



TNOVA

NETWORK FUNCTIONS AS-A-SERVICE
OVER VIRTUALISED INFRASTRUCTURES

GRANT AGREEMENT NO. 619520

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Specification of the Infrastructure Virtualisation, Management and Orchestration - Interim

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Executive Summary

The specification presented in this document utilises the requirements described in previous deliverables together with the latest NFV and virtualisation requirements defined by various industry bodies including the ETSI ISG NFV and ITU-T, as well as excerpts of relevant parts of the ETSI ISG MANO WG architecture and associated Functional Entities (FEs). Information assembled via this process was used as the critical input into a two stage process. Stage 1 consisted of a research and design phase, where a systems engineering approach was adopted to define the key functional blocks and their associated capabilities. Stage 2 defined both the reference architectures and its FEs, which are described in this document. Both the architecture and associated FEs are presented in a technology agnostic manner to decouple the specifics of the implementations details. An additional third stage which constitutes the key activities within WP3/4 will address the specifics of the appropriate technologies to be utilised and their operation.

Section 1 introduces the main technical areas addressed by this deliverable such as virtualisation, the evolution of IT compute technologies in to the carrier domain, the advent of software defined networking etc. In addition, it also presents the T-NOVA solution constituted by both the T-NOVA Orchestration platform and the T-NOVA Infrastructure Virtualisation Layer (IVM) platform. This section concludes by presenting and describing its functional architecture.

Section 2, provides a concise review of the current state-of-the-art technologies and industry/academic initiatives that are relevant to the Orchestration and Infrastructure Virtualisation layers in T-NOVA. While there is strong focus on ETSI related activities, a broad perspective has been adopted in this deliverable in order to ensure that all relevant influences are suitably considered and filtered to make sure that the architectural components considered in this document include the state-of-the-art architectural and technology related approaches in their design and specification.

Section 3 provides the Orchestration layer specifications by starting with an overview of its framework, the Orchestrator Domain, followed by the requirements of the associated FEs, and concluding by presenting and describing its functional architecture.

Section 4 presents the overall integrated architecture for the IVM layer together with the architecture of the various domains that comprise the IVM with their respective internal and external interfaces. Collectively, these reference architectures and FEs instantiate the requirements that were identified for the T-NOVA Orchestrator and IVM together with their goals and objectives.

Section 5 presents the key Virtualised Network Function (VNF) and Network Service (NS) workflows that should be supported by the T-NOVA architecture. The reference architectures were interrogated and validated at a functional level through the development of these NS and VNF workflow diagrams, which illustrated the key actions and interactions within the T-NOVA system during standard operational activities related to the deployment and management of NS and VNF services.

Section 6 provides the results of a focused gap analysis that was carried out to determine what steps need to be taken in order to move NFV/SDN from its current state to a position that can fully realise the needs of carrier grade deployments.

Annexes A and B contain the requirements for Orchestrator's and IVM's Functional Entities, while Annex C contains a definition for several terms used throughout the present deliverable. Finally, Appendix I constitute a repository of relevant information on the ETSI ISG NFV framework.

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1. INTRODUCTION

This deliverable outlines the outputs and the results of the activities carried out in Tasks 2.3 and 2.4 in Work Package 2 (WP2). These outputs and results are focused on the infrastructure virtualisation layer as well as of the management and orchestration layer within the T-NOVA system.

1.1. Virtualisation

Virtualisation is a general term that can apply to a variety of different technology approaches such as hardware, operating system, storage, memory and network. It is the key enabler technology that allows traditional physical network functions to be decoupled from fixed appliances and to be deployed onto industry standard servers large Data Centres (DCs). This approach is providing operators with key benefits such as greater flexibility, faster delivery of new services, a broader ecosystem enhancing innovation in the network etc.

1.1.1 The Virtualisation Concept

From a computing perspective virtualisation abstracts the computing platform and, in doing so, hides its physical characteristics from users or applications. Dating back to the 1960's, the concept of virtualisation was first introduced with the Atlas Computer with the concept of virtual memory, and paging techniques for system memory. IBM's M44/44X project building on these innovations developed an architecture which first introduced the concept of virtual machines (VMs). Their approach was based on a combination of hardware and software allowing the logical slicing of one physical server into multiple isolated virtual environments (1). Virtualisation has now evolved from its initial mainframe origins to now being supported by the X86 architecture and being adopted by other non-computing domain such as storage and networking.

The term **Full Virtualisation** describes the technique where a complete simulation of the underlying hardware is provided. This approach has its origins in IBM's control programs for the CP/CMS operating system. Today this approach is used to emulate a complete hardware environment in the form of a VM, in which a guest Operating System (OS) runs in isolation. Full virtualisation wasn't completely possible with the x86 architecture until the addition of Intel's VT and AMD-V extensions in 2005-2006. In fact, full x86 virtualisation relies on binary translation to trap and virtualise the execution of certain sensitivity "non-virtualisable" instructions. With this approach, critical instructions are discovered and replaced with traps into the Virtual Machine Manager (VMM), also called a *hypervisor*, to be emulated in software.

Virtualisation is now found in applications for other domains such as storage, and network to deliver similar benefits to those realised in the compute domain.

- *Storage virtualisation* refers to a process by which several physical disks appear to be a single unit. Virtualised storage is typically block-level rather than file-level, meaning that it looks like a normal physical drive to computers.

The key advantages of the approach are: (i) easier management of heterogeneous storage environments, (ii) better utilisation of resources, (iii) greater flexibility in the allocation of storage to VMs,

- *Network virtualisation* comes in many forms like Virtual Local Area Networks (VLANs), Logical Storage Area Networks (LSANs) and Virtual Storage Area Networks (VSANs) that allow a single physical Local Area Networks (LAN) or Storage Area Networks (SAN) architecture to be carved up into separate networks without dependence on the physical connection. Virtual Routing and Forwarding (VRF) allows separate routing tables to be used on a single piece of hardware to support different routes for different purposes. The benefits of network virtualisation are very similar to server virtualisation, namely increased utilisation and flexibility.

These technologies in the form of cloud computing are now being rapidly adopted by network operators in their carrier network domains in order to consolidate traditional network devices onto standard high volume x86 servers, switches and storage in the form of VNFs. In doing so, they allow service providers to transform their network functions into an elastic pool of resources while seeking compatibility with network and operational management tools. Building on cloud DCs allows operators to create an orchestration environment for the management and control of their compute, network and storage resources. For VNFs to function properly the configuration of the network underneath them is critical. To provision or adapt VNFs to changing network conditions or customer requests requires the ability to configure or adapt network routes in a highly expeditious manner.

The advent of Software Defined Networking (SDN) with its support for programmatic provisioning transforms service delivery from weeks to a matter of minutes or even seconds. SDN is based around a new networking model where control of the network is decoupled from the physical hardware allowing a logically centralised software program (a network controller) to control the behaviour of an entire network. The use of centralised network control and a common communication layer protocol across the switching elements in the network can enable increased network efficiency, centralised traffic engineering, improve troubleshooting capabilities and the ability to build multiple virtual networks running over a common physical network fabric. In SDN, network elements are primarily focused on packet forwarding, whereas switching and routing functions are managed by centralised network controller which dynamically configures network elements using protocols such as OpenFlow. SDN is starting to be deployed in data centre and enterprise environments e.g. Google. Virtual networks to support VNF deployment can be deleted, modified or restored in a matter of seconds in much the same manner that we provision virtual machines in cloud environments.

Virtualisation and its adoption in the key constituent elements of networks and data centres has created an agility for service providers that was not previously possible. Virtualisation of infrastructure, networks as well as the applications and services that run on top will allow service providers to rapidly transform their networks and to embrace new innovations.

1.1.2 The Pros and Cons of NFV Deployments

As highlighted by the ETSI ISG NFV in its first white paper (2), the scenario which defines the situation faced by most network operators nowadays, relates to the physical components of their networks, which are characterised by the use of a wide range of proprietary hardware appliances. This problem of appliance and technology diversity continues to grow for operators as new equipment is added to previous generations of equipment in the network.

This leads to significant challenges related to the launch of new services, increasing energy costs and capital investments coupled with the difficulty of finding people with the most appropriate skills to handle the design, integration and operation of increasingly complex hardware-based appliances. In addition, the trend towards shorter operational lifespan of hardware also affects revenues, leading to situations where there is no return on investment or where there is no time for innovation.

As previously outlined in the T-NOVA project scope (3), Network Functions Virtualisation (NFV) will address these challenges by leveraging standard Information Technology (IT) virtualisation technology to consolidate various network equipment types onto industry standard high volume servers, switches and storage located in DCs, Network Nodes and in the end user premises. In this context, NFV refers to the virtualisation of network functions carried out by specialised hardware devices and their migration to software-based appliances, which are deployed on top of commodity IT (including Cloud) infrastructures.

Virtualising Network Functions potentially offers many benefits, including:

- Reduction in both equipment costs and power consumption,
- Reduced time to market,
- Availability of network appliances that support multiple-versions and multi-tenancy, with the ability to share resources across services,
- Targeted service introduction based on geography or customer type, where services can be quickly scaled up/down as required,
- Enabling a wide variety of eco-systems,
- Encouraging openness within the ecosystem.

