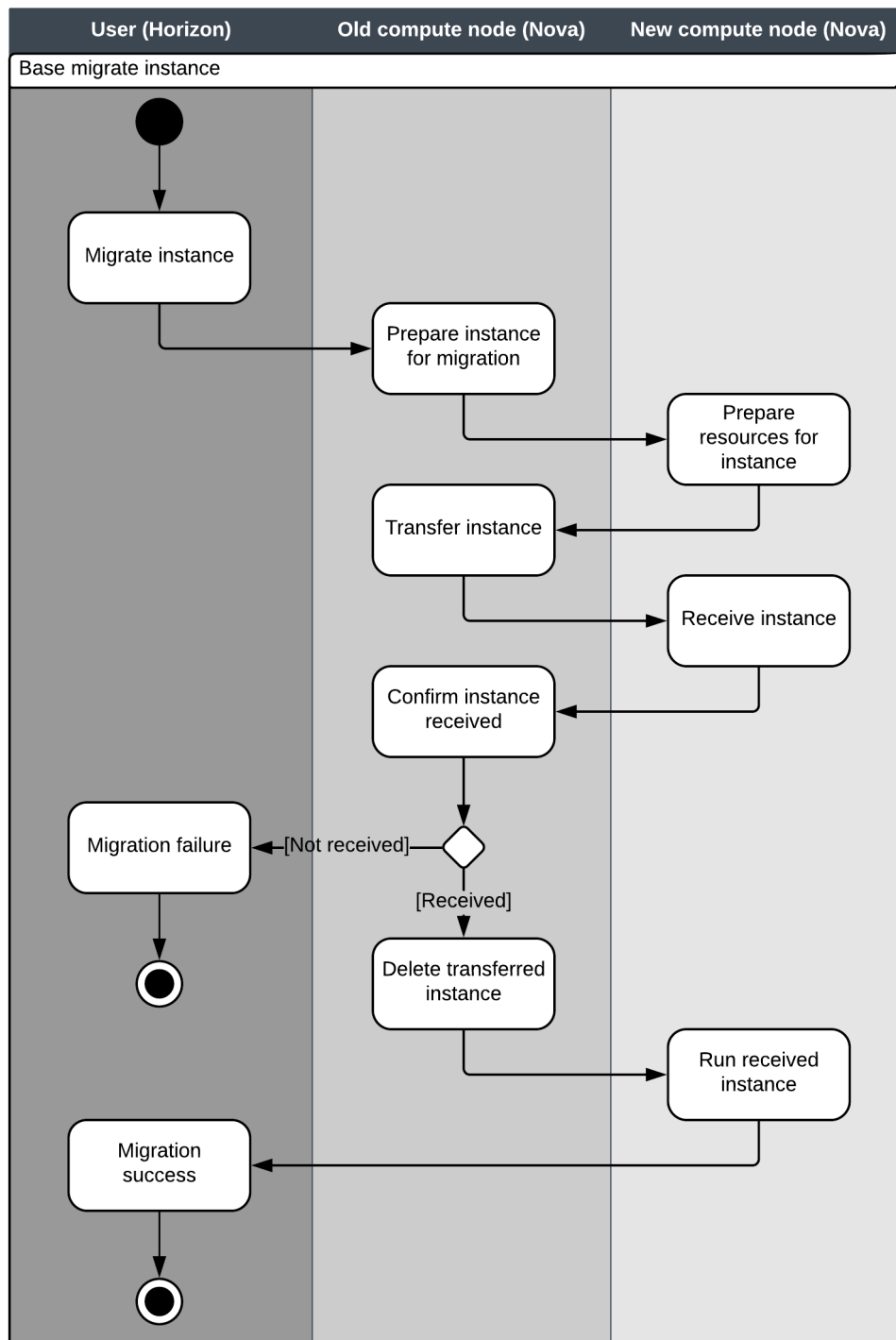


Figure 7: OpenStack migrate VNF instance

### 2.6.1 Trusted NFVIaaS Success Scenario

The actors in trusted **NFVIaaS** are the cloud tenant and the service provider. The cloud tenant wants **VNF** instances that are trusted throughout their life cycles, while the service provider should provide this capability.

The success scenario of trusted **NFVIaaS** allows the cloud tenant **VNF** to be trusted in its entire life cycle. All actions by the cloud tenant are done through the OpenStack management software. The steps for the success scenario are listed below.

1. Service provider adds trusted hardware elements to the cloud.
2. Service provider installs a trusted OpenStack configuration.
3. Cloud tenant adds a trusted **VNF** image.
4. Cloud tenant deploys a **VNF** image on trusted hardware.
5. Cloud tenant performs trusted **VNF** operations.
6. Cloud tenant audits the trust decisions.

These steps cover all OpenStack entities and available OpenStack cloud operations. OpenStack entities were described in Section 2.5, while the available OpenStack cloud operations were described in Section 2.2.

The available trust will be examined in this chapter for base OpenStack, in Chapter 3 for the existing OpenStack trust solutions and in Chapter 6 for the solution proposed by this thesis.

### 2.6.2 Trusted NFVIaaS on Base OpenStack

Base OpenStack does not perform any integrity checks and therefore cannot provide any of the steps needed for trusted **NFVIaaS**. However, OpenStack does have some recommendations for trust, some trusted features have existed in the past and some will in future releases.

OpenStack recommends ways of adding trust to hardware elements at both boot time [20] and run time [16]. OpenStack has had the notion of trusted hardware elements in the past [22]; however, this functionality has been removed [16]. Signed **VNF** images are included in the coming release of the OpenStack service project Barbican<sup>9</sup> [18].

Despite existing recommendations, current OpenStack release (Pike) does not provide any trust in **NFVIaaS**.

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<sup>9</sup><https://docs.openstack.org/barbican/>

## 2.7 Trusted Computing

Trusted computing is a set of solutions conforming to the standards and specifications formulated by the [Trusted Computing Group \(TCG\)](#) <sup>10</sup>. TCG technologies aim to secure critical systems, authentication, user identities, machine identities and network integrity. TCG technologies are in use in over a billion devices and TCG has working groups for technologies such as the [TPM](#), trusted network communications and virtualized platforms [29]. This section presents the TCG specified [TPM](#) and how it can be used together with [trusted execution environments \(TEEs\)](#) to enable measured boot.

### 2.7.1 Trusted Platform Module

[Trusted Platform Modules \(TPMs\)](#) are cryptographic coprocessors that are nearly ubiquitous in commercial PCs and servers [5]. They were designed by the TCG to be hardware anchors on which secure systems could be built; therefore, [TPMs](#) are physically attached to the motherboard of a PC [5]. This allows computing platforms to verify the software configuration from a place outside of the system memory space [56].

This thesis only consider hardware [TPMs](#) on the x86 platform. This is the most widely deployed [TPM](#) platform; however, the TCG also has [TPM](#) working groups for other platforms, including mobile and virtualized platforms [29]. [TPMs](#) first widely deployed version was 1.1b and the most recent version is [TPM 2.0](#). Figure 8 shows the components of a [TPM 2.0](#). The remaining paragraphs of this section summarize some of the main [TPM 2.0](#) features and use cases; however, many of these were similar in earlier [TPM](#) versions.

A [TPM](#) has at least two pairs of public/private keys available, namely the [endorsement key \(EK\)](#) and the [attestation key \(AK\)](#). The [EK](#) is created from an endorsement seed that is added to the [TPM](#) at production time. The [AK](#) is created from the [EK](#) and is intended for signing. These keys are created by the [TPM](#) key generation component, while the endorsement seed is stored in [TPM](#) non-volatile memory. Both of these components can be seen in Figure 8. Endorsement seed, [EK](#) and [AK](#) are unique and their private parts never leave the [TPM](#) [30].

[TPMs](#) have special registers, named [platform configuration registers \(PCRs\)](#), which stores hash values. These registers are stored in volatile memory, as seen in Figure 8. [TPM 2.0](#) supports multiple [PCR](#) banks, where each [PCR](#) bank is associated with a specific hashing algorithm. Figure 9 shows example [PCR](#) values from the SHA-1 [PCR](#) bank. [PCR](#) values cannot be set directly, instead they are extended from other [PCR](#) values. When extending a [PCR](#) value, the new value becomes the

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<sup>10</sup><https://trustedcomputinggroup.org/>

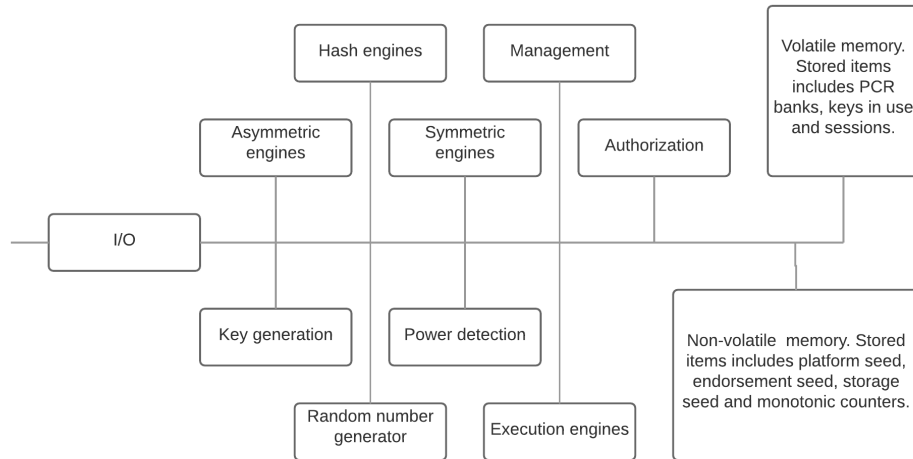


Figure 8: TPM 2.0 block structure [30]

hash of the old **PCR** value concatenated with the input hash value. Hash functions are assumed to be a one-to-one function and therefore **PCRs** represents a unique operation sequence. **TPM PCRs** are used to safely store software measurements and are critical for solutions such as measured boot [56].

A **TPM** can seal keys or other data to known states of a platform. This means that the availability of these keys or data will depend on platform measurements stored in the **TPM**. One use case for this is Microsoft's BitLocker [49]. It seals the encryption key in the **TPM** and links it to **PCR** values. With this seal, the encryption key can only be accessed if the **PCRs** are a certain value, i.e., the measured software is in a known state [49].

**TPMs** can report their software configuration over a network connection by using what is known as a **TPM** quote. A **TPM** quote is a signed collection of **TPM** stored data, including a hash of given **PCRs**, **TPM** clock value and a given nonce. Since the **TPM** signing key, the **AK**, is unique for each **TPM**, then a signed **TPM** quote will be a hardware based assurance of both identity and software configuration.

### 2.7.2 Trusted Execution Environments

A **trusted execution environment (TEE)** is an execution environment that is separated from normal processing and provides a higher level of security. **TEEs** originated as part of an initiative by the **TCG**. This thesis uses a **TEE** recommended for use in **NFV** named **Intel Trusted Execution Technology (Intel TXT)** [24]; however, other options for **TEEs** exists, such as AMD Secure Execution Environment<sup>11</sup> and ARM

<sup>11</sup><https://www.amd.com/en/technologies/security>

```

sha1 :
 0 : ae62d40b59561f52419a6dbb1fe3f589e7c67856
 1 : b2a83b0ebf2f8374299a5b2bdfc31ea955ad7236
 2 : b2a83b0ebf2f8374299a5b2bdfc31ea955ad7236
 3 : b2a83b0ebf2f8374299a5b2bdfc31ea955ad7236
 4 : b2a83b0ebf2f8374299a5b2bdfc31ea955ad7236
 5 : b2a83b0ebf2f8374299a5b2bdfc31ea955ad7236
 6 : b2a83b0ebf2f8374299a5b2bdfc31ea955ad7236
 7 : 4037336fa7bc0eabe3778fcfff5fcd0ee6adcde3
 8 : 0000000000000000000000000000000000000000
 9 : 0000000000000000000000000000000000000000
10 : d61c6a58cb72e81f5b5043440d2b50f597d10ffc
11 : 0000000000000000000000000000000000000000
12 : 0000000000000000000000000000000000000000
13 : 0000000000000000000000000000000000000000
14 : d701bb26d3597931f4b1c6ed5a3cd8d72d15b977
15 : 0000000000000000000000000000000000000000
16 : f0e5a9f7d5a33a281fff32e565cb407df5b191c1
17 : bfb0f7c615ba4f7f76e440202a9701461ad7504c
18 : 9b8547051d0e68839490e82f99a17d78e3e94fed
19 : 0000000000000000000000000000000000000000
20 : 0000000000000000000000000000000000000000
21 : ffffffffffffffffffffffffffffffffffffffffffffff
22 : ffffffffffffffffffffffffffffffffffffffffffffff
23 : 0000000000000000000000000000000000000000

```

Figure 9: SHA-1 PCRs of a TPM

TrustZone<sup>12</sup>.

**Intel TXT** is a set of CPU extensions that can create a measured launch environment [28]. This measured launch environment is used in solutions that provide verified launch, **Launch Control Policy (LCP)**, secret protection and attestation [28]. Verified launch boots a trusted **operating system (OS)** by doing an accurate and cryptographically verified comparison of critical elements of a launch environment against a known good source. **LCP** prevents a platform from booting if the boot measurements are not as expected. Secret protection writes secrets to protected memory. Finally, attestation provides the ability to attest the verified launch to local or remote users in a secure manner.

**Intel TXT** does not function unless multiple other components exist on a platform, including trusted extensions in the processor, authenticated code modules for secure measurements and a **TPM** for secure storage [28]. **Intel TXT** does not do the actual measurements itself, instead it enables other applications, such as **tboot**<sup>13</sup>, to measure the kernel safely.

<sup>12</sup><https://www.arm.com/products/security-on-arm/trustzone>

<sup>13</sup><https://sourceforge.net/projects/tboot/>

## 2.8 Chain of Trust

Chains of trust extend trust originating from a trust anchor into a platform. The most common chain of trust is used with X.509 architecture, where a root certificate is used as the trust anchor. This thesis constructs a chain of trust based on firmware and software measurements and utilizes the [TPM](#) as a trust anchor. This Section explains how to construct a chain of trust using both boot time and run time measurements and the complete chain of trust can be seen in [Figure 10](#)

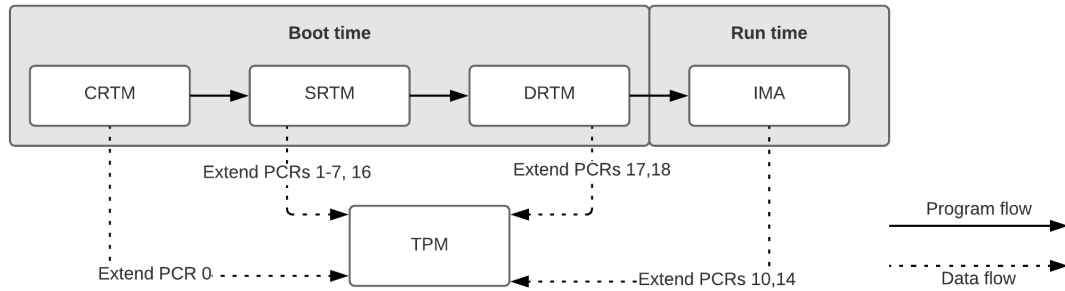


Figure 10: Chain of trust with a TPM trust anchor

### 2.8.1 Boot Time Measurements

Boot time measurements are measurements done before the [OS](#) kernel is running. Typically, code is measured before it is run and all measurements are written into the [TPM](#).