One of the challenges in the deployment of NFV in the carrier domain is to leverage the advantages of the IT ecosystem while minimising any of the associated disadvantages. Standard high volume servers and software must be modified to meet the specific reliability requirements in the telecoms environment, including 99.999 percent uptime availability. This mission critical level of reliability is a key requirement and differentiates traditional IT (just reboot the system!) and telecom (where downtime or poor performance is not acceptable) environments. To meet design goals without sacrificing performance, software applications must be specifically designed or rewritten to run optimally in virtualised telecom environments to meet carrier grade requirements. Otherwise, applications ported to virtualised environments may experience significant performance issues and may not scale appropriately to the required network load. An additional challenge for virtualisation in a telecom network environment is the requirement to deliver low latency to handle real-time applications such as voice and video traffic. In addition to performance,

other operational characteristics that are crucial to successful deployments include: maturity of the hypervisor; Reliability, Availability, and Serviceability (RAS); scalability, security, management and automation; support and maintainability.

Deploying NFV also incurs other well-defined risks, e.g. scalability in order to handle carrier network demands; management of both IT and network resources in support of network connectivity services and Network Functions (NFs) deployment; handling of network fault and management operations; Operations Supporting System (OSS) / Business Supporting System (BSS) backwards compatibility in migration situations; interoperability required to achieve end-to-end services offerings, including end-to-end Quality of Service (QoS). In addition, essential software appliances should achieve performance comparable to their hardware counterparts which is currently not always possible due a variety of reasons such as the performance of the virtualisation technologies.

1.2 The T-NOVA Solution

The T-NOVA project is focused on addressing some of the key challenges of deploying NFVs in carrier grade environments by designing and implementing an integrated architecture, which includes a novel integrated open-source Orchestration platform. This platform is explicitly dedicated to the orchestration of cloud and network resources for NFVs, as well as the automated provisioning, management, monitoring and optimisation of Network Functions-as-a-Service (NFaaS) over virtualised Network/IT infrastructures. The T-NOVA Orchestrator controls the infrastructure resources that host the VNFs via the T-NOVA IVM. The IVM is comprised of a number of functionalities, which collectively provide the virtualised compute, storage and network connectivity required to host VNFs.

The overall T-NOVA system architecture is depicted in the next figure and is on the basis of the T-NOVA solution, which includes two platforms specified in the present deliverable: the T-NOVA Orchestration platform and the T-NOVA IVM platform.

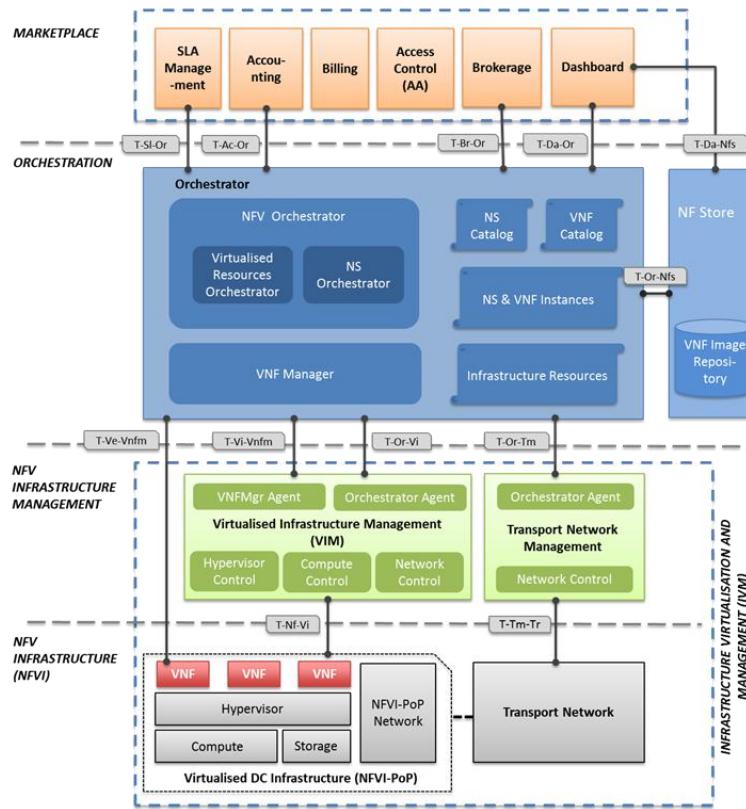


Figure 1: High-level view of overall T-NOVA System Architecture

(Source: D2.21 (4))

1.2.1 The T-NOVA Orchestration Platform

The T-NOVA architecture has been conceived using a layer stratification approach where the Orchestration layer is positioned between the Service Layer and the Infrastructure Management layers. This stratification approach, together with the envisaged high level modules within the Orchestrator layer, is illustrated in Figure 1 above.

The capabilities of the T-NOVA Orchestrator are required to extend beyond traditional cloud management as the T-NOVA scope is not restricted to a single DC. The Orchestrator therefore needs to manage and monitor Wide-Area Networks (WANs) as well as distributed cloud (compute/storage) services and resources in order to couple basic network connectivity services with added-value NFs.

Orchestration layer capabilities that could improve the deployment of VNFs onto private, heterogeneous cloud, includes:

- Application assignment to hardware platforms capable of improving its performance through specific features, such as special purpose instructions or accelerators,
- Allocation of an Single Root I/O Virtualisation (SR-IOV) virtual function to VMs running VNFs that can benefit from the capability,
- Enabling live-migration.

The Orchestrator's requirements together with its detailed conception and description in terms of FEs constitute the outputs of Task T2.3 which are described in Section 3.

1.2.2 The T-NOVA IVM Platform

The IVM layer in the T-NOVA system is responsible for providing the hosting and execution environment for VNFs. The IVM is comprised of a Network Function Virtualised Infrastructure (NFVI) domain containing a Virtualised Infrastructure Manager (VIM) and a Transport Network Manager (TNM). The IVM provides full abstraction of these resources to VNFs. The IVM achieves this by supporting separation of the software that defines the network function (the VNF) from the hardware and generic software that creates the NFVI. Control and management of the NFVI is carried out by the VIM in unison with the Orchestrator. While the IVM provides orchestration of the virtualised resources in the form of compute, storage and networking, responsibility for the orchestration of the VNFs is solely a function of the Orchestration layer given its system wide view of the T-NOVA system and centralised coordination role in the system.

A major challenge for vendors developing NFV-based solutions is achieving near-native performance (i.e., similar to non-virtualised) in a virtualised environment. One critical aspect is minimising the inherent overhead associated with virtualisation, and there has been significant progress thanks to a number of key innovations. An example is hardware-assisted virtualisation in CPUs, such as Intel's Xeon microprocessors with Intel VT, which reduces VM context switching time, among other things.

Another challenge is ensuring the orchestration layer fully exploits the capabilities of the servers it manages. Typical orchestration layer products can identify infrastructural features (e.g., CPU type, Random Access Memory (RAM) size and host operating system); however, some orchestrators are unaware of attached devices, like acceleration cards or network interface cards (NICs) with advanced capabilities. In such cases, they are unable to proactively load an application onto a platform capable of accelerating its performance, as in assigning an IP security (IPsec) VPN appliance to a server with cryptographic algorithm acceleration capabilities. Other features of the platform may be of interest, i.e. the model and version of CPU, the number of cores, and other specific features.

The lack of platform and infrastructural awareness is a major drawback since many virtual appliances have intense I/O requirements and could benefit from access to high-performance instructions, accelerators and Network Interface Cards (NICs) for workloads such as compression, cryptography and transcoding. This will be a key focus in WP3 (Task 3.2) and WP4 (Task 4.1). Undoubtedly, making the orchestration layer aware of the innate capabilities of the devices attached to server platforms can help maximise network performance.

The outputs of Task 2.4 with respect to the overall integrated architecture of the IVM layer are presented in Section 4.

2. SOTA SURVEY

The following sections present a concise review of the current state-of-the-art (SOTA) technologies and industry/academic initiatives that are relevant to T-NOVA Orchestration and T-NOVA IVM layers. While there is strong focus on European Telecommunications Standards Institute (ETSI) related activities, a broad perspective is adopted. This is to ensure that all relevant influences are appropriately considered and filtered so that architectural components considered in this deliverable include the most appropriate state-of-the-art approaches in their design and specification.

2.1. Global specifications coming from main SDOs/Fora

2.1.1 ETSI ISG NFV

The ETSI ISG NFV framework has been previously presented in deliverable D2.21 (D2.21) (4). The main outputs i.e. the high-level NFV framework and the reference architecture as well as the work carried out in the most relevant Working Groups (WGs) have been described in detail. In addition, the current status of the work has been outlined and their key achievements since the beginning of 2013. Finally their planned roadmap up to the end of 2014 has been discussed. By that time, the current ETSI ISG NFV mandate will end and publication of documents for ETSI ISG NFV Release 1 will take place. However, plans and activities that are being promoted in order to create an ETSI ISG NFV phase 2, which is expected to start by the beginning of 2015, have also been described. Among those activities special focus on the creation of the Open Platform for NFV (OPN) has been provided.