The measurements are divided into multiple sets: the [core root of trust for measurement \(CRTM\)](#), the [static root of trust measurement \(SRTM\)](#) and the [dynamic root of trust measurement \(DRTM\)](#). [CRTM](#) is at a well established location in firmware and it is read by the CPU after a power on reset [30]; [SRTM](#) includes the measurements of the [basic input/output system \(BIOS\)](#), option ROM and bootloader and [DRTM](#) includes measurements of the [OS](#), its kernel modules and early drivers [28, 70].

[CRTM](#) and [SRTM](#) measurements are supported by [TPM](#) drivers, while [DRTM](#) requires a [TEE](#) and a measurement software, such as [TrustedGrub](#)<sup>14</sup> or [tboot](#). All the measurements, both firmware and software, are stored in the [TPM PCRs](#). As [PCRs](#) use hash extension, any change in the software, firmware or boot order will be reflected in written [PCRs](#).

<sup>14</sup><https://github.com/Rohde-Schwarz-Cybersecurity/TrustedGRUB2>

Implementations of boot time measurements are known as measured boot or trusted boot. These solutions are similar and in some cases identical. Measured boot is a part of the [TCG](#) architecture and its aim is to detect any changes in the platforms pre-boot environment [56].

## 2.8.2 Run Time Measurements

Run time measurements begin after the kernel has loaded and measures files while the system is running. Unlike boot time trust, which can only detect persistent changes [7], a run time trust implementation can track ephemeral changes in files.

Run time measurements can be provided by Linux [Integrity Measurement Architecture \(IMA\)](#)<sup>15</sup>. [IMA](#) is an open source trusted computing component comprising several Linux kernel modules with the goal of documenting the integrity of files. It has been included in the Linux kernel since version 2.6.30.

Linux also have other means of run time measurements, including the userspace component [auditd](#) [67]. However, only Linux [IMA](#) is used in this thesis.

[IMA](#) maintains a runtime measurement list of selected files in the filesystem. It can be implemented with or without a hardware anchor, such as a [TPM](#). If [IMA](#) is implemented without a hardware anchor, then an adversary can alter the measurement list undetected [43]. A hardware anchor ensures that any change in the files themselves or a change in the measurement list is detected. [IMA](#) measurements do not prevent changes to files, as in integrity protection, they only document changes in real time [43]. However, [IMA](#) can be extended with [IMA](#)-appraisal, which can make files unable to open if the measured values do not match known good values [43]. If implemented with a [TPM](#), then a hash of the measurement list can be written into [TPM PCR](#)s.

[IMA](#) has quite wide measurement policies and lacks a manner of marking specific files for measurement. An approach to get more granularity in measurement selection is to use [Security-Enhanced Linux \(SELinux\)](#)<sup>16</sup>.

[SELinux](#) is a Linux security module for improved access control. Base Linux access controls are modifiable by both user and running applications and provide limited security options [47]. [SELinux](#) provides enhancement not only in the granularity of access control, but also greater restrictions on who can load access control policies to the system [47]. In addition to security enhancements, [SELinux](#) allows a user to tag files. Linux [IMA](#) can use these tags for measurements policies. This enables [IMA](#) run time measurements of any chosen set of [SELinux](#) tagged files.

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<sup>15</sup><https://sourceforge.net/p/linux-ima>

<sup>16</sup><https://github.com/SELinuxProject>



## 2.9 Secure Boot

Another approach to trust-enhanced boot is Microsoft's secure boot [50], where an approved signer signs critical programs, such as bootloaders and OS. When a platform with secure boot starts, these programs are then checked for correct signature using a key stored in firmware. In this way, only signed code is allowed to run on the platform [50]. Secure boot alone is not enough for current trusted NFV implementations nor the solution proposed by this thesis as they all rely on boot-time measurements [34, 59]. However, measured boot and secure boot are complementary and can be used together.

One security issue with secure boot is that also malware can be signed and cases of this have been found in recent research [38, 39, 40]. With secure boot, signed malware will be verified as trusted and the system will run as normal.

Note that the NFV documentation also operates with a notion of secure boot [11]. NFV secure boot is a version of measured boot and not Microsoft secure boot [50].

## 2.10 Summary

This Chapter introduced NFV, NFVIaaS and trusted computing. First, the Chapter explored the NFV architecture, how it is most commonly implemented in OpenStack and the entities in OpenStack NFV. Then, the Chapter introduced NFVIaaS and discovered that a base installation of OpenStack currently supplies no trust solution. Finally, the Chapter showed some of the most important elements of trusted computing and how trust can be constructed in a single platform.

The next Chapter explores the challenges in combining NFV and trusted computing and reviews existing solutions from both the NFV architecture view and for the NFVIaaS use case.

## 3 Trusted NFV Challenges and Existing Research

This Chapter reviews the challenges of implementing a trusted **NFV** cloud and existing solutions. Although there has been a large amount of research on trusted clouds, there exists only two trusted **NFV** implementations. This Chapter starts by introducing these two implementations. Then, the Chapter presents the challenges and existing solutions for the **NFVI**, **MANO** and **VNF** blocks respectively. Then, the **NFVIaaS** use case is extended with existing trust implementations. Finally, the Chapter identifies limitations in existing implementations and research.

### 3.1 Intel Cloud Integrity Technology

The most used trusted **NFV** cloud implementation is **Intel Cloud Integrity Technology (Intel CIT)**. **Intel CIT** is the second generation of Intel's trusted **NFV** cloud. Their first generation, **OpenAttestation**<sup>17</sup>, was recommended by **OpenStack** as a way to create trusted compute pools [22]. This recommendation has been removed, and **Intel CIT** is not officially recommended by either **ETSI** or **OpenStack**.

**Intel CIT** secures cloud workload with workload placement, encryption and launch control [34]. It provides infrastructure boot time trust and extends this into **OpenStack** and **Docker**. This summary will only cover the infrastructure and **OpenStack** parts.

**Intel CIT** adds multiple elements to the **NFV** architecture. This Section focuses on the attestation server and the trust agent functionalities, which allows infrastructure trust to be used with **OpenStack**. Infrastructure trust is built with measured boot and includes measurements of **CRTM**, **SRTM** and **DRTM**. This trust is reported to **OpenStack** from the trust agent via the attestation server. Infrastructure trust is used to build a trusted pool of hypervisors, on which trusted workload can be placed [34].

**Intel CIT** allows trusted **VNF** images to be manually added to the attestation server. A trusted **VNF** image is in this context selected parts of a **VNF** image and its expected hash value. **VNF** image trust is checked during boot for multiple **OpenStack VNF** operations. The **VNF** operations supported by **Intel CIT** are launch from image, suspend, resume, hard reboot, shut off and start [34].

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<sup>17</sup><https://01.org/OpenAttestation>

## 3.2 Master Thesis Trust Implementation

In addition to [Intel CIT](#), there is one alternative trust implementation available. This trust implementation was made in a master thesis at Aalto University [59]. The implementation provides infrastructure trust at boot time and extends this to cover workload placement. Furthermore, the implementation checks [VNF](#) images through signatures and measurements [59].

This implementation adds some elements to [NFV](#) architecture. These elements are an attestation server and the [Trusted Security Orchestrator \(TSecO\)](#). The attestation server is from [Intel CIT](#)'s solution and the [TSecO](#) was developed for this implementation. The attestation server reports integrity measurements of the servers to the [TSecO](#). The [TSecO](#) has multiple roles in this implementation, including binding [TPM](#) values to a server via the attestation server, signing [VNF](#) images through a signing authority and assisting OpenStack in workload placement [59]. In addition to signing [VNF](#) images, the integrity of images are checked during workload placement [59].

The infrastructure trust in this trust implementation is constructed similarly to [Intel CIT](#). It builds on measured boot and covers [CRTM](#), [SRTM](#) and [DRTM](#). The trust implementation offers different trust-policies based on sets of [TPM PCR](#) values. In addition to infrastructure trust, this implementation offers trusted workload placement. This places [VNFs](#) on infrastructure matching their trust requirements by using OpenStack filters [59].

## 3.3 NFVI Trust

Creating and maintaining trust in infrastructure is a hot research topic [32, 71, 73] and the main challenges are in two areas: creating a trusted element and attesting other elements.

There are multiple ways to create a trusted element, such as secure boot [50] and measured boot. Both the existing trusted [NFV](#) implementations use measured boot through the trust agent component from [Intel CIT](#) [34, 59]. Common approaches in research are measured boot [11] or a combination of measured boot and secure boot [7].

The information from measured boot is commonly distributed through a process of [remote attestation \(RA\)](#). [RA](#) can be done with or without a trust anchor. This thesis assumes a [TPM](#) trust anchor is available; however, there exists many [RA](#) schemes that do not depend on a [TPM](#) [1, 51, 64]. In [RA](#) with a [TPM](#) available on an element, the process is as follows.

- User, verifier or attestation server send a nonce and a list of [PCRs](#) to an element

with a [TPM](#).

- The [TPM](#) on the element creates a signed [TPM](#) quote containing the received nonce and a hash of the given [PCRs](#).
- The sender of the attestation request checks the received [TPM](#) signature, nonce and received [PCR](#) hash against known good values.

This approach of [TPM](#) enabled [RA](#) is used in both existing implementations [[34](#), [59](#)] and in research [[27](#), [72](#), [73](#)].

### 3.4 MANO Trust

OpenStack implements the [MANO](#) functionalities of [OPNFV](#); therefore, trust in OpenStack is equivalent to trust in [MANO](#). To enable trusted OpenStack, both the server running OpenStack and the OpenStack installation have to become trusted. The server running OpenStack can become trusted using [NFVI](#) trust as described in the previous Section. However, [NFVI](#) trust does not secure the OpenStack installation.

The two existing implementations build trust in operations running on top of OpenStack, but does not build trust in the OpenStack installation itself [[34](#), [59](#)]. There is a large body of research dedicated to OpenStack security [[3](#), [7](#), [36](#), [45](#), [62](#), [63](#)]; however, most of these focus on security issues other than integrity, such as access control and communication security [[3](#), [45](#), [62](#), [63](#)]. Two available research papers [[7](#), [36](#)] extend measurements into run time; however, they are mostly theoretical and do not measure the OpenStack installation.

### 3.5 VNF Trust

[VNFs](#) change state at many points during their life cycles. Therefore, their trust needs to be evaluated not only during [VNF](#) boot, but at every major state change. In this section, [VNF](#) trust is reviewed for adding images to the supply chain, starting a [VNF](#) and managing a [VNF](#) life cycle.

#### 3.5.1 Supply Chain

Before [VNFs](#), network functions were bound to hardware and securing an image could be done with physical security measures [[13](#)]. This is no longer the case since [VNF](#) images can be altered and run on any general purpose server.

In OpenStack, [VNF](#) images are added to an internal OpenStack database. This process is currently secured in a multitude of ways.

- [Intel CIT](#) hashes selected parts of the image and checks these parts during image boot [34].
- The master thesis trust implementation both signs and measures images [59]. The signature and measurement hashes are then verified before an image is started [59].
- The most common approach in research is to hash the entire image and check the hash against known values before an image is started [6, 13, 46].

### 3.5.2 Starting a VNF

In OpenStack, starting a [VNF](#) takes an image, selects a hypervisor and runs the image. Since [VNF](#) images are covered in the supply chain, the remaining element that needs trust is the hypervisor selection.

OpenStack select a hypervisor by going through a set of hypervisor filters that checks for sufficient computational resources, including the number of available CPUs and the amount of available RAM [21]. Among the hypervisors that satisfies the filter, the one with most available resources is chosen. The process of selecting a hypervisor is called workload placement.

Workload placement based on infrastructure trust has existed in earlier OpenStack versions [22]; however, it is now removed [16]. Both the current trusted [NFV](#) implementations adds trust to workload placement [34, 59]. In the existing implementations, trust in hypervisors is constructed and checked using measured boot and [RA](#), as explained above under [NFVI](#) trust. Then a filter is added which removes all hypervisors that have failed the [RA](#). Both of the current implementations rely on an outdated OpenStack, where the trusted filter still existed [22, 34, 59].

### 3.5.3 VNF Instance Life Cycle Operations

In addition to being trusted when started, [VNFs](#) need to maintain trust throughout their life cycles. OpenStack has a large set of [VNF](#) operations, which may change the [VNF](#) state. A full [VNF](#) state diagram is found in Appendix B Figure B1.

There are many theorized methods of securing a running [VNF](#), including virtualized [TPMs](#) [2, 35], software [TPMs](#) [58] and [IMA](#) measurements within a running [VNF](#) [35]. [Intel CIT](#) is the only practical implementation that adds trust to [VNF](#) operations other than start [VNF](#).

**Intel CIT** supports the following OpenStack **VNF** operations: launch from image, suspend, resume, hard reboot, shut off instance and start instance. All of these operations hash parts of the **VNF** image when the **VNF** instance is shut down or paused. These partial hashes are then verified when the **VNF** image is booted [34]. However, as neither suspend nor resume contains a boot action [21], it is unknown how, or if, the hashes are actually verified.

A larger set of **VNF** operations, such as migration [13, 26] and suspend [6, 46], are covered in patents; however, these are theoretical and directed at **VMs** in general.

### 3.6 Trusted NFVIaaS

While the rest of this Chapter has reviewed trust in **NFV** from an architectural view, this Section reviews trust in the trusted **NFVIaaS** use case. This use case was presented in Section 2.6 and aims to provide a cloud tenant with a trusted **VNF** instance. The remainder of this Section examines how trust can be added to the steps in the use case success scenario described in Section 2.6.1. For all the steps, a superset of the two existing implementations [34, 59] are used to provide trust.

**Service provider adds trusted hardware elements to the cloud.** Both of the existing implementations use measured boot and measures **CRTM**, **SRTM** and **DRTM** in a hardware element at boot time [34, 59]. With this, a service provider can guarantee the trust of an element at boot time.

**Service provider installs a trusted OpenStack configuration.** None of the existing implementations do run time attestation of software [34, 59]. Therefore, the OpenStack configuration can not be trusted, as the service provider can not validate its integrity.

**Cloud tenant adds a trusted VNF image.** The two existing implementations allows for different methods of trusting a **VNF** image. **Intel CIT** hashes parts of the image and verifies this hash during boot [34], while the master thesis implementation both signs and hashes the image and verifies these before boot [59]. Both of these methods allow a cloud tenant to add trust to their **VNF** image.

**Cloud tenant deploys a VNF image on trusted hardware** Both existing implementations provide what is known as trusted workload placement [34, 59]. This is done by modifying OpenStack filters to only run trusted **VNF** images on trusted hardware elements. With trusted workload placement, a cloud tenant can deploy **VNF** images on trusted hardware.

**Cloud tenant performs trusted VNF operations.** Only Intel CIT provides trusted VNF operations [34]. However, they only support a few operations and no operations where the VNF changes hypervisor [34]. Therefore, the cloud tenant can only perform a very limited set of trusted VNF operations.

**Cloud tenant audits the trust decisions.** The two existing implementations has some auditability. Intel CIT offers a trusted or not trusted decision for each element [34], while the master thesis implementation keeps an audit log over trust decisions [59]. Only relying on a trusted or not trusted decision allows for very limited auditing [34]. Although the alternate implementation offers an audit log, the implementation does not cover any VNF operations [59]. Without VNF operations, a cloud tenant can audit hardware element trust but not VNF instance trust.

### 3.7 Limitations in Existing Solutions

Although existing trusted NFV cloud solutions improve greatly on base OpenStack trust, they still have large limitations. Limitations for trust in an NFV cloud are listed below. Other limitations are out of the scope of this thesis and will not be considered.