As stated above, this extensive research work has already been outlined in D2.21 (4), as such the contents of this subsection will focus on the activities of the INF, SWA and MANO WGs that have specific relevance to T2.3 (Orchestration) and T2.4 (Infrastructure Virtualisation).

The complete output of the research work carried out can be found in Appendix I.

2.1.1.1. WG INF (Infrastructure Architecture)

This WG is responsible for the NFVI. They have identified three sub-domains within the NFVI, which are as follows:

- **Hypervisor Sub-domain**, which operates at a **virtual level**, encompassing the computing and storage **slices**,
- **Compute Sub-domain**, which operates at the **lowest level**, also in the computing and storage **slices**,
- **Network Sub-domain**, which operates both at the **virtual level** and the **hardware level**, of the network **slice**.

The global architecture of the NFVI domain details the specific infrastructure-related Functional Entities. Basically, all the three sub-domains are decomposed into smaller

functional blocks, both at the virtual and hardware levels as well as the three domains outlined above. In addition, the VIM, part of the MANO domain, is also shown in Figure 2 as it manages this specific infrastructure level from the architecture level, or functional level perspective.

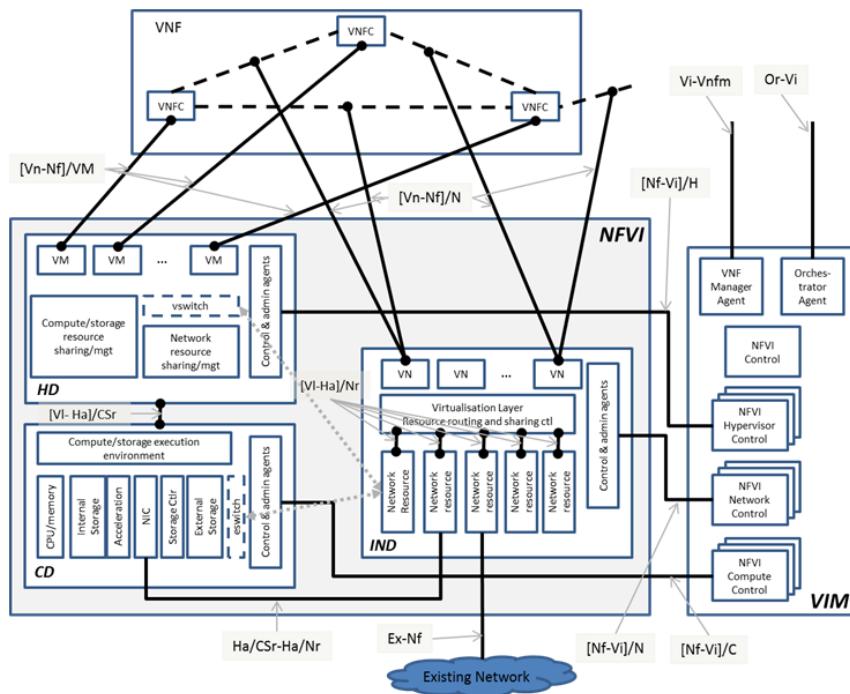


Figure 2 High Level Overview of the NFVI Domains and Interfaces
(Source: DGS NFV INF 005 v0.3.0 (2014-05) (5))

2.1.1.2. WG SWA (Software Architecture)

As described in the Terms of Reference (ToR) of the NFV SWA WG in the ETSI portal (<http://portal.etsi.org/TBSiteMap/NFV/NFVWGSGsToR.aspx>) (6), the main responsibilities of this group are to:

- Define a reference software architecture for network functions to be deployed, provisioned, run and managed on virtualised infrastructure,
- Describe the functionalities specific to VNFs, i.e. functional behaviour, deployment model, and characteristics such as security and performance,
- Identify/define the reference points/interfaces with other NFV WG building blocks, typically MANO and INF, and preserve reference points/interfaces to legacy OSS and BSS,
- Collect and define requirements for this reference SWA architecture from relevant stakeholders, i.e. provided by MANO, INF and legacy OSS/BSS,
- Validate this reference functional software architecture with concrete use cases,
- Identify gaps, where existing standards/specifications do not fulfil the requirements of the reference architecture.

With respect to the architecture, and taking into account that the WG is devoted to the domain that handles the VNFs and their manager, i.e. the VNF lifecycle, the detailed architecture is depicted in Figure 3.

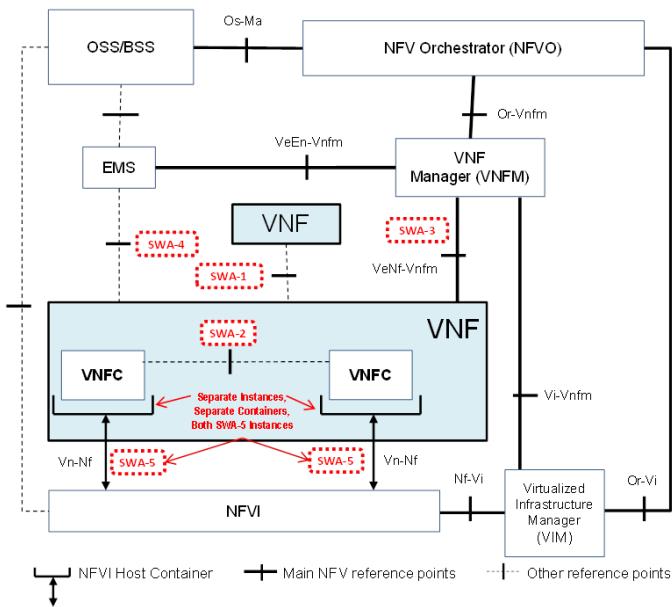


Figure 3: SWA Architectural Framework and interfaces types
(Source: DGS NFV SWA 001 v0.2.0 (2014-05) (7))

2.1.1.3. WG MANO (Management and Orchestration Architecture)

The ToRs indicated in the ETSI portal for this WG are to:

- Develop ETSI deliverables on the issues related to the deployment, instantiation, configuration and management framework of network services based on NFV infrastructure, focused on:
 - abstraction models and Application Programming Interfaces (APIs),
 - provisioning and configuration,
 - operational management,
 - interworking with existing OSS/BSS,
- Provide requirements for orchestration and management,
- Identify gaps in current standards and best practices.

The current working architecture conceived by the NFV MANO WG is shown in Figure 4.

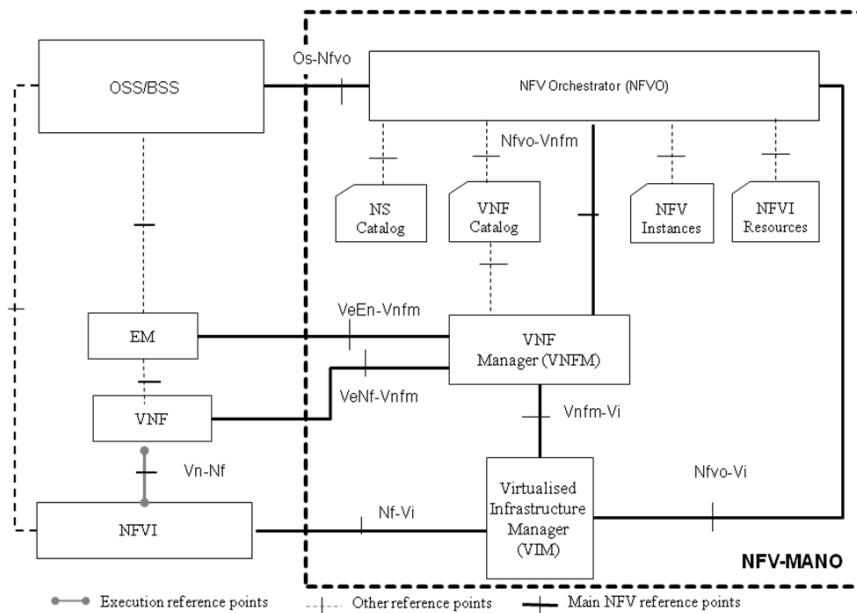


Figure 4: NFV MANO reference architectural framework
(Source: DGS NFV MAN 001 v0.6.3 (2014-09) (8))

2.1.2 ITU-T

2.1.2.1 Virtualisation in ITU-T

The ITU Telecommunication Standardization Sector (ITU-T) has been active in virtualisation although its specification constitutes part of a broader area designated by Future Networks, which will be briefly described in the last part of this section.

The framework that characterises virtualisation in ITU-T is described, in order to indicate the manner in which this technology is being handled. A brief explanation on the work that is being carried out in the ITU-T as well as other associated areas in of standardisation is provided.

2.1.2.1.1 The Virtualisation concept

In the ITU-T virtualisation framework, the definition of Network Virtualisation (NV) associated to a network that enables the creation of Logically Isolated Network Partitions (LINPs) over shared physical network infrastructures so that multiple heterogeneous virtual networks can simultaneously coexist over the shared infrastructures. This includes the aggregation of multiple resources and makes the aggregated resources appear as a single resource.