- All existing implementations depend on Intel CIT for parts of their solution [34, 59].
- Boot time measurements are not extended into run time in any NFV cloud implementation [34, 59].
- OpenStack configuration is not measured in any OpenStack implementation or research [3, 7, 34, 36, 45, 59, 62, 63].
- Only a minimal set of OpenStack VNF operations are covered in existing implementations [34, 59]. Moreover, the available research is only theoretical and not adapted for VNFs on OpenStack [6, 13, 26, 46].
- Logging in current implementations is limited [34, 59], which makes auditing trust decisions difficult.

### 3.8 Summary

This Chapter has introduced existing trust implementations, presented trusted cloud challenges, reviewed previous trust research, applied existing trust solutions to NFVIaaS and uncovered limitations in existing solutions.

There is a large body of trust research, which enable a far higher level of trust than what was offered by a base OpenStack [NFV](#) platform. However, many trust issues remain unsolved and both the [NFV](#) architecture and the [NFVIaaS](#) use case have untrusted areas.

The next Chapter presents how this thesis plans to overcome the existing trust limitations and introduces the thesis extensions.



## 4 Proposed Extensions

This Chapter presents the extensions proposed by this thesis and explains how they solve or mitigate the current trusted [NFV](#) cloud limitations. To enable these extensions, an attestation server is added to the [NFV](#) architecture. This Chapter begins by introducing the attestation server, then it proceeds with the extensions in the order they were presented in Chapter 1.

In addition, each section will clarify how it solves or mitigates limitations introduced in Chapter 3.

### 4.1 Attestation Server

This thesis extends the [NFV](#) architecture by adding an attestation server. The attestation server attests hardware elements via remote attestation; attests [VNFs](#) and tracks [VNF](#) state via OpenStack [VNFM](#); logs all trust events in the system and enables a user to audit all events.

The attestation server communicates with [MANO](#) elements from the [NFV](#) architecture shown in Chapter 2 Figure 2 and users. The functional blocks of the attestation server and its communication with the [NFV](#) architecture is shown in Figure 11. All blocks of the attestation server communicate with each other. The functional blocks not implemented in this thesis are used for ongoing research into more extensive attestation and root cause analysis [53]. Figure 12 shows a sample [VNF](#) instance in the full attestation server. Note that the graphical user interface was not developed for this thesis, but is a part of ongoing research [53].

The attestation server tracks the system trust status with a set of entries. These entries are different elements, quotes and policies. The attestation server elements are the OpenStack [NFV](#) entities introduced in Chapter 2 Section 2.5, which are hardware elements, [VNF](#) images and [VNF](#) instances. The attestation server determines the trust status of hardware elements using quotes and policies. Furthermore, it tracks the trust status and state of [VNF](#) images and [VNF](#) instances.

The attestation server also acts as a logging hub. All attestation actions in the cloud are logged in the attestation server. These logs are not actively used to determine trust; however, they allow any user to audit the trust decisions via command line tools.

This attestation server is different from [Intel CIT](#) and no parts of the solution depend on [Intel CIT](#). This solves the limitation of all existing implementations having that as a single common element.

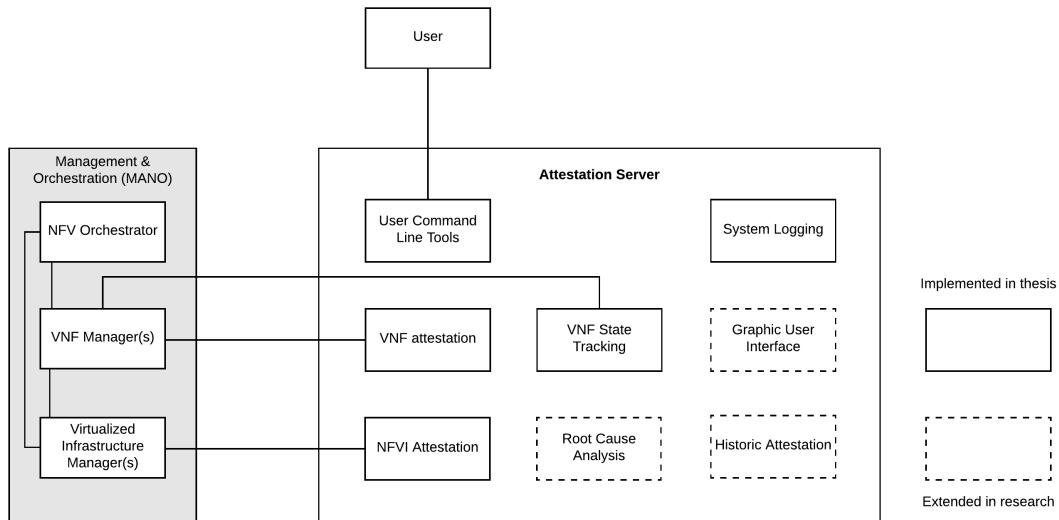


Figure 11: Attestation server functional blocks and communication with NFV MANO

Home Elements Policies Policy Sets Quotes Events Trust Graph Known Hashes Rules Records Cloud Health About

### Element Details

status	✓
kinds	[u'VNFElement::VMInstance']
name	migrate-vnf
timestamp	2018-08-17 05:24:04.678000
policy_set_id	None
migration_record	5b765bf4352c65376cbca063
VM_image	85a7cf0b-cd2f-429a-b3c3-44c88b923e4e
state	migrated
running_on	controller
openstack_id	784ec95b-36ec-4ca4-b78f-615732ab040d
previous_suspend_hash_list	[]
_id	5b765bc9352c65376cbca05e

Figure 12: VNF instance entry in the attestation server

## 4.2 Extending Cloud Infrastructure measurements

This thesis extends measured boot and measures the OpenStack installation at run time. OpenStack operation is governed by a set of configuration files (the full set can be seen in Appendix B Section B.2) and only these needs to be measured to

ensure correct OpenStack operation. The OpenStack configuration files are tagged by SELinux and the tagged files are measured by Linux IMA. Linux IMA writes the hash of these files into a TPM PCR.

This measurement is used in two ways. The first way is when doing RA. When deciding the trust status of a hypervisor, also the run time measurements can be quoted, as it is written in TPM PCRs. The second way is to disable communication between OpenStack and the attestation server if OpenStack has changed. TPMs have the ability to seal data to a certain value in a PCR. This thesis seals the communication setup between OpenStack and the attestation server to a known good value of the IMA measured PCR.

This extension solves the limitations of boot time measurements not being extended into run time and the lack of OpenStack configuration measurements.

### 4.3 Extending VNF Life Cycle Trust

This thesis extends current solutions for measuring VNF life cycle operations. The VNF operations covered by this thesis are start, suspend, resume and migrate. This is still only a small subset of operations; however, most other operations are a variation of these. Some examples of similar operations are shelve and pause, which both use the same flow as suspend.

This trusted VNF extension does not only cover new VNF operations, but also adds to the supply chain of VNF images. In previous implementations, new images had to be added manually and were only used for the start VNF operation. This extension allows suspend and migrate to add new images to the supply chain, which can be used by OpenStack when resuming a suspended VNF or when migration has completed.

The base OpenStack start, suspend, resume and migrate can be seen in Chapter 2 Figures 4, 5, 6 and 7, while the extended OpenStack start, suspend, resume and migrate can be seen in Figures 13, 14, 15 and 16 respectively.

This extension mitigates the lack of OpenStack VNF operations covered in existing implementations and presents a flow that can easily be extended to a larger set of operations.

### 4.4 Extending the Auditability

This thesis extends the auditability of the cloud by logging all actions to the attestation server. These logs contains enough info so that a user could quote the different TPMs, hash the relevant VNF images and replay the operations taken to verify the

trust decisions themselves. Some of these audit capabilities existed in the previous master thesis solution [59], but in Intel CIT the user is left with little more than a trusted or not trusted decision [34].

When all actions are logged, a user can also find normal patterns for failure and attempt to track down the causes of these. One normal failure pattern in this cloud is due to synchronization failure in OpenStack compute nodes. This causes a compute node to not be available in workload scheduling, which would be difficult to discover without adequate logging.

This thesis only enables logging and it does not use the logs for any pattern recognition. The logging of all actions solves the last limitation from Chapter 3, which was the difficulty of auditing a trust decision.

## 4.5 Summary

This Chapter has described the extensions added by this thesis and clarified how they solve and mitigate current trusted NFV cloud limitations. In addition, it has presented the attestation server added to the NFV architecture. The next Chapter implements the extensions in a state-of-the-art trusted NFV cloud.