As such, NV is seen as a method that allows multiple virtual networks, called LINPs, to coexist in a single physical network. In order to provide LINPs, physical resources are partitioned and abstracted as virtual resources and the virtual resources are interconnected to create an LINP.

The definition of LINP states that it is a network that is composed of multiple virtual resources which is isolated from other LINPs. Moreover, the term virtual resource, or logical resource, is related to an independently manageable partition of a physical

resource, which inherits the same characteristics as the physical resource and whose capability is bound to the capability of the physical resource.

In terms of reference architecture, it is necessary to consider that NV is implemented introducing a virtualisation layer or an adaptation layer, where the virtualisation layer creates and manages LINPs. The virtualisation layer is a layer positioned between physical hardware and the software running on a physical resource. This layer enables the creation of an isolated partition of the physical resource. Each partition is designed to accommodate different architectures and applications. Figure 5 illustrates the conceptual or reference architecture of a NV:

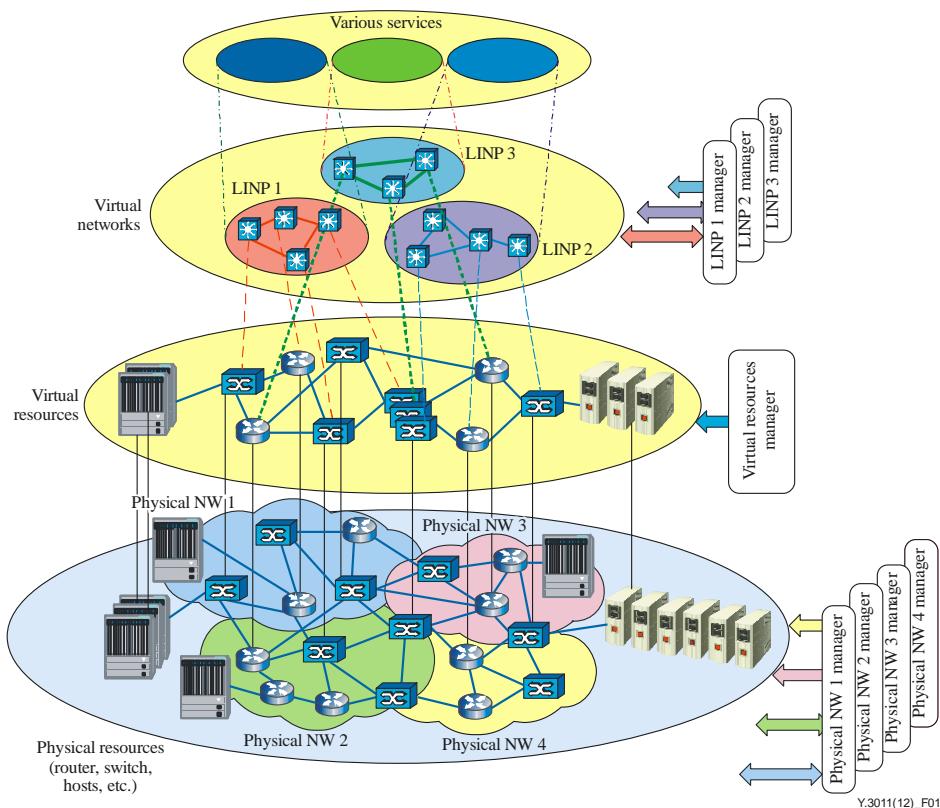


Figure 5: Conceptual architecture of network virtualization
(Source: Rec. ITU-T Y3011 (9))

2.1.2.1.2 Problems addressed by VNs

This section lists the problems of current networks that network virtualisation is expected to address in order to mitigate their impact, according to ITU-T Rec. Y.3011 (9):

- Coexistence of multiple networks,
- Simplified access to resources,
- Flexibility in provisioning,
- Evolution.

2.1.2.1.3 Design and goals of VNs

This section addresses the design goals of realising network virtualisation covering various aspects such as capabilities, characteristics and some challenging issues, once again according to ITU-T Rec. Y.3011 (9):

- Isolation,
- Network abstraction,
- Topology awareness and quick reconfiguration,
- Performance,
- Programmability,
- Management,
- Mobility,
- Wireless.

In addition to the problems, design and goals listed above, the deployment of virtualised networks should also be taken into account including the impact that environmental and security issues may have in this context.

2.1.2.1.4 Virtualisation requirements

When considering the evolution of networks, it should be considered that while some requirements for new networks do not change, other requirements are evolving and changing, while new requirements may also arise, forcing networks and their architecture to evolve.

It is, therefore, reasonable to expect that some requirements can be realised by the new network architectures and supporting technologies, and that these could be the foundation of networks of the future, whose trial services and phased deployment ITU-T estimates to fall approximately between 2015 and 2020.

This target date does not mean that a network will change by that estimated timeframe, but that parts of a network are expected to evolve. Evolution and migration strategies may be employed to accommodate emerging and future network technologies. Such evolution and migration scenarios are topics for further study.

In the following, a list of the requirements identified by ITU-T in ITU-T Rec. Y3012 (10) will be indicated:

- Physical resource management,
- Virtual resource management,
- L1NP management,
- Service management,
- Authentication, authorisation, and accounting,
- L1NP federation,
- Service Mobility.

Again, in addition to the handling of these virtualised requirements, the deployment of virtualized networks should also be taken into account the impact that environmental and security issues may have in this context.

2.1.2.2 Work carried out by ITU-T SG13

This section outlines the status of the work that has been carried out in ITU-T, and in particular in Study Group 13 (SG13), which has held responsibility for virtualisation since 2009.

As stated before, the virtualisation technology doesn't constitute a standalone area, instead it is included in a broader scope designated by Future Networks (FNs).

In the following subsections, FNs are briefly described, in terms of their formal definition, objectives, design and goals. Finally the attributes that characterise NV are discussed in order to determine their suitability for deployment in FNs.

2.1.2.2.1 Future Networks

According to ITU-T Rec. Y.3011 (9), FNs are networks that will be able to provide revolutionary services, capabilities, and facilities that are difficult to support using existing network technologies. One of the basic objectives of FNs is service awareness. The number and range of services are expected to explode in the coming years and FNs need to adapt to the surge in the number of services. That surge makes it difficult to satisfy the requirements of every service on a common network architecture. However, it is unrealistic to realise heterogeneous network architectures using multiple physical networks because of the installation, operation, and maintenance costs.

Therefore one of the key requirements of a FN is to realise diverse services and heterogeneous network architectures on a common physical network.

Objectives of FNs

The list of the objectives for FNs identified by ITU-T in ITU-T Rec. Y3001 (11) are as follows:

- Service awareness,
- Data awareness,
- Environmental awareness,
- Social and economic awareness.

Design goals of FNs

According to ITU-T Rec. Y3001 (11), the set of design and goals that must be considered when elaborating specifications for FNs are as follows:

- Service diversity,
- Functional flexibility,
- Virtualisation of resources,
- Data access,

- Energy consumption,
- Service universalisation,
- Economic incentives,
- Network management,
- Mobility,
- Optimisation
- Identification,
- Reliability and security.

Figure 6 shows the relationships between the four objectives outlined in the previous section and the design goals described above. It should be noted that some design goals, such as network management, mobility, identification, and reliability and security, may relate to multiple objectives. Figure 6 shows only the relationships between a design goal and its most relevant objectives.

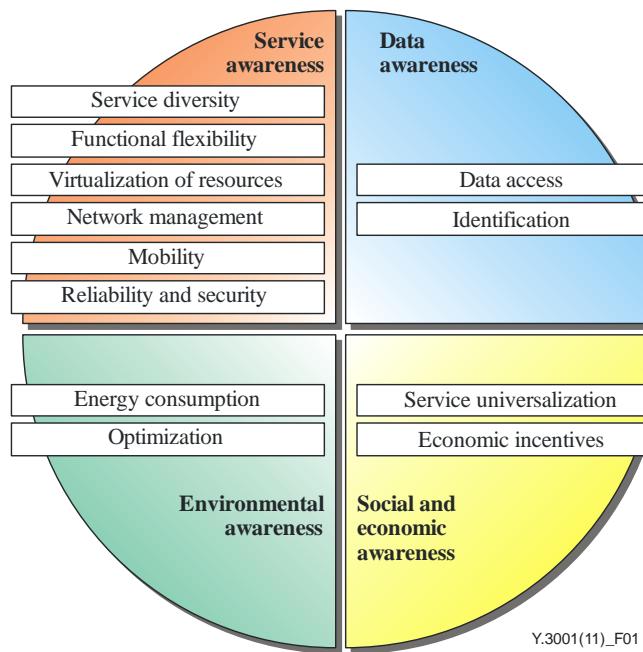


Figure 6: Y.3001: Four objectives and twelve design goals of future networks
 (Source: Rec. ITU-T Y3001 (11))

Virtualisation as a key candidate technology for deploying FNs

Network virtualisation is a technology that realises isolated and flexible networks in order to support a broad range of network architectures, services, and users that do not interfere with others. It also enables the establishment of experimental networks with greater ease and accelerates research and development on future network technologies. Therefore, network virtualisation is considered as a key technology for realising FNs.