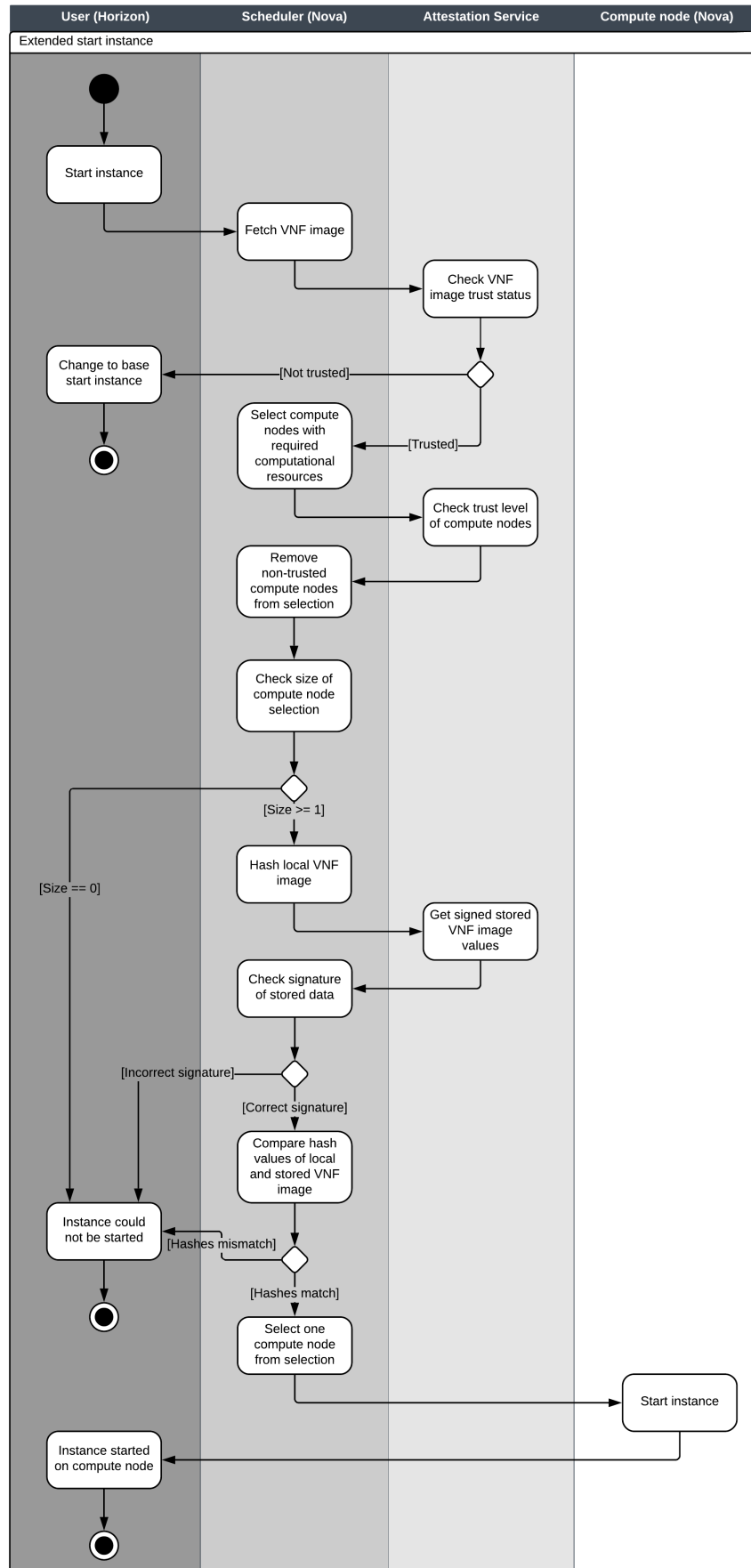


Figure 13: Extended OpenStack start VNF instance

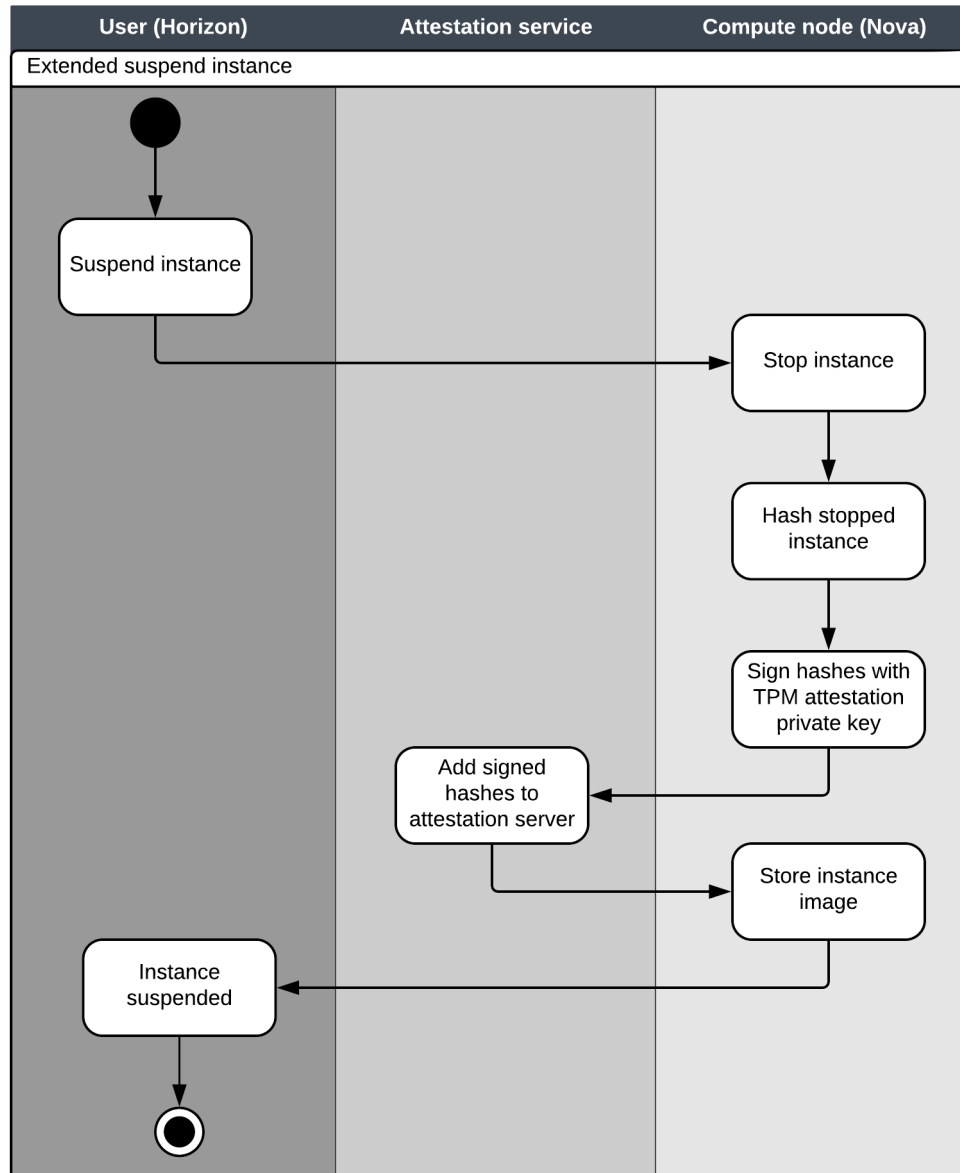


Figure 14: Extended OpenStack suspend VNF instance

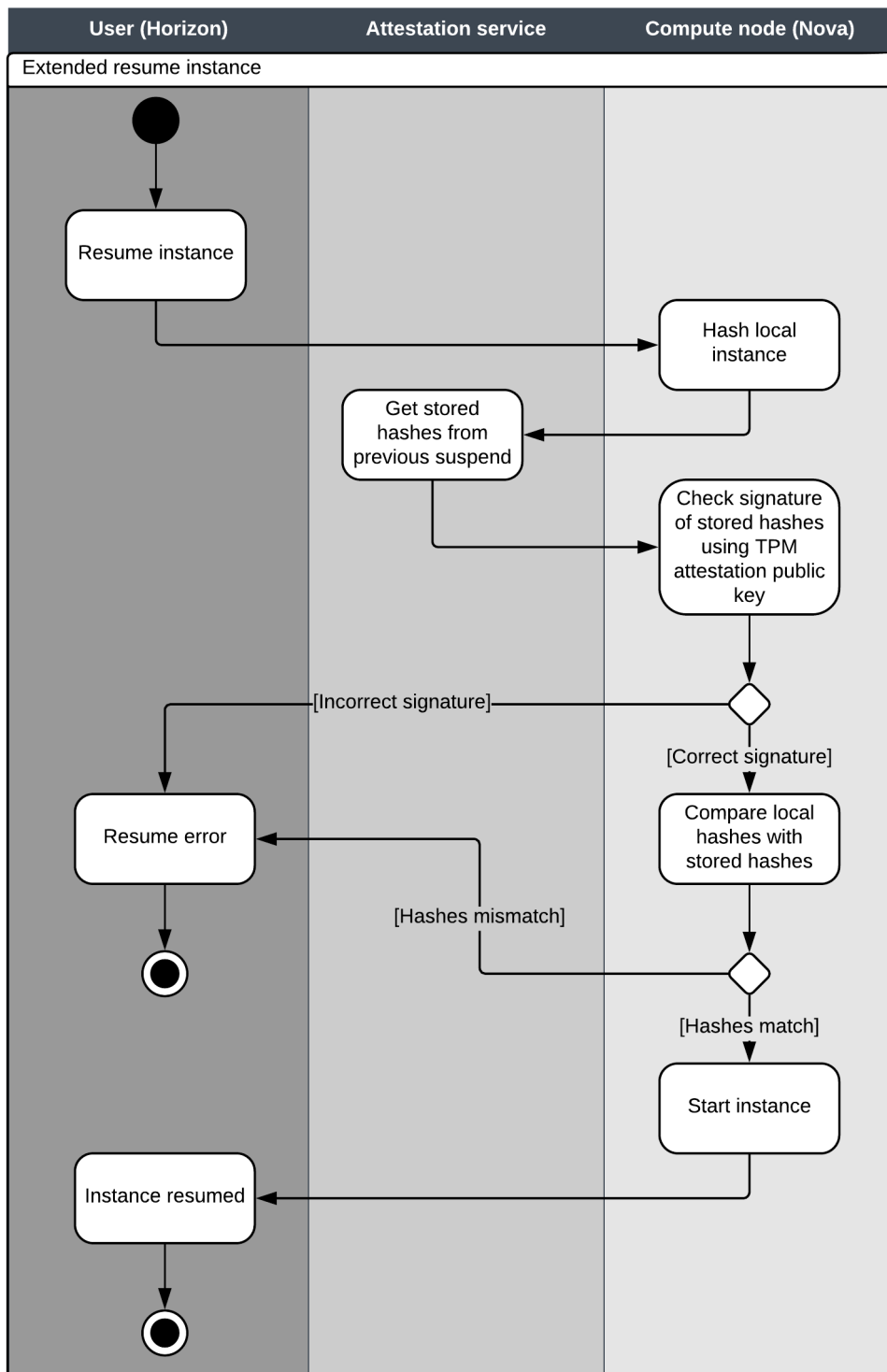


Figure 15: Extended OpenStack resume VNF instance

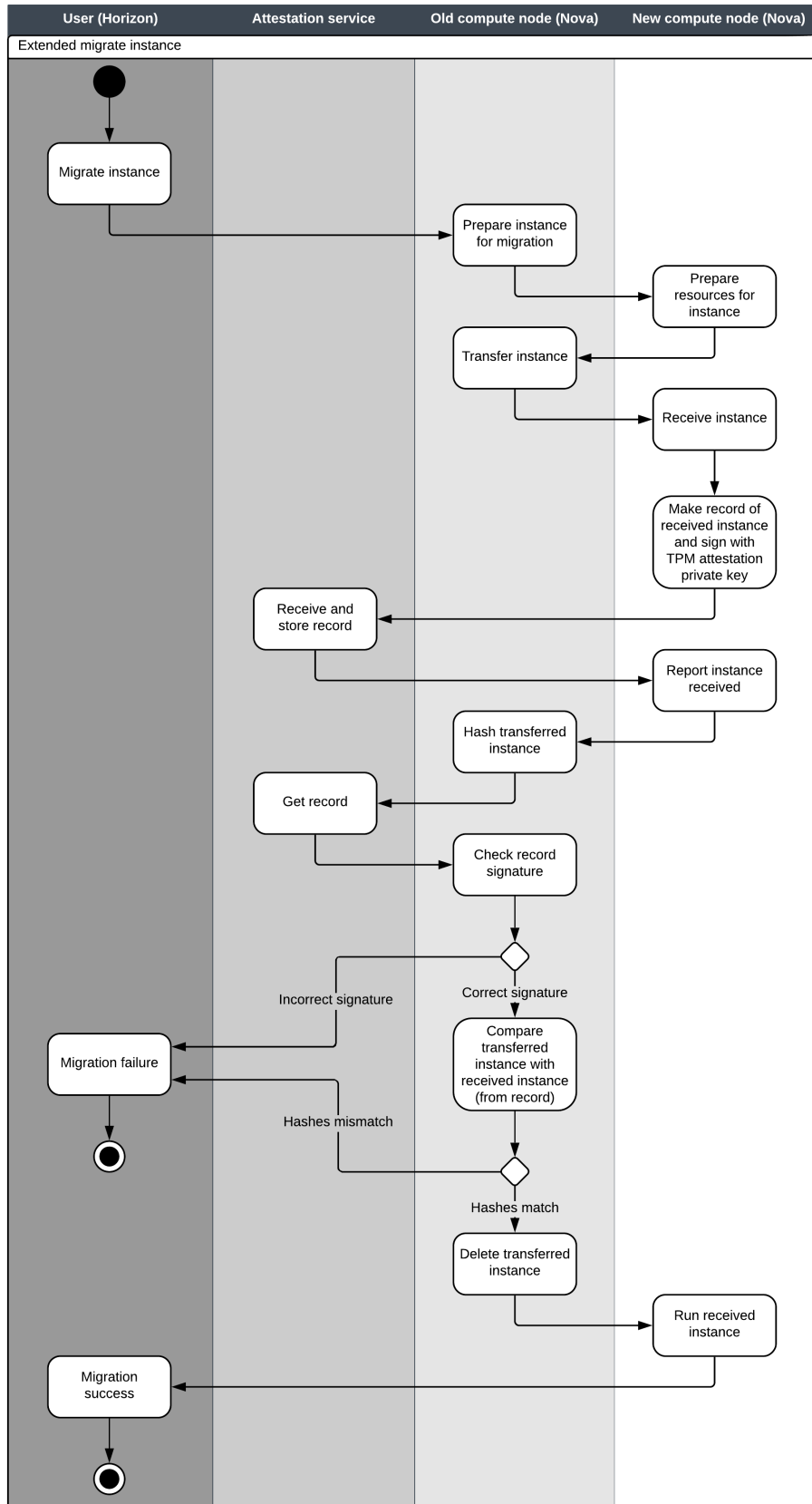


Figure 16: Extended OpenStack migrate VNF instance



## 5 Implementation

This Chapter presents a state-of-the-art trusted cloud implementation including the extensions proposed by this thesis. The implementation is a functional [NFV](#) cloud and includes a full OpenStack installation, running [VNF](#) instances and the trust elements introduced by previous implementations. The trust elements introduced by previous implementations are rebuilt in this thesis and no code is reused or copied.

This Chapter is organized by first describing the attestation server implementation before the trusted cloud is implemented from the bottom up architecture wise.

### 5.1 Attestation Server

This implementation extends the [NFV](#) architecture by adding an attestation server. The attestation server is used for storing, checking and auditing measurement values. The server communicates with the hypervisors managed by OpenStack and the OpenStack controller.

The attestation server stores entries for [TPM](#) elements, [VNF](#) image elements, [VNF](#) instance elements, policies, [TPM](#) quotes, events and records. These entries and their entry fields will be introduced in detail as they are used throughout this implementation. Example values for all entry fields can be found in [Appendix D Section D.2](#).

The attestation server is developed in Python and communicates over HTTP requests via a [representational state transfer \(REST\) application programming interface \(API\)](#). A Python example of a HTTP request for getting OpenStack elements can be seen in [Listing 1](#), while the full [REST API](#) is found in [Appendix D Section D.1](#).

```
1 requests.get('http://' + ATTESTATION_SERVER_IP + ':' + str(
    ATTESTATION_SERVER_PORT) + '/elements/openstack/' +
    openstack_uuid)
```

Listing 1: Python HTTP request

The attestation server database is a [MongoDB](#)<sup>18</sup>; however, it is simply used for storing entries and could have been any database software. The main ID for database entries is their assigned MongoDB ID for policies, quotes, events and records and their OpenStack UUID for [TPM](#) elements, [VNF](#) image elements and [VNF](#) instance elements.

Database entries are signed when added. These signatures are done using

<sup>18</sup><https://www.mongodb.com/>

OpenSSL<sup>19</sup>. Listing 2 shows an example OpenSSL signing command.

```
1 $ openssl dgst -sha256 -sign signing_key.key -out signed_example.txt
   example.txt
```

Listing 2: OpenSSL sign

For this implementation, the public keys of authorized signers are distributed manually.

## 5.2 Trusted NFVI

This implementation uses three **NFVI** elements, which all have a **TPM** and run OpenStack. All three servers function as OpenStack compute nodes, also known as hypervisors. Additionally, one server has the role of controller and therefore runs the **MANO** functionality of OpenStack. The OpenStack install was done according to the default install for the Pike release of OpenStack<sup>20</sup>. All the compute nodes are running the OpenStack Nova and Neutron services, while the controller node additionally runs the OpenStack Keystone, Glance and Horizon services. Appendix A shows the full server specification.

Each server is set up with the appropriate TPM drivers and tboot. **SELinux** has issues in Ubuntu; therefore, the Linux **IMA** and **SELinux** tests in Appendix C Section C.3 were performed on a different server running Fedora. However, **SELinux** is officially supported in Ubuntu and should function in future implementations [65]. The rest of this implementation uses **IMA** measurements on the AirFrame servers without accurate **SELinux** tagged OpenStack files.

Setup for tboot and Linux **IMA** can be found in Appendix C, while **SELinux** can be installed via your chosen package manager, such as Dandified YUM for Fedora Linux. With these programs, the servers have measurements for boot time CRTM, SRTM and DRTM and run time IMA.

The servers also have Intel's **TPM** software stack installed to simplify communication with the **TPM**. This software stack conforms to the **TCG TPM 2** specification [30] and comprises **TPM2-tss**<sup>21</sup>, **TPM2-abrmd**<sup>22</sup> and **TPM2-tools**<sup>23</sup>. The **TPM2-tools** are userland tools to simplify the communication with the **TPM**. In addition to the **TPM** software stack, each server runs a trust agent. The trust agent in this thesis is a simple Python wrapper that allows external elements to request **TPM** quotes from the **TPM** via the **TPM** software stack. Communicating to the **TPM** via userland

<sup>19</sup><https://www.openssl.org/>

<sup>20</sup><https://docs.openstack.org/pike/install/>

<sup>21</sup><http://github.com/intel/tpm2-tss>

<sup>22</sup><https://github.com/intel/tpm2-abrmd>

<sup>23</sup><https://github.com/intel/tpm2-tools>

tools is not ideal and future implementations should communicate with the [TPM](#) directly. Figure 17 shows the implemented [TPM](#) communication and recommended future communication. The [TPM 2](#) software stack is under active development and

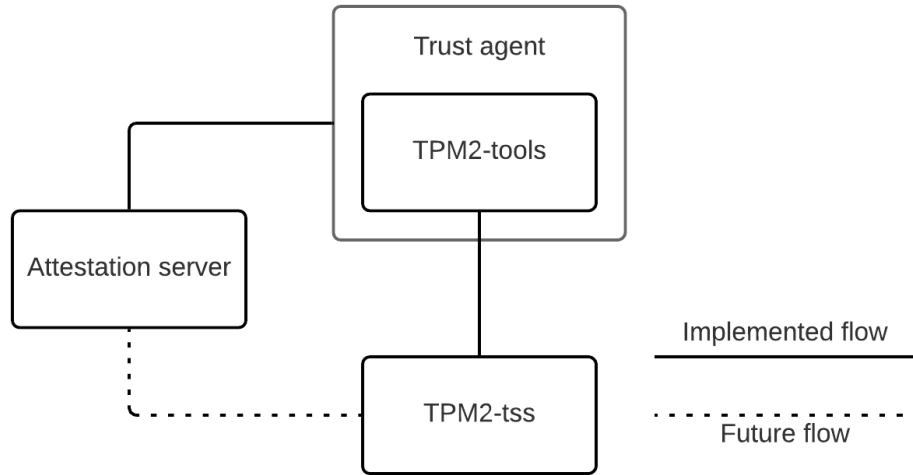


Figure 17: Attestation server TPM communication

this implementation uses the syntax from TPM2-tss version 1.4.0, TPM2-abrmd version 1.3.1 and TPM2-tools version 3.0.3. All [TPM](#) calls in this thesis are to this software stack, either directly or via the trust agent.

All of the servers are added to the attestation server as [TPM](#) elements. These attestation server entries include the identities of the servers, their configuration, their public [TPM](#) keys and their trust status. [TPM](#) element entry fields and their descriptions can be seen in Table 1. This thesis uses quotes and policies to determine the trust status of a [TPM](#) element.

A TPM quote is defined by the [TCG](#) [30] and contain the values of chosen [TPM PCR](#) registers and extra data, such as the [TPM](#) firmware version. This thesis only use the values of the quoted [TPM PCRs](#). [TPM](#) quote entry fields and their descriptions are seen in Table 2. Quotes are taken using the `tpm2_quote` command from Intel's [TPM2](#) software stack. An example quote command for SHA-256 PCR registers 0–7 is shown in Listing 3.

```
1 $ tpm2_quote -k 0x81010003 -L sha256:0,1,2,3,4,5,6,7 -m message.
   output -s signature.output -G sha256
```

Listing 3: TPM quote command

A policy gives an expected value for a specific measurement. In this thesis, all policies are for [TPM](#) elements and have a set of [PCRs](#) and their expected value. To

Field name	Description
<code>_id</code>	MongoDB ID of the <a href="#">TPM</a> element.
<code>ak</code>	The public part of the <a href="#">TPM</a> element's <a href="#">AK</a> .
<code>ek</code>	The public part of the <a href="#">TPM</a> element's <a href="#">EK</a> .
<code>ip</code>	IP of the <a href="#">TPM</a> element.
<code>kind</code>	What kind of element it is.
<code>name</code>	Name of the <a href="#">TPM</a> element.
<code>openstack_id</code>	OpenStack UUID of the <a href="#">TPM</a> element.
<code>status</code>	Trust status of the <a href="#">TPM</a> element.
<code>timestamp</code>	Time when this entry was made to the database.
<code>uname</code>	Info about the <a href="#">TPM</a> element platform.
<code>policy_list</code>	List of policies for this element.
<code>signature</code>	Signature of a system administrator.