FNs should provide a broad range of applications, services, and network architectures. Network virtualisation is a key technology supporting these goals and

enables the creation of logically isolated network partitions over a shared physical network infrastructure so that multiple heterogeneous virtual networks can simultaneously coexist over the same infrastructure. It also allows aggregation of multiple resources and makes the aggregated resources appear as a single resource.

According to ITU-T Rec. Y3011 (10), many key properties of network virtualisation, such as flexibility, reconfigurability and network abstraction, make network virtualisation one of the key technologies for FNs.

2.1.2.2.2 List of recommendations

A non-exhaustive list of ITU-T recommendations elaborated by SG13 are as follows:

- Rec. ITU-T Y.3001 "*Future Networks: Objectives and Design Goals*" (11),
- Rec. ITU-T Y.3011 "*Framework of network virtualization for future networks*" (9),
- Rec. ITU-T Y.3012 "*Requirements of network virtualization for future networks*" (10),
- Rec. ITU-T Y.3021 "*Framework of energy saving for future networks*" (12),
- Rec. ITU-T Y.3031 "*Identification framework in future networks*" (13),
- Rec. ITU-T Y.3033 "*Framework of data aware networking for future networks*" (14),
- Rec. ITU-T Y.3300 "*Framework of software-defined networking*" (15),
- Rec. ITU-T Y.3320 "*Requirements for applying formal methods to software-defined networking*" (16),
- Rec. ITU-T Y.3501 "*Cloud computing framework and high-level requirements*" (17),
- Rec. ITU-T Y.3502 "*Information technology - Cloud computing - Reference architecture*" (18),
- Rec. ITU-T Y.3510 "*Cloud computing infrastructure requirements*" (19),
- Rec. ITU-T Y.3512 "*Cloud computing - Functional requirements of Network as a Service*" (20),
- Rec. ITU-T Y.3513 "*Cloud computing - Functional requirements of Infrastructure as a Service*" (21).

2.1.2.2.3 Roadmap

The envisaged timeline by ITU-T for the elaboration of recommendations regarding FNs and their four objectives is depicted in Figure 7.

This timeline involves two study periods (2009-2012 and 2013-2016). The conceptual phase has been completed and preparation of detailed document is underway. With respect to network virtualisation, the first set of recommendations related to the requirements and architecture are in the process of being approved or have already been approved.

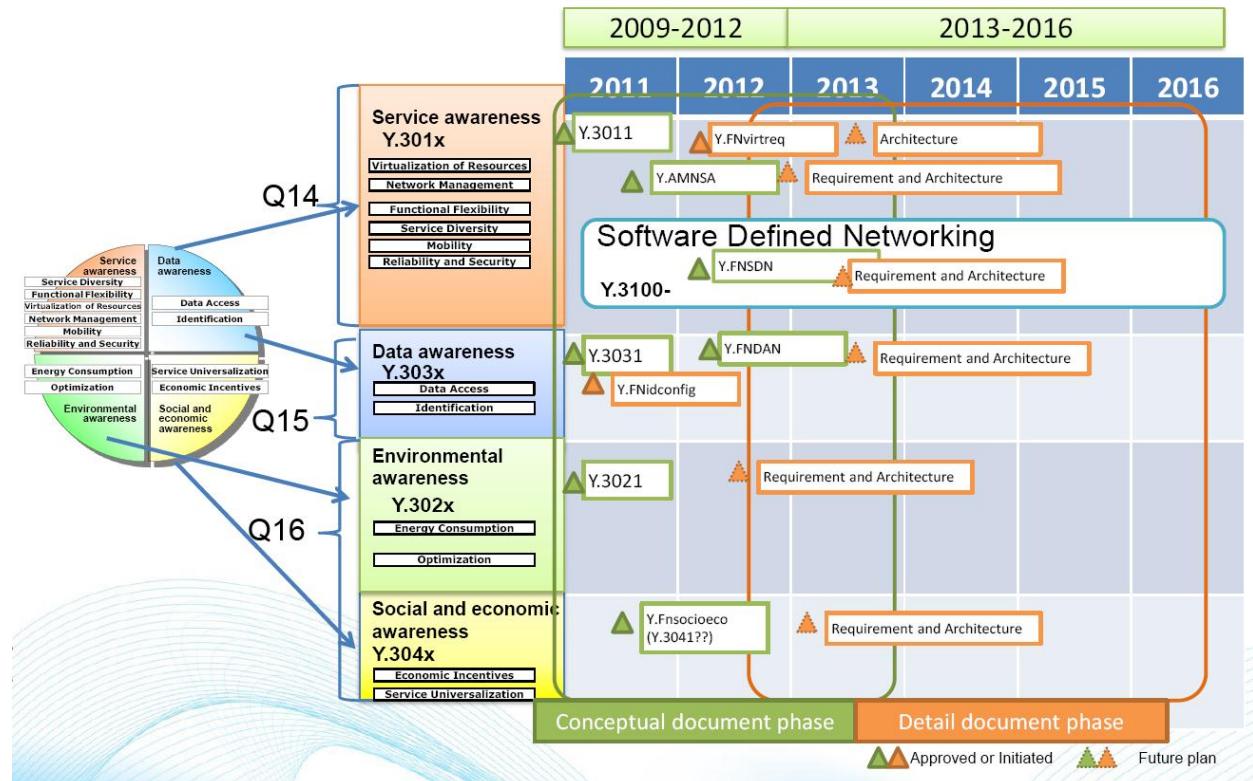


Figure 7: ITU-T Future networks activity timeline (Roadmap)
(Source: ETSI 3rd Future Networks Workshop (22))

2.1.3 IETF

2.1.3.1 NETCONF

NETCONF is designed to be a replacement for Command Line Interface (CLI) based programmatic interfaces. Network automation is currently blocked by available approaches where we need to write device specific CLI scripts. The CLI is used by humans, but increases the complexity and reduces the predictability of the API for real application usage. NETCONF allows the management console (manager or client) to issue commands and change configuration of networking devices (NETCONF agent or server). In this respect, it is somewhat similar to Simple Network Management Protocol (SNMP), but since it uses Extensible Markup Language (XML), provides a much richer set of functionality than the simple key/value pairs of SNMP. It is both session and connection-oriented and uses RPC for protocol operations, which are encoded in XML. Both the device configuration data, and the protocol itself, are encoded in XML. In order to exchange NETCONF messages, a client must first establish a NETCONF session with a server. When a session is established, each NETCONF peer exchanges a list of its capabilities with the other peer.

2.1.3.2 YANG

YANG is a data modelling language used to model configuration and state data manipulated by the NETCONF, NETCONF remote procedure calls, and NETCONF notifications in a "human readable" format (23).

YANG is used to model both configuration and state data of network elements. YANG structures the data definitions into tree structures and provides many modelling features, including an extensible type system, formal separation of state and configuration data and a variety of syntactic and semantic constraints. YANG data definitions are contained in modules and provide a strong set of features for extensibility and reuse.

2.1.4 TMF – ZOOM

The TM Forum has initiated a project to create a living blueprint for a new generation of service provider support systems to deliver true business agility and expert guidance on how to navigate the complexity of the journey– project Zero-touch Orchestration, Operations & Management (ZOOM).

ZOOM specifically targets business agility by defining a framework that enables the delivery and management of physical and virtual resources and services while simultaneously dramatically lowering associated capital and operational expenditures. This necessitates a new architecture that supports dynamic adaptation between changing needs and the capabilities of the infrastructure, enabling targeted and personalised services to be rapidly created, changed, and retired. ZOOM leverages the capabilities of NFV and SDN.

The main benefits of the ZOOM project are (24):

- Zero-touch, self-service operations that can respond with the speed and agility to outpace competitors;
- Adaptive automation, where changes in user needs, business goals, and/or environmental conditions are recognised, and a new, agile OSS uses these inputs to provide the resources and services needed at that point in time;
- Customer-centric services that are easily configured to fit individual customer preferences and requirements, by the customer themselves;
- Significantly lower operating costs and capital expenses achieved through automation of manual tasks, simplification of configuration, virtualisation and use of commodity-based resources;
- Technology-driven innovation, where business agility meets rapid development and experimentation and enables the transition from NetOps and SysOps to DevOps.

Three main Working Items (WIs) are under the scope of ZOOM (25):

- DevOps Transformation Framework for the Digital Ecosystem;
- Blueprint for End-to-End Management;
- Operations & Procurement Readiness.

The **DevOps Transformation Framework for the Digital Ecosystem** WI is focused on clarifying the requirements for a digital world in terms of approaches to hybrid and virtualised operations, specifically outlining how to transform from

SysOps/NetOps to an agile DevOps approach to introduce new services that make it possible to better compete in a digital world.

The **Blueprint for End-to-End Management** will define the essential requirements for effective management of physical and virtualised services end-to-end across multiple provider environments, specifically outlining how to make end-to-end management happen and what common practices, architectural and integration principles are needed to get there.