Table 1: TPM element fields

Field name	Description
<code>_id</code>	MongoDB ID of the TPM quote.
<code>element_id</code>	The ID of the TPM element on which the quote was taken.
<code>quote</code>	The actual TPM quote.

Table 2: TPM quote fields

find expected values, this thesis uses reference devices. A reference device is made by configuring a server to a known good configuration and quoting sets of [PCRs](#). The quoted value is then stored as the expected value for the quoted [PCRs](#). Policy entry fields and their descriptions are seen in [Table 3](#).

Field name	Description
<code>_id</code>	MongoDB ID of the policy.
<code>name</code>	Name of the policy.
<code>timestamp</code>	Time when this entry was made to the database.
<code>pcrs</code>	Which <a href="#">PCRs</a> this policy is for.
<code>expected_value</code>	The expected value of the <a href="#">PCRs</a> .
<code>signature</code>	Signature of a system administrator.

Table 3: Policy fields

Trust is determined in a [TPM](#) element by checking its policies. To check the policies, a [TPM](#) element is quoted for the [PCRs](#) required by its policies. These quoted values are then compared with the expected values in the policies. If these are equal, then the [TPM](#) element is set to trusted. The full process determining [TPM](#) element trust is described below.

- Get element contact info from a [TPM](#) element entry.
- See which policies are in the elements policy list.
- For each policy, ask the element to upload a quote of the required [PCRs](#).
- Check the added quote entry signatures with the public [TPM AK](#) of the element. An example command for checking a [TPM](#) signature is found in [Listing 4](#).
- For each policy, check the quoted value against the expected value.
- If all policy checks are successful, then the [TPM](#) element is marked as trusted

```
1 $ tpm2_verifysignature -k 0x81010003 -g sha256 -m verify_input -s
signature.sig -t validation.ticket
```

Listing 4: TPM quote command

### 5.3 Trusted MANO

In this thesis, OpenStack implements the [MANO](#) functionality. Therefore, [MANO](#) trust is built by enabling trust in the OpenStack controller installation. OpenStack

controller functionality is determined by a number of configuration files so we can create a trusted MANO by trusting the content of these configuration files.

These configuration files can be measured by Linux [IMA](#). Since [IMA](#) itself lacks an accurate way of tagging files, this implementation uses [SELinux](#) tags to mark the configuration files. [IMA](#) can then define a policy where [IMA](#) measures all files with a certain [SELinux](#) tag. Appendix C Section C.3 shows the process of tagging a single OpenStack configuration file for [IMA](#) measurement, while Appendix B Section B.2 shows the full list of OpenStack configuration files.

The process described in Appendix C Section C.3 measures OpenStack configuration files and saves the measurements in [TPM PCR 14](#). Other [PCR](#) numbers could also have been chosen. To make [MANO](#) trusted, attestation server communication is made dependant on [PCR 14](#) remaining at a known good value. This is done by protecting the communication configuration in [TPM NVRAM](#). The configuration for this thesis is only the IP of the attestation server; however, for a future implementation this could have been a shared secret key. The steps to add configuration data to [TPM NVRAM](#) is shown below, while the code to perform the steps is shown in Listing 5.

- Write [PCR 14](#) to an output file.
- Create a policy for the output file.
- Find space for the policy by checking the [TPM NVRAM](#). The code in Listing 5 checks available memory and releases the `0x1800007` memory location. This is done under the owner hierarchy, stored in memory location `0x4000001`.
- Define the policy.
- Choose the file to protect with the policy.
- The trust configuration is now stored in [TPM NVRAM](#) and can only be read if [PCR 14](#) has not changed.
- The file can later be read with `tpm2_nvread`.

When these steps are taken, OpenStack configuration files are measured and the communication configuration between OpenStack and the attestation server is sealed against this measurement. This entails that OpenStack can only communicate with the attestation server if its configurations files have not been modified. The attestation server is needed for all [VNF](#) operations and losing communication will prevent OpenStack from starting or changing [VNFs](#).

```
1 $ tpm2_pcrlist -L sha1:14 -o output_file
2 $ tpm2_createpolicy -P -L sha1:14 -F output_file -f policy_name
3 $ tpm2_nvlist
4 $ tpm2_nvrelease -x 0x1800007 -a 0x40000001
5 $ tpm2_nvdefine -x 0x1800007 -a 0x40000001 -s 700 -L policy_name -t "
  policyread||policywrite"
6 $ tpm2_nvwrite -x 0x1800007 -a 0x1800007 -L sha1:14 -F output_file
  trust_configuration
7 $ tpm2_nvread -x 0x1800007 -a 0x1800007 -L sha1:14
```

Listing 5: TPM sealing commands

## 5.4 Trusted Supply Chain

To be able to run trusted workload in OpenStack, images are added to the attestation server. The image entry fields can be seen in Table 4. These images have an ID and

Field name	Description
<code>_id</code>	Database ID of the VNF image element.
<code>hash_list</code>	A signed list of expected hashes for the VNF image element.
<code>kinds</code>	What kind of element it is.
<code>name</code>	Name of the VNF image element.
<code>openstack_id</code>	OpenStack UUID of the VNF image element.
<code>status</code>	Trust status of the VNF image element.
<code>timestamp</code>	Time when this entry was made to the database.
<code>signature</code>	Signature of a system administrator.

Table 4: VNF image element fields

a set of hash methods and their expected values. At least one hashing method need to be available and this implementation supports the hash algorithms MD5, SHA-1 and SHA-256.

When starting a [VNF](#) instance, OpenStack checks the metadata of the chosen [VNF](#) image. This thesis adds metadata to OpenStack VNF images with the following steps.

- Add a trusted field to `/usr/lib/python2.7/dist-packages/nova/objects/fields.py`.

```

—
1 class Trusted(BaseNovaEnum):
2     TRUE = 'True'
3     FALSE = 'False'
4     ALL = (TRUE, FALSE)
5
6 class TrustedField(BaseEnumField):
7     AUTO_TYPE = Trusted()

```

- Add a metadata trusted property to `/usr/lib/python2.7/dist-packages/nova/objects/image_meta.py`.

```

—
1 class ImageMetaProps(base.NovaObject):
2     ...

```



```

3 dictionary fields = {
4   'trusted': fields.TrustedField(),
5   ...
6 }

```

- Set the metadata of an image with `$ openstack image set --property trusted='True' image_name`

This metadata determines if the VNF image requires to be launched on a trusted OpenStack hypervisor. Any image marked as not trusted will ignore added functionality and will not run on trusted hypervisors.

Adding metadata and measurements to VNF images greatly improves the supply chain trust. However, important supply chain elements outside of OpenStack, such as VNF descriptors, are not covered by this implementation.

## 5.5 OpenStack Trust Filter

OpenStack filters are used to schedule VNFs starting in OpenStack. Filters are stored in `/usr/lib/python2.7/dist-packages/nova/scheduler/filters/` and this thesis adds a filter called `trusted_filter`. This filter is enabled in OpenStack Pike by adding the following code to `/etc/nova/nova.conf`.

```

1 [scheduler]
2 ...
3 driver = filter_scheduler
4
5 [filter_scheduler]
6 ...
7 available_filters=nova.scheduler.filters.all_filters
8 available_filters=nova.scheduler.filters.trusted_filter
9 enabled_filters=ComputeFilter, TrustedFilter

```

The added filter is run as part of the OpenStack start VNF instance operation. Base OpenStack start instance activity diagram can be seen in Chapter 2 Figure 4 and the extended process with an added trust filter can be seen in Chapter 4 Figure 13.

To run a filter, it needs to implement the `host_passes` method. An absolute minimum filter showing the syntax for getting host and image info from a filter and returning the trusted property of an image is shown in Listing 6 and the code for getting an image out of the Glance repository is shown in Listing 7.

The remaining code in the Python filter is for creating an event (example events shown in Appendix D Section D.3), verifying the trust status of hypervisors through

the attestation server [REST API](#) (shown in [Appendix D Section D.1](#)) and doing comparisons of measured values and expected values.

```

1 class TrustedFilter(filters.BaseHostFilter):
2     def host_passes(self, host_state, spec_obj):
3         hypervisor_name = host_state.host
4         hypervisor_openstack_id = host_state.uuid
5         vnf_image_openstack_id = spec_obj.image.id
6         vnf_instance_openstack_id = spec_obj.instance_uuid
7         return spec_obj.image.properties.trusted

```

Listing 6: Example of OpenStack filter syntax

```

1 auth = v3.Password(
2     auth_url='OPENSTACK_CONTROLLER_IP:5000/v3',
3     username=GLANCE_USER,
4     password=GLANCE_PASSWORD,
5     project_name="admin",
6     project_domain_id="default",
7     user_domain_id="default"
8 )
9 sess = session.Session(auth=auth)
10 glance = Client('2', session=sess)
11 image = glance.images.data(vnf_image_openstack_id)

```

Listing 7: Getting a Glance image from a Python filter

## 5.6 Trusted OpenStack Operations

To enable trusted OpenStack operations, this thesis intercepts the normal [RabbitMQ](#) flow shown in [Chapter 2 Figure 3](#). [RabbitMQ](#) flow is changed using [RabbitMQ](#) management command line tool<sup>24</sup>. This interception adds a trusted step before any message is able to reach a consumer.

To intercept [RabbitMQ](#) messages, all the three compute nodes are thrown out of the `Nova` exchange and added to a new exchange called `Trusted`. New consumers are added on each node and these consumers perform the trust checks. The new consumers consume messages from the `Nova` exchange and publish messages that have passed the trust check on the `Trusted` exchange. Messages that do not pass the

<sup>24</sup><https://www.rabbitmq.com/management-cli.html>

trust checks do not get passed to the compute nodes, instead the added consumers create an error event.

[RabbitMQ](#) syntax uses nested Python dictionaries which vary depending on the message. The syntax for getting [VNF](#) instance info out of a [RabbitMQ](#) message for a [VNF](#) operation is shown in Listing 8.

```

1 def callback(ch, method, properties, body):
2     message_dict = json.loads(body_dict['oslo.message'])
3     object_dict = message_dict['args']['instance']['nova_object.
        data']
4     openstack_operation_name = message_dict['method']
5     openstack_instance_uuid = object_dict['uuid']
6     openstack_instance_state = object_dict['vm_state']

```

Listing 8: Example of RabbitMQ message syntax

[RabbitMQ](#) does not only send messages for [VNF](#) operations, but also events named `external_instance_event`. These events signal completed [VNF](#) operations and state changes in [VNF](#) instances.

The steps added to [VNF](#) start, suspension, resume and migrate are shown in the extended activity diagrams in Chapter 4 Figures 13, 14, 15 and 16 respectively. The Python code for trust checks in extended [VNF](#) operations is similar to the code for performing trust checks in OpenStack filters; therefore, it is not documented in greater detail.

In addition to doing trust checks, the new trusted [RabbitMQ](#) consumers add entries to the attestation server. These entries are [VNF](#) instance entries, shown in Table 5, and migration records entries, shown in Table 6. The [VNF](#) instance entries tracks the status and state of [VNF](#) instances at all times and gets updated according to data found in [RabbitMQ](#) messages. Furthermore, the [VNF](#) instance entries are used to keep the hash values of a [VNF](#) image upon suspension and to link [VNF](#) instances to migration records. The migration record entry is used to verify that the migrated [VNF](#) image is the correct one and that the receiver is the correct hypervisor. Both of these added entries are signed with the hypervisors [TPM](#). The [TPM](#) commands for hashing and signing are shown in Listing 9.

```

1 $ tpm2_hash -H e -g sha256 -o hash_output.hash -t validation.ticket
   hash_input
2 $ tpm2_sign -k 0x81010003 -m sign_input -s signature.sig -g sha256 -t
   validation.ticket

```

Listing 9: TPM hash and sign

Field name	Description
<code>_id</code>	Database ID of the VNF instance element.
<code>previous_suspend_hash_list</code>	A list of expected hashes renewed every VNF instance suspension.
<code>kind</code>	What kind of entry it is.
<code>name</code>	Name of the VNF instance element.
<code>openstack_id</code>	OpenStack UUID of the VNF instance element.
<code>status</code>	Trust status of the VNF instance element.
<code>timestamp</code>	Time when this entry was made to the database.
<code>original_image_openstack_id</code>	OpenStack UUID of the VNF image element this VNF instance element is based upon.
<code>state</code>	The current state of the VNF instance.
<code>migration_record</code>	The record of any migration actions taken by the VNF instance.
<code>running_on</code>	The element on which the VNF instance runs.
<code>signature</code>	Signature of the <a href="#">TPM AK</a> from the element that added the entry.

Table 5: VNF instance element fields

<code>_id</code>	Database ID of the migration record.
<code>completed</code>	If the instance has started on the new hypervisor.
<code>from_host</code>	The hypervisor the instance has migrated from.
<code>to_host</code>	The hypervisor the instance has migrated to.
<code>from_instance</code>	The instance entry pre-migration.
<code>to_instance</code>	The instance entry post-migration.
<code>kind</code>	What kind of entry it is.
<code>openstack_id</code>	OpenStack UUID of the VNF instance element.
<code>status</code>	Trust status of the migration.
<code>timestamp</code>	Time when this entry was made to the database.
<code>transfer_hash_list</code>	A list received VNF instance hashes.
<code>signature</code>	Signature of the <a href="#">TPM AK</a> from the element that added the entry.

Table 6: Migration record fields

## 5.7 User Auditing

All the actions described in this chapter creates events. These events are sent to the attestation server through its [REST API](#) and are meant for enabling user auditing of the system. By looking at the events, a user can verify the information used for a trust decision and do not have to trust the central attestation server. There are many different events, as they document all actions, and some example events can be found in [Appendix D Section D.3](#). This thesis does not automate any event reasoning.

## 5.8 Summary

This Chapter has shown how to implement a state-of-the-art trusted [NFV](#) cloud. The implementation included elements from base OpenStack, from previous trusted cloud solutions and all the extensions proposed in [Chapter 4](#).

This extended trusted cloud implementation added an attestation server to the [NFV](#) architecture. The attestation server was used for storing and verifying measurements at critical points during the cloud operation. These measurements checks were implemented for hardware elements, [VNF](#) images and [VNF](#) instances. Hardware elements were checked during boot time and run time, [VNF](#) images were checked during initialization and deployment while [VNF](#) instances were checked during a set of [VNF](#) operations. All the trust information gained by the measurement checks were distributed and made auditable through the attestation server.

The next Chapter evaluates the trusted cloud extensions and this implementation.

## 6 Evaluation

This Chapter evaluates the trusted [NFV](#) implementation and trust extensions added by this thesis. The evaluation criteria was given in Chapter 1, where this thesis defined trust as the confidence in the integrity of hardware and software throughout their life cycles and set the aim to fulfill the [NFV](#) specified goal to integrity protect hardware and software [11].

Part of this evaluation has been done in previous chapters. Chapter 3 reviewed current solutions and discovered several limitations. These limitations were solved or mitigated through extensions introduced in Chapter 4 and implemented in Chapter 5. With these implemented extensions, this thesis has created a stronger confidence in the integrity of hardware and software in an [NFV](#) cloud.

The remainder of this Chapter finishes this evaluation, reviews trusted [NFV-aaS](#) with the added trust extensions and measures the performance of the thesis implementation.

### 6.1 Improvements over Existing Solutions

Existing trusted cloud solutions have several limitations that were described in Section 3.7. All of these have been solved or mitigated by this thesis.

**All existing implementations depend on Intel CIT for parts of their solution.** The thesis does not depend on [Intel CIT](#) for any parts of its solution.

**Boot time measurements are not extended into run time in any [NFV](#) cloud implementation.** This thesis extends boot time measurements into run time with Linux [IMA](#) and [SELinux](#).

**OpenStack configuration is not measured in any OpenStack implementation or research.** This thesis measures the OpenStack configuration with run time measurements.

**Only a minimal set of OpenStack [VNF](#) operations are covered in existing implementations.** This thesis extends the set of trusted OpenStack [VNF](#) operations and introduces a new method to support an even larger set of operations. However, this thesis does not cover all OpenStack operations.

**Logging in current implementations is limited, which makes auditing trust decisions difficult.** This thesis adds extensive logging to all trust operations and allows for extensive auditing of trust decisions via an attestation server.

## 6.2 Trusted NFVIaaS

While earlier thesis Sections have discovered and mitigated **NFV** trust limitations from an architectural view, this Section performs the final evaluation of the trusted **NFVIaaS** use case. The use case was presented in Section 2.6 and extended in Section 3.6. The steps below describe the **NFVIaaS** success scenario steps from Section 2.6.1 and compares them to previous state-of-the-art.

**Service provider adds trusted hardware elements to the cloud.** The implementation in this thesis measures **CRTM**, **SRTM** and **DRTM** in a hardware element. This was also done in earlier implementations [34, 59]. With these measurements, a service provider can add trusted cloud hardware elements.

**Service provider installs a trusted OpenStack configuration.** This thesis adds run time measurements that measures the integrity of a OpenStack installation and shuts down **VNF** operations if any OpenStack configuration file changes. No run time measurements were done in existing implementations [34, 59].

Therefore, a service provider now has the new option of installing trusted OpenStack software.

**Cloud tenant adds a trusted VNF image.** This thesis adds **VNF** images using both measurements and signatures. In addition, new **VNF** images are created as a result of suspend and migrate. Earlier implementations had either just measurements [34] or a combination of measurements and signatures [59]. None of them added new **VNF** images due to **VNF** operations.

A cloud tenant now has the same amount of trust in its own added images as current state-of-the-art. This thesis adds trusted **VNF** images that are automatically created and added to the cloud as needed. This enables more **VNF** operations, but does not affect cloud tenant added **VNF** images.

**Cloud tenant deploys a VNF image on trusted hardware.** This thesis adds trusted workload placement that depend not only on hardware element boot time measurements, but also run time measurements. The run time measurements extend the level of trust offered by existing solutions [34, 59].

As with previous solutions, a cloud tenant can deploy **VNF** images on trusted hardware. However, the hardware trust level has been increased.

**Cloud tenant performs trusted **VNF** operations.** This thesis added more **VNF** operations to the trusted **NFV** cloud, including changing hypervisor through migration. Existing implementations covered either no **VNF** operations [59] or a small subset of operations on the same hypervisor [34].

With this thesis, a cloud tenant can perform more trusted **VNF** operations than before.

**Cloud tenant audits the trust decisions.** This thesis added auditability to all trusted actions, both by the trust solution and by the **VNF** instances. This improved existing implementations who either provided no audit log [34] or only an audit log of hardware actions [59].

With the implementation in this thesis, a cloud tenant can audit all trust decisions taken in the **NFV** cloud.

## 6.3 Performance

To measure the performance of the implementation, all covered **VNF** operations have been timed. This Section first measures the performance, then evaluates the result.

### 6.3.1 Performance Measurements Environment

The performance test were taken in the running OpenStack implementation. The OpenStack servers were Nokia AirFrame machines and their full specification can be found in Appendix A. The images used for time testing were three different Linux distributions and their specification is seen in Table 7. All tests were run on a local network, so any network latency would be minimal.

Image name	Linux distribution	Size
Small	Cirros	12.65 MB
Medium	Ubuntu	276.56 MB
Large	CentOS	1.27 GB

Table 7: Images used for time testing



### 6.3.2 Performance Measurements

Measurements were taken not only for the extended VNF operations proposed by this thesis, but also for the individual steps in these operations.

The time usage of base OpenStack operations and extended operations varied; therefore, the stated time is the average of 10 runs. The extended operations were done using only a SHA-256 hash and not the complete set of MD5, SHA-1 and SHA-256. All the operations were performed on the same servers, and the servers were not running any workload beyond OpenStack. Start, suspend and resume were done on AirFrame 2 while migration was done from AirFrame 2 to AirFrame 3.

Table 8 compares the total time and time difference of OpenStack operations both with and without extensions. Table 9 and Table 10 shows the time for the separate operations.

Operation name	Base average time	Extended average time	Percentage added
Start small image	11.21s	12.72s	13,47 %
Start medium image	18.31s	21.98s	20,04 %
Start large image	24.56s	33.23s	35,30 %
Suspend small image	5.34s	8.26s	54,68 %
Suspend medium image	9.11s	13.64s	49,73 %
Suspend large image	9.86s	19.36s	96,35 %
Resume small image	5.28s	7.07s	33,90 %
Resume medium image	9.12s	12.52s	37,28 %
Resume large image	9.76s	19.24s	97,13 %
Migration small image	20.54s	25.27s	23,03 %
Migration medium image	50.37s	56.34s	11,85 %
Migration large image	62.82s	74.16s	18,05 %

Table 8: Time difference of base OpenStack operations and extended OpenStack operations

Operation	Time small image	Time medium image	Time large image
MD5 hash	0.06s	0.70s	2.52s
SHA-1 hash	0.07s	0.79s	3.02s
SHA-256 hash	0.13s	1.75s	7.14s

Table 9: Time for image dependent operations

### 6.3.3 Performance Evaluation

The implemented extensions have a large effect on performance and the percentage of added time ranges from 11.85 % to 97.13 %. Most of the added time comes from image hashing and TPM operations. Therefore, the time added is related mostly to image size and not to the operation performed.

Operation	Time
TPM SHA-256 hash	1.02s
TPM SHA-256 quote	0.68s
TPM SHA-256 sign	1.79s
TPM SHA-256 verify	1.69s
OpenSSL SHA-256 sign	0.03s
OpenSSL SHA-256 verify	0.01s

Table 10: Time for image independent operations

The added time can be minimised by signing with OpenSSL or by using a quicker hashing algorithm. However, this will lead to a lower level of trust as the TPM is used for host verification and quicker hashing algorithms are easier to break.

Although the implemented extension have a large effect on performance, the most impacted VNF operations do not affect the telecommunications consumer directly. Both start, suspend and resume instance will mostly affect power usage for the cloud provider. The only measured VNF operation directly affecting the consumer is migration. Migration has the smallest percentage of added time and it might also be the operation benefiting the most from added trust due to changing hypervisor.

The level of trust needed should be balanced against the need for highest possible performance and not all VNFs benefit from running as trusted. It is also possible to only add trust to some operations.

## 6.4 Summary

This Chapter has evaluated the added extensions and implementation of this thesis. All the trust goals were met and all the NFVaaS success scenario steps were fulfilled. Although the trust goals were met, the performance cost for VNF operations were high. However, the performance impact affect mostly the cloud provider. Nevertheless, the trust and performance trade-off should be considered carefully for each VNF. The next Chapter concludes this thesis and presents future work.

## 7 Conclusion and Future Work

This Chapter concludes the thesis and proposes future work. The conclusion summarizes the thesis aim, method and results, while future work outlines how to improve the solution in this thesis and extend it further.

### 7.1 Conclusion

This thesis has investigated how to add trust to a **NFV** cloud. We have looked into the **NFV** architecture and how it is most commonly implemented in OpenStack. In **NFV** on OpenStack there were three high level architectural concepts that needed to become trusted. These were the **NFVI**, **MANO** and **VNF** concepts. In addition we have reviewed trust in the **NFVIaaS** use case. This use case required trust in the OpenStack **NFV** entities, which were hardware elements, **VNF** images and **VNF** instances.

The **NFVI** comprises the hypervisors running the **NFV** cloud. We reviewed how hypervisor trust was added by earlier implementations and existing research. The most popular approach was using boot time measurements stored in a **TPM**. This thesis added another layer to this by introducing run time measurements. Run time measurements were done with Linux **IMA**.

**MANO** is the management layer of **NFV**. In **OPNFV** on OpenStack, **MANO** refers to the OpenStack controller. The OpenStack controller actions are governed by configuration files which can not be measured at boot time. None of the existing implementations has extended boot time measurements into run time. Even though some existing research utilizes run time measurement of files, no research measures the OpenStack installation itself. This thesis added trust to **MANO** by tagging files with **SELinux** and measuring them with Linux **IMA**. These measurements were used to seal important configuration in the **TPM** so that all **VNF** operations were shut down if the OpenStack configuration changed.

**NFV** virtualizes the network functions of telecommunications and allows them to run as **VNFs**, which are the virtual workload running on the **NFVI**. **VNF** trust was implemented in previous implementations only for a very limited number of operations and operations such as **VNF** migrate were not covered. This thesis introduced a method of adding trust to **VNF** operations by intercepting the internal communication of OpenStack. This new method was applied to a larger set of **VNF** operations than earlier covered and provided an alternative to modifying OpenStack source code. This method could easily be extended to cover most OpenStack operations.

In addition to adding trust to **NFVI**, **MANO** and **VNFs**, this thesis added an attestation server. This server tracked all the cloud elements and created events of

trust decisions made by the server. These events were made available to all users. In previous implementations, users had limited options to review trust decisions. With the attestation server events, users can redo the measurements themselves and do not have to blindly trust the attestation server.

This thesis aimed to enable a higher level of integrity protection of the hardware and software in a **NFV** cloud. This aim was evaluated by measuring the level of trust in the **NFV** architecture and in the **NFVIaaS** use case. For both of these, the trust aim was reached. However, the performance costs for **VNF** operations were quite high. Therefore, this thesis suggests that the proposed trust extensions should be used in situations where increased trust is more important than maximized performance or when **VNF** operations are rarely performed.

## 7.2 Future Work

There are large possibilities for future work in creating trusted **NFV** clouds, as **NFV** itself is quite recent. This Section proposes future work within the thesis scope of integrity measurements. Other important security features are out of scope, including secure communication and access control.

Infrastructure trust is in this thesis only based on **TPM 2.0**. Future work should expand on infrastructure trust and enable other security architectures, such as other hardware or software security modules. Infrastructure trust can also be expanded into virtual machines, through technologies such as virtual **TPMs** or software **TPMs**.

This thesis made the simplification that **VNFs** and **VMs** had a one-to-one relation. Future work should also cover the cases where a **VNF** is deployed over multiple **VMs** and also include extra **VNF** configuration data.

OpenStack is not the only **NFV** platform and trust in other platforms should also be considered. Especially Docker is relevant for telecommunications and trust concepts explored in this thesis would also be important for Docker.

A fully functional **NFV** cloud would have smaller physical edge elements in addition to the **NFVI** infrastructure servers. Future work should expand trust to these more resource constrained elements.

Previous trusted **NFV** implementations and this thesis only consider trust as a binary trusted or not trusted decision. Future work could remove this binary limitation and develop scalable trust.

Finally, the events created by this thesis implementation can be utilized to reason over the system, for example to find the root cause of failures. This could ease in error correction and help system administrators find the errors in their systems.

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## A Hardware Specification

This Appendix shows the hardware used for the OpenStack implementation in this thesis. Hardware details are shown in Tables [A1](#), [A2](#) and [A3](#).

Name	AirFrame 1 (A1)
Processor	Intel(R) Xeon(R) CPU E5-2630 v3 @ 2.40GHz - 31 Cores
System Memory	62GB
Hard Drive	1.8TB LVM
Operating System	Ubuntu 17.10 with kernel 4.10.0-42-generic
OpenStack version	Pike
OpenStack roles	Controller and compute
TPM version	2.0

Table A1: AirFrame 1 hardware specification

Name	AirFrame 2 (A2)
Processor	Intel(R) Xeon(R) CPU E5-2630 v4 @ 2.20GHz - 32 cores
System Memory	62GB
Hard Drive	1.5TB LVM
Operating System	Ubuntu 17.10 with kernel 4.10.0-42-generic
OpenStack version	Pike
OpenStack role	Compute
TPM version	2.0

Table A2: AirFrame 2 hardware specification

Name	AirFrame 3 (A3)
Processor	Intel(R) Xeon(R) CPU E5-2680 v4 @ 2.40GHz - 53 cores
System Memory	125GB
Hard Drive	1.8TB LVM
Operating System	Ubuntu 17.10 with kernel 4.10.0-42-generic
OpenStack version	Pike
OpenStack role	Compute
TPM version	2.0

Table A3: AirFrame 3 hardware specification

## B OpenStack Details

This Appendix contains the full state diagram for [VNF](#) instances and a list of the OpenStack configuration files.

### B.1 VNF State Diagram

[VNF](#) instances can perform many operations that change the state of the [VNF](#). A full state diagram is shown in [Figure B1](#).

### B.2 Configuration Files

An OpenStack installation is configured through a set of configuration files. This sections lists the configuration files for the OpenStack services Glance, Keystone, Neutron, Horizon and Nova.

```
1 /etc/glance/glance-api.conf
2 /etc/glance/glance-cache.conf
3 /etc/glance/glance-registry.conf
4 /etc/glance/glance-scrubber.conf
5 /etc/glance/glance-registry-paste.ini
6 /etc/glance/glance-api-paste.ini
7 /etc/keystone/keystone.conf
8 /etc/keystone/keystone-paste.ini
9 /etc/neutron/neutron.conf
10 /etc/neutron/dhcp_agent.ini
11 /etc/neutron/l3_agent.ini
12 /etc/neutron/api-paste.ini
13 /etc/neutron/metadata_agent.ini
14 /etc/neutron/plugins/evs/evs_plugin.ini
15 /etc/openstack_dashboard/local_settings.py
16 /etc/apache2/2.4/httpd.conf
17 /etc/apache2/2.4/conf.d/openstack-dashboard-http.conf
18 /etc/nova/nova.conf
19 /etc/nova/api_paste.ini
```