The **Operations & Procurement Readiness** WI will identify the key requirements – including technical, business, organizational, and cultural changes – necessary for service providers to include when sourcing agile services in a hybrid environment, specifically outlining how to best adhere to these requirements throughout the full sourcing lifecycle. This will help meet the NFV promise of service agility, Operational Expenditure (OPEX) reductions (NetOps to DevOps), and Capital Expenditure (CAPEX) reductions (migration from specialised and expensive telco hardware to standard low-cost IT fabric).

At the time of writing this document, the TMF ZOOM group has released three documents, namely:

- TR227: TM Forum Specifications relevant to MANO Work (26).

The contents provide a description of the set of TM Forum documents that are relevant to MANO related activities. It identifies areas where each TM Forum document can help standardise the information presented and the interfaces of the MANO reference points.

- TR228: TM Forum GAP Analysis related to MANO Work (27).

The contents provide an initial ETSI NFV MANO Gap Analysis of the TM Forum specifications for MANO Interfaces and Information Elements.

- TR229: ZOOM/NFV User Stories (24).

This technical report provides a snapshot of the User Stories that have been identified by the ZOOM project team and have been derived from:

- Scenarios being developed in The TM Forum NFV Catalyst program;
- Requirements in ETSI and ATIS Reports;
- Agile brainstorming sessions amongst Service Providers active in the ZOOM Project.

2.1.5 CloudNFV

CloudNFV is an industry lead initiative that is focused on the design of an open, highly flexible, cloud-driven implementation of the ETSI NFV specification, and secondly to develop an implementation of that design. The founding members of CloudNFV are 6WIND, CIMI Corporation, Dell, EnterpriseWeb, Overture Networks and Qosmos. CloudNFV has delivered a number of public demos during the 2014 including the OpenStack Summit in Atlanta.

CloudNFV is based around the concept of an **Active Contract** that utilises service templates representing the structures of network functionality, which can be ordered, and includes variable parameters such as service locations, QoS, etc. When these values are specified, a **Service Contract** is created. The service contract is then dispatched to an Orchestrator for fulfilment. Policy rules and resource status from Active Resources (as shown in Figure 8) are used by the Orchestrator to determine the optimal location for the deployment of a VNF service and how to provide appropriate connectivity.

This combination of where to host and how to connect instructions is known as a **Manifest**. The manifest is given to OpenStack, which uses NOVA compute and Neutron APIs to create VMs, provision network connectivity to the VMs and to deploy the VNF service. When virtual resources are deployed and connected they report their status and traffic to the Active Resource. Management processes can run against the Active Resource, which can take the form of a Multifunctional Information Distribution System (MIDS) that support current management systems or can be implementation specific depending on the customer requirements.

Virtual management states are derived from the status of the hosts and networks. This approach represents what CloudNFV designates by **contract resource management**. The data model of the Active Contract is structured in a manner to reflect the TMF SID (GB922) (28) description of services and forms the basis for CloudNFV vision for contract-driven management.

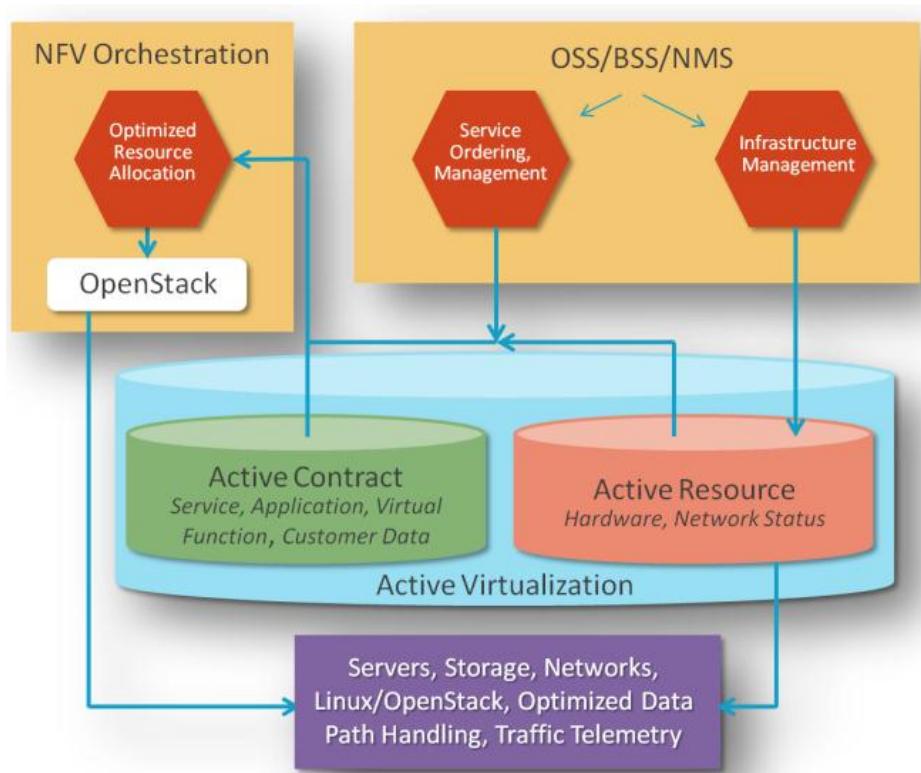


Figure 8: The CloudNFV Architecture (29)

2.2 VIM and Control specific areas

The following sections review the key virtualisation technologies that are relevant to the T-NOVA virtualised infrastructure management and control capabilities together with their respective pros and cons. While not exhaustive the focus is on the leading candidate technologies, which will be most likely adopted during the implementation tasks in WP3 and WP4. A mapping of the technologies and their relationship to architectural components within the T-NOVA IVM is presented in Figure 9. The candidate technologies represent an initial starting point, however it is expected that these technologies choices will evolve and be refined during the course of the T-NOVA project as new technology options emerge or as candidate technologies are found to be insufficient to meet the needs of the T-NOVA implementation or prove to be difficult to extent in an appropriate manner.

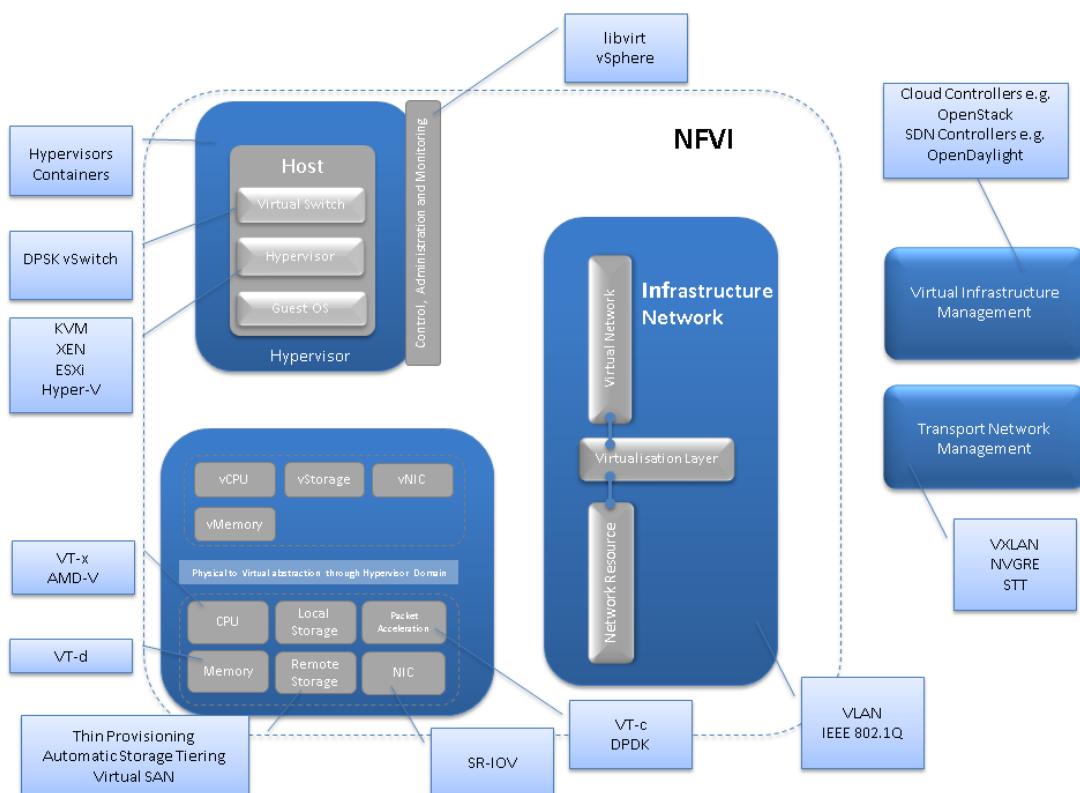


Figure 9: Relation between virtualisation technologies and T-NOVA architecture

2.2.1 IT Virtualisation Methods

There are two primary methods commonly used nowadays to implement virtualisation: **hypervisors** and **containers**. The former is based on the usage of a Virtual Machine Monitor, whereas the latter is an operating system virtualisation mechanism, where the virtualisation software layer is installed on top of the operating system. The following sections will look both of these approaches in more detail.