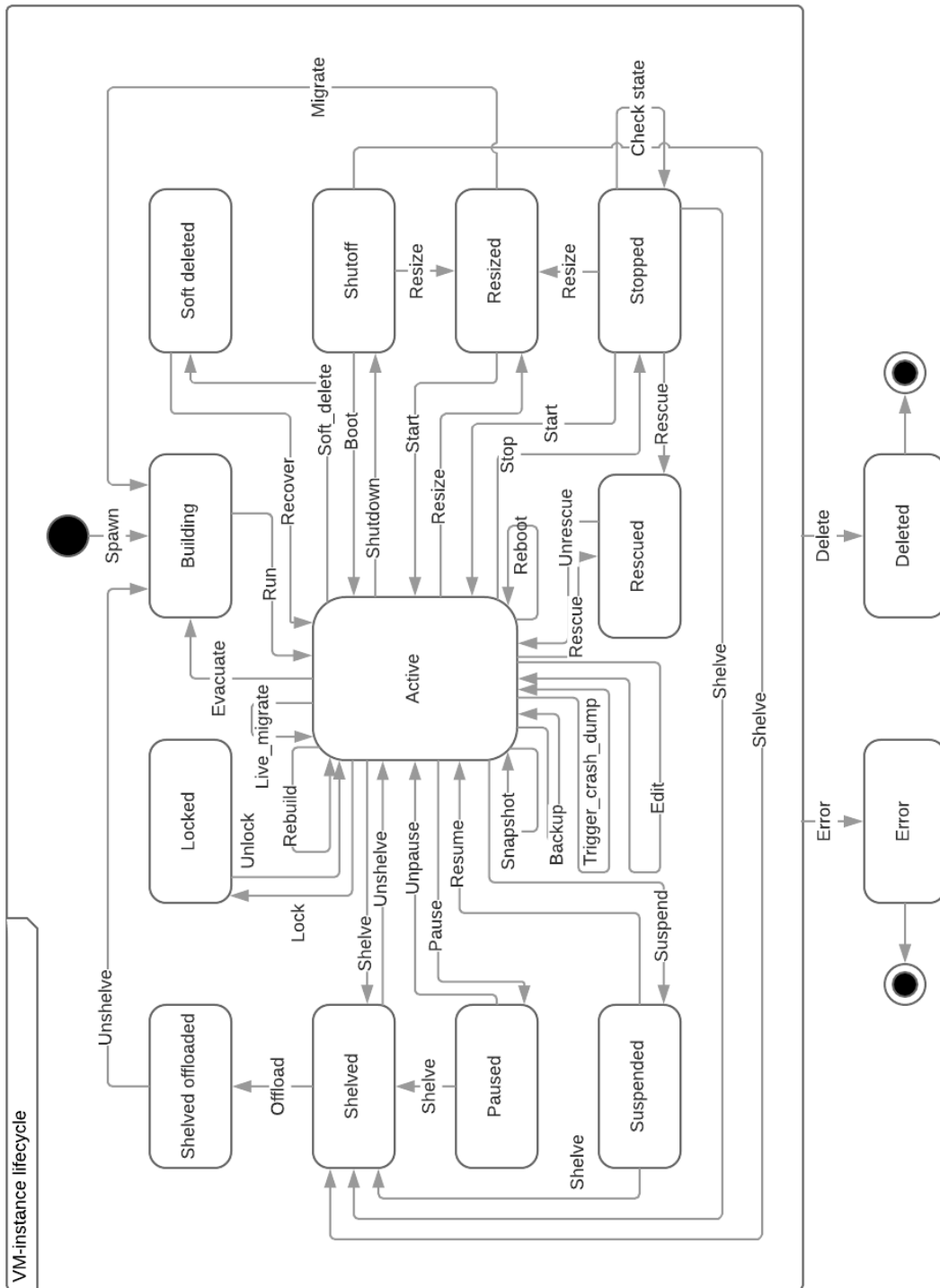


Figure B1: Full OpenStack VM state diagram

## C Enabling Trust

To enable trust in a system many software solutions need to work together. This Appendix shows how to use tboot, Linux IMA and SELinux for secure system measurements.

### C.1 Tboot

These steps enable tboot<sup>25</sup> for a server with TPM 2.0 running Ubuntu with Linux-4.10.0-42 kernel. Unless otherwise defined, tboot fills the DRTM in PCRs 17 and 18.

- Enable TPM in BIOS then reboot.
- Enable Intel TXT, SMX and VMX in BIOS then reboot.
- Check that TPM drivers are working and that the TPM can be found with `$ ls /dev/ | grep tpm`.
- Install tboot with `$ apt install tboot`.
- Update grub with `$ update-grub` or `$ update-grub2` depending on local grub version.
- Reboot computer and choose tboot in boot menu. This can be made automatic by updating `/etc/default/grub` and reloading grub.
- Check for valid boot with `txt-stat | grep secret`. This should return `secrets: TRUE`.

### C.2 Linux IMA

Linux IMA<sup>26</sup> is part of the Linux kernel. Many recent Linux distributions have it included; however, if it is not included the kernel would have to be rebuilt with Linux IMA to be able to use it. The following steps enables Linux IMA in Ubuntu with Linux-4.10.0-42 kernel.

- Check that IMA exists in securityfs with `$ ls /sys/kernel/security/ | grep ima`.

---

<sup>25</sup><https://sourceforge.net/projects/tboot/>

<sup>26</sup><https://sourceforge.net/projects/linux-ima/>

- If [IMA](#) does not exist, upgrade to a newer kernel or rebuild current kernel with IMA enabled.
- Check that securityfs is mounted with `$ mount | grep securityfs`.
  - If it is not mounted, mount with `$ mount -t securityfs securityfs /sys/kernel/security`.
- Define a policy for what to measure. The default policy can be found at `/etc/ima/ima-policy`.
- Add one or more [IMA](#) policies to grub. To enable TCB default policy, add `ima_policy=tcb` to `GRUB_CMDLINE_LINUX_DEFAULT` in `/etc/default/grub`.
- Reload grub and reboot to enable grub changes.

### C.3 SELinux Tags for Linux IMA Measurements

This Section presents the process of measuring the main OpenStack Nova configuration file, which is stored in `/etc/nova/nova.conf`. This measurement will be written by Linux [IMA](#) and stored in [TPM PCR 14](#). A full list of OpenStack configuration files can be found in [Appendix B Section B.2](#).

This process depends on SELinux and Linux IMA being enabled in the Linux kernel. The process of enabling Linux IMA is described in [Section C.2](#). The following steps measures `/etc/nova/nova.conf` by marking it using SELinux types and adding the SELinux tag to the Linux [IMA](#) policy.

- Create a `openstack_measure` module.
  - `$ mkdir /usr/share/selinux/packages/openstack_measure`
  - Make file `/usr/share/selinux/packages/openstack_measure/openstack_measure.te` with the content below.
 

```
policy_module(openstack_measure, 1.0)
type openstack_measure_t;
```
- Build module with `$ make -f /usr/share/selinux/devel/Makefile`
- Load module with `$ semodule -i openstack_measure.pp`
- Tag `/etc/nova/nova.conf` with `openstack_measure_t` using `$ chcon -v --type=openstack_measure_t /etc/nova/nova.conf`

- Tell [IMA](#) to measure all files marked with `openstack_measure_t` in [PCR 14](#) by adding `measure func=FILE_CHECK obj_type=openstack_measure_t pcr=14` to the default [IMA](#) policy in `/etc/ima/ima-policy`.
- Reboot to enable [IMA](#) measurements.



## D Attestation Server Details

This Appendix lists the attestation server [REST API](#) and presents example attestation server entries and events.

### D.1 REST API

This Section has the [REST API](#) for the attestation server block added to the [NFV](#) architecture, which can be seen in [Table D1](#).

Endpoint	Methods	Description
/element/tpm	POST	Add <a href="#">TPM</a> element.
/element/vnf_image	POST	Add VNF image.
/element/vnf_instance	POST	Add VNF instance.
/element/<database_id>	GET   DELETE   PUT	Get or modify an element.
/element/openstack/<openstack_id>	GET   DELETE   PUT	Get or modify an element.
/event	POST	Add event.
/policy	POST	Add policy.
/policy/<database_id>	GET   DELETE   PUT	Get or modify a policy.
/tpm_quote	POST	Add TPM quote.
/tpm_quote/<database_id>	GET	Get a TPM quote.
/record	POST	Add record.
/record/<database_id>	GET   DELETE   PUT	Get or modify a record.

Table D1: Attestation server REST API

### D.2 Example Database Entries

This Section has example values for database entries implemented in this thesis.

```

1 {
2   "_id": {
3     "$oid": "5b4894d419af5157a0f61260"
4   },
5   "ak": "-----BEGIN PUBLIC KEY-----
6   MIIBIjANBgkqhkiG9w0BAQEFAAOCAQ8AMIIBCgKCAQEAmZtDWjzQFuZPi
7   qkDLOJhF3kWsu0pXT1zzjwDkbMBYtVnZB99c4w8afG5hQWNswqaDg/tik
8   B55vJ7tS94tPM8T/CvWt0qLoR0z8Pg1o+V2WcTJEnqYi/X9Rs0e9jNNRz
9   rp40LquRR6BCJIwt9tDvW\n4GnU2AEDpRDodUGYUsN4tN84sYLesDKCZc
10  `VjEInxBidWoA4CUPdJ3NexZAIgYRFsXgi3joPTYne2ySKhKpTV8g7rkO
11  9Jjkfd7EE00vvPx4aQ2ke0tWBGDi+HwTrBMOzNRKo5mNnS32H9cl0yeaC
12  6qkAio2LvbwhJMEL1AAOmgmAAEc4P0fSwgqZJdkXfhUmmwIDAQAB
13  -----END PUBLIC KEY-----",
14  "ek": "-----BEGIN PUBLIC KEY-----

```

```

15 MIIBIjANBgkqhkiG9w0BAQEFAAOCAQ8AMIIBCgKCAQEAh6V2QY/i15sdH
16 j+U4Y9r\nWSUU6jejZPScL+8K0LWrCxQmEycLGTNMwXw4f0TabeIKPpY2
17 BcmWRKWJ7c2a/b4vp7exqgYGBru0B//qdrZvcth1OKEZUsrIFYGvORjUf
18 aSAoMiB4LQkqpEf/1jxO/zI6EanTHm1oN/qqHh2AkKHJUJ2rQUobwE+2w
19 xEmvnW7AVD67xliBfGczC9LDbwDOagDalbLRLeiFt1qTj23tDhJGjtYqK
20 vLMBTp4mzBukAqnuEEU+GwX8/Bdy7NPGQE/GVXvfB0q6XHHgn8EQSNTNs
21 zPUwMhPRgbL3mJ8NWoQ+BuNSdnifC7+M3WCfi0TVUePb/QIDAQAB
22 -----END PUBLIC KEY-----",
23 "ip": "10.144.104.19",
24 "kinds": [
25     "NFVIElement::TpmMachine",
26     "NFVIElement::Machine"
27 ],
28 "policy_list": [
29     "5b4da33c352c656e9247a043",
30     "5b3f081b19af5170379043a0"
31 ],
32 "name": "compute",
33 "openstack_id": "4d4542b2-37a6-44fe-9c84-45bd750b5b90",
34 "status": true,
35 "timestamp": {
36     "$date": 1533022285447
37 },
38 "uname": "Linux compute 4.10.0-42-generic #46-Ubuntu SMP Mon Dec 4 14:38:01
39     UTC 2017 x86_64 x86_64 x86_64 GNU/Linux\n",
40 "signature": "eqh7JzKIdXDpdMdJsjEic7XEku43bJmYm/nKPu++xJn+
41 Zj7ijGZ6HbHkBsyoDoUfSrfpcMYgZwu2pMNLcAancw/2y+RBSa66s3x9nX
42 1I3lfU0wAWinp43xh9d/Jkux9H4cWLMb5IWYXuJsTJ6CDpEBdjME/xIx4M
43 L13S8K95vu3x4/ul7A4eul2NDkJ6tok7jZ1NWGCyL5pB2znHT4RHkLwU1i
44 sTVRN 8iJxUh6mrU2ycBUop09eS3IQhB4Jm92BQR2deiqNZWnbFrPXeqX
45 NX/X9IANVgQEca1dHI5tD7HUioSNnUncaTe+ZIctoi8P4yN8j0z4EaUmBe
46 a2qjUF7KeB7XdWrHTXjfaorqwJbKu85QHsQwmsoSHr2Yc4pYXEuANoAfjO
47 xGJABR4rn6949TRQh+puXqXHRmVqaiLo9heZAtzckrUANWGPdBAfTDD7ka
48 ryuXZP4rfLsMSPC65kWxOT9JU4dVjCp7mO4/nvEFGdrEybdPUNALKkp4uP
49 CxJfU+ZM9zu+EV7d1oRvokXT22QBPfcRAKQhXofnMLYUhwSjNUqNCjzP+h
50 Bg0RlySyw//IzoGqhJ2C1A4pNcZ+2QVqn27qeb/Ng2ZNTXhcOKyycA3tma
51 oTLpTxuH26akXFMudma6Zli1s6xLkxBJW+hT+nM5kRkFoSEfVJigBuRVEi
52 /ZE="

```

Listing 10: Example TPM element entry

```

1 {
2   "_id": {
3     "$oid": "5b4d9b71352c656e92479f19"
4   },
5   "expected_value": "Sl7gGpD2R7mcGNzKwd/6huDsspWsJ4GwpNZbe+3M1Yw=",

```

```

6  "kind": "Policy :: TPM2.0",
7  "name": "compute's CRTM (SHA1)",
8  "pcrs": "sha1:0",
9  "timestamp": {
10     "$date": 1531812721688
11  },
12  "signature": "eqh7JzKIdXDpdMdJsJic7XEku43bJmYm/nKpu++xJn+
13  Zj7ijGZ6HbHkBsyoDoUfSrfpcMYgZwu2pMNLcAancw/2y+RBSa66s3x9nX
14  1I3lfU0wAWinp43xh9d/Jkux9H4cWLMb5IWYXuJsTJ6CDpEBdjME/xIx4M
15  L13S8K95vu3x4/ul7A4eul2NDkJ6tok7jZ1NWGCyL5pB2znHT4RHkLwU1i
16  sTVRN 8iJxUh6mrU2ycBUop09eS3IQhB4Jm92BQR2deiqNZWnbFrPXeqX
17  NX/X9IAAnVgQEca1dHI5tD7HUioSNnUncaTe+ZIctoi8P4yN8j0z4EaUmBe
18  a2qjUF7KeB7XdWrHTXjfaorqwJbKu85QHsQwmsoSHr2Yc4pYXEuANoAfjO
19  xGJABR4rn6949TRQh+puXqXHrmVqaiLo9heZAtzckrUANWGPdBAfTDD7ka
20  ryuXZP4rfLsMSPC65kWxOT9JU4dVjCp7mO4/nvEFGdrEybdPUNALKkp4uP
21  CxJfU+ZM9zu+EV7d1oRvokXT22QBPfcRAKQhXofnMLYUhwSjNUqNCjzP+h
22  Bg0RlySyw//IzoGqhJ2C1A4pNcZ+2QVqn27qeb/Ng2ZNTXhcOKyyca3tma
23  oTLpTxuH26akXFMudma6Zli1s6xLkxBJW+hT+nM5kRkFoSEfVJigBuRVEi
24  /ZE="
25  }

```

Listing 11: Example policy entry

```

1  {
2    "_id": {
3      "$oid": "5b5af087352c6520115e5300"
4    },
5    "hash_list": [
6      {
7        "hash": "7c921ce7b7696c80d5e04914a8de5d3512cb48dedacde
8        f79434588d9c1570701",
9        "hash_type": "sha256"
10     },
11     {
12       "hash": "e924d1602ff88edca0a02e2ff129a810",
13       "hash_type": "md5"
14     },
15     {
16       "hash": "cb6f44d6986d407fbb2be638f1f44c67d1562d42",
17       "hash_type": "sha1"
18     }
19   ],
20   "kinds": [
21     "VNFElement::VNFImage"
22   ],
23   "name": "Ubuntu_trusted",
24   "openstack_id": "dcb8967e-890a-43ab-bf49-55893575fe34",

```

```

25 "status": true,
26 "timestamp": {
27   "$date": 1532689593964
28 },
29 "signature": "eqh7JzKIdXDpdMdJsJie7XEku43bJmYm/nKPU++xJn+
30 Zj7ijGZ6HbHkBsyoDufSrfpcMYgZwu2pMNLcAancw/2y+RBSa66s3x9nX
31 1I3lfU0wAWinp43xh9d/Jkux9H4cWLMb5IWYXuJsTJ6CDpEBdjME/xIx4M
32 L13S8K95vu3x4/ul7A4eul2NDkJ6tok7jZ1NWGCyL5pB2znHT4RHkLwUli
33 sTVRN 8iJxUh6mrU2ycBUop09eS3IQhB4Jm92BQR2deiqNZWnbFrPXeqX
34 NX/X9IAAnVgQEca1dHI5tD7HUioSNnUncaTe+Zlctoi8P4yN8j0z4EaUmBe
35 a2qjUF7KeB7XdWrHTXjfaorqwJbKu85QHsQwmsoSHr2Yc4pYXEuANoAfjO
36 xGJABR4rn6949TRQh+puXqXHrmVqaiLo9heZAtzckrUANWGPdBAfTDD7ka
37 ryuXZP4rfLsMSPC65kWxOT9JU4dVjCp7mO4/nvEFGdrEybdPUNALKkp4uP
38 CxJfU+ZM9zu+EV7d1oRvokXT22QBPfcRAKQhXofmMLYUhwSjNUqNCjzP+h
39 Bg0RlySyw//IzoGqhJ2C1A4pNcZ+2QVqn27qeb/Ng2ZNTXhcOKyyca3tma
40 oTLpTxuH26akXFMudma6Zli1s6xLkxBJW+hT+nM5kRkFoSEfVJigBuRVEi
41 /ZE="
42 }

```

Listing 12: Example VNF image entry

```

1 {
2   "_id": {
3     "$oid": "5b6c0ffa352c65376cbc9fa2"
4   },
5   "element_id": "5b4894d419af5157a0f61260",
6   "kind": "Quote::TPM2.0",
7   "pcrs": {
8     "sha1": {
9       "0": "ae62d40b59561f52419a6dbb1fe3f589e7c67856",
10      "1": "b2a83b0ebf2f8374299a5b2bdfc31ea955ad7236",
11      "2": "b2a83b0ebf2f8374299a5b2bdfc31ea955ad7236",
12      "3": "b2a83b0ebf2f8374299a5b2bdfc31ea955ad7236",
13      "4": "b2a83b0ebf2f8374299a5b2bdfc31ea955ad7236",
14      "5": "870a58e79a43e9dcdd273b6efa9975d882ce7420",
15      "6": "b2a83b0ebf2f8374299a5b2bdfc31ea955ad7236",
16      "7": "4037336fa7bc0eabe3778fcff5fcd0ee6adcde3",
17      "8": "0000000000000000000000000000000000000000",
18      "9": "0000000000000000000000000000000000000000",
19      "10": "144851a7c93d96ceff3ab81eaa75ae021deb350f",
20      "11": "0000000000000000000000000000000000000000",
21      "12": "0000000000000000000000000000000000000000",
22      "13": "0000000000000000000000000000000000000000",
23      "14": "0000000000000000000000000000000000000000",
24      "15": "0000000000000000000000000000000000000000",
25      "16": "f0e5a9f7d5a33a281fff32e565cb407df5b191c1",
26      "17": "5ffa409f3d8bb8b339d9e7e9fbceca4a38d6dc817",

```

```

27     "18": "9b8547051d0e68839490e82f99a17d78e3e94fed",
28     "19": "0000000000000000000000000000000000000000",
29     "20": "0000000000000000000000000000000000000000",
30     "21": "          ffffffffffffffffffffffffffffffff          ",
31     "22": "          ffffffffffffffffffffffffffffffff          ",
32     "23": "0000000000000000000000000000000000000000"
33   },
34   "sha256": {
35     "0": "d8a76f44656e5b7ed75ddc6c19071d8594e99edb67c54c0f5f562a8bdaa26bbf",
36     "1": "3d458cfe55cc03ea1f443f1562beec8df51c75e14a9fcf9a7234a13f198e7969",
37     "2": "3d458cfe55cc03ea1f443f1562beec8df51c75e14a9fcf9a7234a13f198e7969",
38     "3": "3d458cfe55cc03ea1f443f1562beec8df51c75e14a9fcf9a7234a13f198e7969",
39     "4": "3d458cfe55cc03ea1f443f1562beec8df51c75e14a9fcf9a7234a13f198e7969",
40     "5": "c38c9900b691c6f2d8b5c4959e3548a14b7ba61713a194560c545c62c4b0b4a5",
41     "6": "3d458cfe55cc03ea1f443f1562beec8df51c75e14a9fcf9a7234a13f198e7969",
42     "7": "b5710bf57d25623e4019027da116821fa99f5c81e9e38b87671cc574f9281439",
43     "8": "0000000000000000000000000000000000000000000000000000000000000000",
44     "9": "0000000000000000000000000000000000000000000000000000000000000000",
45     "10": "0000000000000000000000000000000000000000000000000000000000000000",
46     "11": "0000000000000000000000000000000000000000000000000000000000000000",
47     "12": "0000000000000000000000000000000000000000000000000000000000000000",
48     "13": "0000000000000000000000000000000000000000000000000000000000000000",
49     "14": "0000000000000000000000000000000000000000000000000000000000000000",
50     "15": "0000000000000000000000000000000000000000000000000000000000000000",
51     "16": "4ca16202817eb69aba12b94c1410ba17f0d136879377bf9aeb62a117597870e2",
52     "17": "13271ef5faf9c806e07d33ca81837b7bb8bf2e112e72b7ee3d8e8fe0b8bb784e",
53     "18": "3d403e3eb24aa3a73a766f9782ab728bc9a94c5c11dab7734729aff2fdb2336",
54     "19": "0000000000000000000000000000000000000000000000000000000000000000",
55     "20": "0000000000000000000000000000000000000000000000000000000000000000",
56     "21": "          ffffffffffffffffffffffffffffffff          ",
57     "22": "          ffffffffffffffffffffffffffffffff          ",
58     "23": "0000000000000000000000000000000000000000000000000000000000000000"
59   }
60 },
61 "policy_id": "5b4d9b71352c656e92479f19",
62 "quote": {
63   "attested": "Sl7gGpD2R7mcGNzKwd/6huDsspWsJ4GwpNZbe+3M1Yw=",
64   "clock": 3497869051,
65   "extraData": "8RrHO3pRTf+bFGPFmkso4Q==",
66   "firmwareVersion": 1407374883832066,
67   "magic": "/1RDRw==",
68   "qualifiedSigner": "MXLdgzlTqCViuUynaGjeP3rXmiQyW0q1J6NWxxrABSY=",
69   "quoteFile": "/1
70     RDR4AYACIAczFy3YM5U6glYrlMp2ho3j9615okMltKtSejVscawAUmABDxGs
71     c7elFN/5sUY8WaSyjhAAAAANB9PvsAAADVAAAAQAABQAAAAARBAGAAAA
72     EABAMBAAAAIEpe4BqQ9ke5nBjcysHf+obg7LKVrCeBsKTWW3vtzNWM",
73   "resetCount": 213,
74   "restartCount": 1,

```

```

74   "safe": 0,
75   "signature": "ABQACwEAFoJb2HmsqGNkLv7+0IuvShY1c7Pt/wOf8N666OVW
76   cIbX5PzaUi1s6kdOGUKdnHzqnIFI2C6L+UWRE9EJVAX6lTPJbKlW3AWljfLAmA
77   bCwOZVJaeUplU+CITWWnvxq7zlvXIIXWESRPOodd93qJ+2+Xhc89lMslZUudr2
78   USVVvH+C6hgjxqX8XQtk9gJ0/UjIxG8pNKYIvBlDHjRud/FbNs3yItS0/hHtDs
79   Gg06LIDie/a0FiDOjTQ66OJHqBfUVCW5JZUWAAz2otzdWZ/nUy7EDbAaqrqLgE
80   uytyKrbV/5KngJlBsbPS5JqUBE808bEbp5zXliTmqzashytrmCMTA==",
81   "type": "gBg="
82 },
83 "timestamp": {
84   "$date": 1533808634631
85 }

```

Listing 13: Example quote entry

```

1 {
2   "VNF_image": "85a7cf0b-cd2f-429a-b3c3-44c88b923e4e",
3   "_id": {
4     "$oid": "5b6c4074352c65376cbc9faa"
5   },
6   "kinds": [
7     "VNFElement::VNFInstance"
8   ],
9   "migration_record": null,
10  "name": "test-vnf",
11  "openstack_id": "52de4f85-e12f-48cb-b958-9fd6df080737",
12  "previous_suspend_hash_list": [],
13  "running_on": "compute",
14  "state": "Request_to_start",
15  "status": true,
16  "timestamp": {
17    "$date": 1533821044910
18  },
19  "signature": "ABQACwEAGe9IekxuQcCX9MG7b+ztFNCmJYxC48Nb4AW8n/10Oh
20  6+ycnfauqKairv5A1/gS2sintZWSr06s/x4RUCKV2NC5Ja6Qnk+UqetQlpLN3F5T
21  ZRixgzX5yVamBUD9LvUJjiZsFfmQqQscKco3GsPQMTbklKAbIHS/vJmbK4jHE2d6
22  YURa+RG3qsa4dPESZcykItxt5eM8nYygflc9qp81JIJUHnSCycHaNwgErE3N0DFc
23  VIHESz2X2k+NDKy9KBwxb7Q91sg8S0pLZYAPAWvvKmUz0AAAn++
24   ueAcl5QY52dBQt
25   PUgAETRiYuI/75OcPbsEJbcRMp74ZK2UWFM/TWUVAJWw=="
26 }

```

Listing 14: Example VNF instance entry

```

1 {

```

```

2  "_id": {
3     "$oid": "5b6c4c7f352c65376cbca045"
4  },
5  "completed": true,
6  "from__host": "controller ",
7  "from__instance": "5b6c4c67352c65376cbca040",
8  "kind": "Record::Migration",
9  "openstack__id": "ced3eb65-8882-4fde-9fd6-3de72a93f4c5",
10 "status": true,
11 "timestamp": {
12     "$date": 1533824134428
13 },
14 "to__host": "compute",
15 "to__instance": "5b6c4c7f352c65376cbca044",
16 "transfer__hash__list": [
17     {
18         "hash": "a0392d5f2bee2ca6437591c7146860d43e319f438f34eeaf298607d23fdfa6d0",
19         "hash__type": "sha256"
20     },
21     {
22         "hash": "c890180c571e1677b12319eb3fb5e623e5aaf833",
23         "hash__type": "sha1"
24     },
25     {
26         "hash": "2c10fdfa4816eda0aa3afc5e38cc38f9",
27         "hash__type": "md5"
28     }
29 ],
30 "signature": "ABQACwEAGe9IekxuQcCX9MG7b+ztFNCmJYxC48Nb4AW8n/10Oh
31 6+ycnfauqKairv5A1/gS2sintZWSr06s/x4RUCKV2NC5Ja6Qnk+UqetQlpLN3F5T
32 ZRixgzX5yVamBUD9LvuJiZsFfmQqQscKco3GsPQMTbklKAbIHS/vJmbK4jHE2d6
33 YURa+RG3qsa4dPESZcykItxt5eM8nYygf9c9qp81JIJUHnSCycHaNwgErE3N0DFc
34 VIHESz2X2k+NDKy9KBwxb7Q91sg8S0pLZYAPAWvvKmUz0AAAn++
35 ueAcl5QY52dBQt
36  PUGAETRiYuI/75OcPbsEJbcRMp74ZK2UWFM/TWUVAJWw=="
37 }

```

Listing 15: Example migration record entry

### D.3 Example Event Entries

This Section lists example events for OpenStack scheduler filter and [VNF](#) suspension element update.

```

1  {
2  "_id": {

```

```

3   "$oid": "5b62d836352c65376cbc9ec4"
4   },
5   "event_type": "OpenStack filter",
6   "hypervisor_name": "compute",
7   "hypervisor_openstack_id": "4d4542b2-37a6-44fe-9c84-45bd750b5b90",
8   "nonce": "7ad72cea-9a26-4924-aeaf-f27997d3b08e",
9   "result": true,
10  "result_reasons": [
11    "Trust level set to True",
12    "Hypervisor found in attestation server ",
13    "Hypervisor and instance are both trusted",
14    "Image found in attestation server ",
15    "Expected sha256 has was
        e137062a4dfbb4c225971b67781bc52183d14517170e16a3841d16f962ae7470.\n
        Measured hash was
        e137062a4dfbb4c225971b67781bc52183d14517170e16a3841d16f962ae7470.",
16    "Expected md5 has was f8ab98ff5e73ebab884d80c9dc9c7290.\n Measured hash was
        f8ab98ff5e73ebab884d80c9dc9c7290.",
17    "Expected sha1 has was 615ca705b98c24bf4ccb535ab3e0611486b17c2a.\n Measured
        hash was 615ca705b98c24bf4ccb535ab3e0611486b17c2a.",
18    "VNF image passed hash comparisons"
19  ],
20  "timestamp": {
21    "$date": 1533204534825
22  },
23  "vnf_image_openstack_id": "85a7cf0b-cd2f-429a-b3c3-44c88b923e4e",
24  "vnf_instance_openstack_id": "6ddbbaad8-4c7e-4aa7-bdf5-f87c1a5529c9"
25  }

```

Listing 16: Event for OpenStack scheduler filter

```

1  {
2    "_id": {
3      "$oid": "5b6c440c352c65376cbc9fb1"
4    },
5    "element_id": "5b6c43eb352c65376cbc9fae",
6    "event_type": "Element update",
7    "new_element": {
8      "VNF_image": "85a7cf0b-cd2f-429a-b3c3-44c88b923e4e",
9      "_id": "5b6c43eb352c65376cbc9fae",
10     "kinds": [
11       "VNFElement::VNFInstance"
12     ],
13     "migration_record": null,
14     "name": "test-vnf",
15     "openstack_id": "dc510117-475a-44f2-8ed9-ba21c592e416",
16     "previous_suspend_hash_list": [

```



```

17     {
18       "hash": "bc12d53ee991ff1a745c867fe0a25ce9551debcfec639fd4fe5de24ed266c28c",
19       "hash_type": "sha256"
20     },
21     {
22       "hash": "a897948b229e1b882ac093a552b3591075ae19cf",
23       "hash_type": "sha1"
24     },
25     {
26       "hash": "884a07777dc50457126e9ec86b4266a8",
27       "hash_type": "md5"
28     }
29   ],
30   "running_on": "compute",
31   "state": "suspended",
32   "status": true,
33   "timestamp": "2018-08-09 13:39:24.032000"
34 },
35 "new_parameters": {
36   "previous_suspend_hash_list": [
37     {
38       "hash": "bc12d53ee991ff1a745c867fe0a25ce9551debcfec639fd4fe5de24ed266c28c",
39       "hash_type": "sha256"
40     },
41     {
42       "hash": "a897948b229e1b882ac093a552b3591075ae19cf",
43       "hash_type": "sha1"
44     },
45     {
46       "hash": "884a07777dc50457126e9ec86b4266a8",
47       "hash_type": "md5"
48     }
49   ],
50   "state": "suspended"
51 },
52 "nonce": "ed7452fc-49a2-4ad9-88f0-b4c4d3554c1f",
53 "old_element": {
54   "VNF_image": "85a7cf0b-cd2f-429a-b3c3-44c88b923e4e",
55   "__id": "5b6c43eb352c65376cbc9fae",
56   "kinds": [
57     "VNFElement::VNFInstance"
58   ],
59   "migration_record": null,
60   "name": "test-vnf",
61   "openstack_id": "dc510117-475a-44f2-8ed9-ba21c592e416",
62   "previous_suspend_hash_list": [],
63   "running_on": "compute",
64   "state": "active",

```

```
65     "status": true,  
66     "timestamp": "2018-08-09 13:39:21.295000"  
67   },  
68   "result": true,  
69   "timestamp": {  
70     "$date": 1533821964072  
71   }  
72 }
```

Listing 17: Event for updated suspended VNF instance