2.2.1.1 Hypervisors

A hypervisor is a program that allows multiple operating systems to share the same hardware. By "virtualise", we mean the division of resources (CPU, RAM etc.) in the physical computing environment (known as a host) into several smaller independent 'virtual machines' known as guests. Each guest can run its own operating system, to which it appears the virtual machine has its own CPU and RAM, i.e. it appears as if it has its own physical machine even though it does not.

One of the key functions of hypervisors is *isolation*, meaning that a guest cannot affect the operation of the host or any other guest, in any case. This is achieved by hardware emulation of a physical machine and (except under carefully controlled circumstances) prevention of direct access to real hardware by the guests.

Hypervisor can be classified using different taxonomies.

One approach is centred on the virtualisation approach used by the hypervisor. Three main approaches can be used to implement virtualisation:

Full virtualisation - the hypervisor artificially emulates the hardware device with everything it needs to run an operating system. This allows VMs to run in a single server, each completely independent of the other. The drawback is the addition of another layer of software between the operating system and the hardware which can negatively influence performance,

- *Para-virtualisation* – the hypervisor modifies the VM OS eliminating the need for binary translation. It offers potential performance advantages, but requires the use of specially modified operating system kernels that relies on 'para-virtualised drivers' (an optimised interface to the hardware for the hypervisor is provided). This approach is generally only suited to Open Source OSs, (i.e. Linux and FreeBSD),
- *Hardware-assisted virtualisation* – The underlying hardware has to provide specific instructions for virtualisation support to the hypervisor. This provides a simpler and a better solution in terms of performance in comparison to other solutions, giving direct access to resources without emulation.

Another taxonomy approach relates to the type of hypervisor. There are two types of hypervisors, namely Type 1 and Type 2:

- **Type 1** hypervisors run directly on the system hardware, and are often referred to as a "native" or "bare metal" or "embedded" hypervisors. Each guest operating system runs atop the hypervisor. Examples of Type 1 hypervisors are: VMware ESXi, Microsoft Hyper-V, Citrix XenServer and KVM¹,
- **Type 2** hypervisors (also called 'Hosted' hypervisors) run inside an operating system, which in turn runs on the physical hardware. Each guest operating system then runs atop the hypervisor. Desktop virtualisation systems often

¹There is considerable debate over whether KVM is a type 1 or type 2 hypervisor
<http://searchservervirtualization.techtarget.com/news/2240034817/KVM-reignites-Type-1-vs-Type-2-hypervisor-debate>

work in this manner. Example of Type 2 hypervisors are: Microsoft Hyper-V, Oracle VirtualBox, VMware Workstation, Microsoft Virtual PC.

Table 1 presents a summary of the respective advantages and disadvantages of type 1 and 2 hypervisors.

Table 1: Comparison of Hypervisor Types

Hypervisor Type	Advantages	Disadvantages	Examples
1 – Bare Metal	<ul style="list-style-type: none"> Hypervisor can "own" the device, for security, performance, SLAs, etc. Users cannot break the base environment Possibly more secure due to the smaller attack surface of the hypervisor (And the user cannot interact with the host OS) Better performance since your "OS" is a purpose-built hypervisor instead of a general purpose OS 	<ul style="list-style-type: none"> Server and components need to be certified. Destructive install 	<ul style="list-style-type: none"> VMware ESXi Citrix XenServer KVM Microsoft Hyper-V
2 - Hosted	<ul style="list-style-type: none"> The users can install their own hypervisor Adding the hypervisor doesn't destroy the existing OS Runs on most existing hardware that can run Linux, Windows, or Mac 	<ul style="list-style-type: none"> Possibly not as secure since the client cannot "trust" the base. (End user could run a screen recorder, key logger, etc.) No guarantee of performance. Two OSs to manage (host OS and guest VM OS) 	<ul style="list-style-type: none"> Oracle VirtualBox, VMware Workstation Microsoft Virtual PC

2.2.1.2 Open Source and Commercial Hypervisors

There are a variety of open source and commercial hypervisors available such as Oracle's VirtualBox, Parallels, Bochs, Xen, KVM, Qemu, various flavours of VMware. However, four hypervisors currently dominate the market, namely:

- VMware ESXi,
- Linux KVM,
- Linux Xen (mainly with Citrix XenServer implementation),
- Microsoft's HyperV.

The choice of the hypervisor for the T-NOVA architecture will be fully interrogated in WP4 where the benefits of open source vs commercial will be analysed together with

the level of integrated with the chosen cloud platform.. The next sections present a short overview of the key hypervisor technologies.

KVM



KVM can run unmodified Linux or Windows images, but it requires CPU virtualisation extensions (Intel VT or AMD-V). It consists of a loadable kernel module, that provides the core virtualisation infrastructure, and a processor-specific module.

KVM is used in conjunction with Qemu to emulate other hardware such as network card, hard disk, graphics adapter, etc. Qemu can be used in standalone mode (i.e. does not require a special kernel module, or CPU virtualisation extensions, or a hypervisor layer) and is capable of running unmodified operating system images. KVM and Qemu are normally used with libvirt, a C library for interfacing with the underlying virtual machines, that provides a stable, consistent API for machine management across a variety of virtualisation technologies and currently supports Xen, Qemu, KVM, User Mode Linux and VirtualBox, among others. Libvirt uses XML-based configuration files to define the virtualised hardware. Libvirt is also used by the libvirtd daemon, used to mediate communication with the virtualisation system.

XEN



Xen dates back to a Cambridge University research project in 2003. Since it is a Type 1 hypervisor, its 'dom0' host runs on Linux, which in turn runs on Xen. The Xen community develops and maintains Xen as free and open-source software under GNU GPL licence. In 2013, it was announced that the Xen Project was moving to the Linux Foundation as a Collaborative Project. Key features include: *small footprint and interface; operating system agnostic; driver isolation* (it allows the main device driver for a system to run inside of a VM so that if the driver crashes, the VM containing the driver can be rebooted without affecting the rest of the system) and *compatibility with hardware* that doesn't support virtualisation extensions.

vmware



VMware's ESXi hypervisor is very mature and extremely stable. It is popular among enterprise customers including many telco service providers where brand and the commercial guarantee of a rock solid hypervisor matters more than cost. The performance level of ESXi is similar other hypervisors for most workloads. However the orchestration performance is generally worse than either KVM or Xen (30). vSphere was developed as an enhanced suite of tools for cloud computing utilising VMware ESX/ESXi hypervisors. Some key components of this platform are: *vMotion* and *Storage vMotion* (for live migration of respectively VMs and vDisks); *VMware High Availability* (automatic restart of the VMs if the underlying hardware goes down); DRS (Distributed Resource Scheduling for VM placement at the VM provisioning and VMs balancing among hosts; both can be manually or automatically done) and SDRS (Storage DRS); Fault Tolerance (a more powerful High Availability (HA) that runs in real time a mirrored VM); *Distributed*

Power Management and *VMware Consolidated Backup* (for both energy efficiency and data consolidation) and SRM (Site Recovery Manager, that manages a full failover and fallback of a disaster event from a centralised console. Additionally full disaster simulation and testing is supported without interrupting the production environment).

Hyper-V



Hyper-V is a commercial hypervisor provided by Microsoft. While designed for running Windows, being a hypervisor it will run any operating system supported by the hardware platform. As a commercial hypervisor, the licensee must bear the cost of licensing Hyper-V itself. Arguably, the hypervisor itself is less well tested in the market place than any other hypervisor. Guest server performance appears reasonable, and is particularly good with Windows guests as expected. However, many orchestration actions can take more time than with KVM. Both networking and storage are a little limited which can affect the ability to scale. Until recently it has rarely been adopted for large deployments in enterprise environments although it has been used widely in small and medium business environments for a number of years.

Table 2 compares the hypervisors discussed above.

Table 2: Comparison of key open source and commercial hypervisor technologies

Feature	KVM	Xen	ESXi	Hyper-V
Licence	Open Source (free)	Open (free)	Source	Proprietary
Full virtual.	yes	yes	yes	yes
Hw-assisted	no	yes	yes	yes
Para-virtual.	no	yes	yes	yes
Architecture	X86-X64	X86 X86-64 ARM	X86 X86-64	X86 X86-64
CPU Scheduling Features	Linux schedulers (completely fair queuing scheduler, maximum throughput, weighted fair queuing)	SEDF (Simple Earliest Deadline First) Credit - proportional fair share	Proportional Share-based Algorithm, Relaxed Coscheduling, Distributed Locking with scheduling Cell	Control with VM reserve, VM limit, relative weight
SMP Scheduling Features	SMP-Aware Scheduling	Work-Nonconserve, WorkConserve	CPU Topology – aware load balancing	CPU Topology based scheduling
Speed	Up to near native	Up to native	Up to near native	Up to near

Relative to Host OS	native
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2.2.1.3 Containers

The alternative approach to hypervisor-based virtualisation is OS virtualisation, where the virtualisation software layer is installed on top of the operating system. This approach is commonly referred to as "containers". Figure 10 provides a high-level view of the differences between container-based and hypervisor-based virtualisation.

One of the most popular container technologies is Docker (31). All of the guest systems run on top of this layer using the same operating system as the host OS, but with each guest having its own resources and running in complete isolation from the other guest machines. The main identifying differentiator for OS virtualisation is the fact that every guest OS must be identical to the host. This is a cost effective and efficient approach, but it is only practical for certain situations.

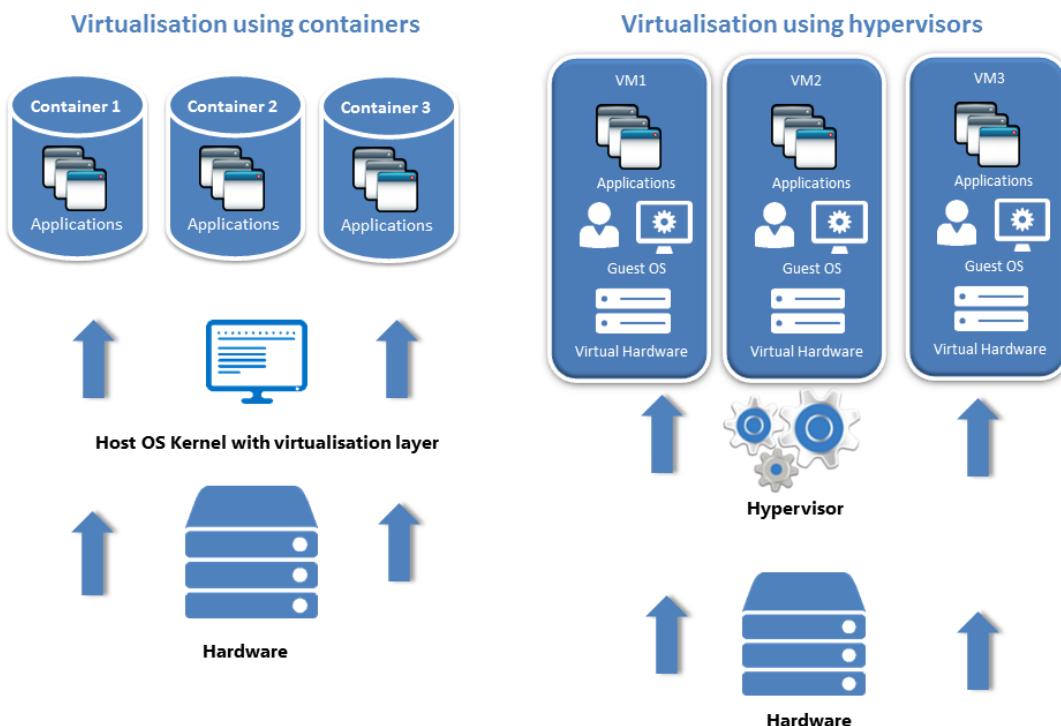


Figure 10: Hypervisor versus container based virtualisation approaches

However containers currently lag behind VMs from a security standpoint particularly for isolation since the only way to have real isolation with Docker is to either run one Docker per host, or one Docker per VM. A comparison of the hypervisor versus container based virtualisation approaches is presented in Table 3.

Table 3: Comparison of Hypervisors and Container Approaches

	Container-based	Hypervisor-based
Common Features	(i) Migration between hardware nodes	

	(ii) Root access (iii) Web-based remote control (restart, shutdown) (iv) Backup.	
Operating System	Limited number of simultaneously OSs, container-based virtualisation.	Highly flexible and allows installation of most operating system.
Advantages	More efficient, high concentration of containers per hardware node (hundreds of containers per hardware node), low overhead per container. Potentially more economical and is charged less than hypervisor-based virtualisation. QoS is best effort. The kernel is upgraded by the provider.	Full control on the operating system and its parameters. Full control on version and upgrade of the OS. Hardware resources are fully dedicated to VMs. QoS (quality of service) is therefore a commitment. The virtual machine presents itself exactly as a hardware node. Mix of operating system on the same hardware node.
Disadvantages	No control on the kernel: only the provider controls the version and upgrades of the kernel. Only one kernel can run on the hardware node. The provider generally supports a limited number of OS. Security isolation concerns.	More costly and higher overhead per virtual machine. Customer has full responsibility on maintenance. Less VMs can run on a hardware node (order of magnitude: a few per hardware node).
Licence	Operating system licence included in the container price.	OS licence fees not included in the virtual machine price. It can be bought over the provider or bring your own licence.
Set-up	Quick, usually ready in a few seconds. Fully automation possible.	Can have a longer set-up phase, from a few minutes to hours depending on the OS. Install times reduced with automation in cloud environments.

2.2.2 Compute, Network I/O and Storage Virtualisation

Virtualisation has now extended into the domains of *storage* and *infrastructure (L2/L3) network* resources. *Storage virtualisation* is replacing the need for locally attached storage through pooling of physical storage from multiple network storage devices into what appears to be a single storage device that is accessed via a controller. Similarly with *network I/O virtualisation*, a single physical network interface

card can be abstracted into virtual NICs or L2 virtual switching and L3 virtual routing to provide inter/intra-VM connectivity or connectivity to the transport network.

The key value that virtualisation brings to those new domains is improved scalability and resource utilisation. Additionally, virtualisation supports the centralisation of administrative tasks such day-to-day updates or large-scale deployments and migrations. These capabilities are very important in enabling the roll-out of VNFs into networks by service providers.

2.2.2.1 Microprocessor Virtualisation

Microprocessor virtualisation extensions consist of extra instruction sets called *virtual machine extensions* (VMX). There are two modes to run under virtualisation: VMX *root* operation and VMX *non-root* operation. Normally only the hypervisor runs under root operation, while OS's run on top of the VMs under non-root operation. Software running on top of the VMs is commonly referred to as 'guest software'.

More recent microprocessors have an extension called EPT (Extended Page Tables) which allow each guest to have its own page table to keep track of memory addresses. Without this extension, the VMM has to exit the virtual machine to perform address translation. The exiting-and-returning task reduces performance. Context switching and its associated cost can have a significant impact on the performance of VNF applications. While EPT increases virtualisation performance, careful consideration must be given to overall design of the VNF.

2.2.2.2 Intel Virtualisation Technology (Intel VT)

Intel Virtualisation Technology (Intel VT) is a set of hardware enhancements to Intel server and client platforms that provide software-based virtualisation solutions. Intel VT allows a platform to run multiple operating systems and applications in independent partitions, allowing one computer system to function as multiple virtual systems. **VT-x** provides basic support for virtualisation software and affords the capabilities needed to deliver hardware assistance to a VMM. VT-x allows virtual machine to run at privilege levels in the processor that enable its proper operation. On some motherboards the VT-x feature must be enabled in the BIOS before applications can make use of it.

2.2.2.3 AMD's Virtualisation (AMD-V) Opteron

AMD's Virtualisation (AMD-V) technology takes some tasks that virtual machine managers (VMMs) perform in software, through emulation, and simplifies them through enhancements to the AMD Athlon 64 and Opteron instruction set. AMD Virtualisation Technology was announced in 2004, under the code-name Pacifica, and AMD released technical details in mid-2005. The latest release AMD-V 2.0 includes extra features, such as I/O level Virtualisation, and Extended Migration. AMD-V is supported in almost all latest AMD mobile and desktop processors, whereas AMD V supported only in the latest generation of AMD server-class CPUs.

2.2.2.4 Storage Virtualisation

Storage virtualisation consists in implementing an abstraction layer between physical resources (disks and storage networking) and logical resources that can be served up to applications (VNFs in case of T-NOVA). Multiple benefits are offered by virtual storage. It makes the overall pool of storage easier to manage, and enables the allocation of storage as and when it is needed. Furthermore, it can optimise power utilisation, and improves the ability to support disaster recovery scenarios, as data can be replicated and moved within the overall storage pool with minimum disruption to users and applications.

Storage virtualisation can occur internally within storage arrays (usually known as *storage-based virtualisation*), or externally among storage arrays (usually called *network-based storage virtualisation*). External virtualisation can operate across arrays of the same brand and model or in a network of heterogeneous arrays. External virtualisation can facilitate tiered storage to disparate devices as well as providing simplified management of storage across a large enterprise. Implementation choices should take into account the characteristics of the whole virtualised environment, since there are different underlying technologies whose effectiveness and performance can depend upon the kind of server virtualisation environment in place. The most common enabling technologies are as follows:

- **Thin Provisioning** - storage-optimisation technique that relies on on-demand allocation of blocks of data, rather than on traditional upfront block allocation. This approach makes it possible to implement over-allocation, storage capacity to host applications than has actually been provisioned). It may be paired with other techniques, like thin reclamation and data de-duplication. Thin reclamation automatically reclaim unused space associated with deleted data within system storage volumes, while data de-duplication is a data compression technique for eliminating duplicate copies of redundant data. Both techniques ensure that thin volumes stay as lean and efficient as possible. These techniques are popular and integrated in many enterprise storage array products from companies such as HP, 3PAR, and EMC, VNX (32).
- **Automatic Storage Tiering** - this approach is based on the ability to save data on different tiers of disks, each characterised by different performance and redundancy schemes. For example, a typical 2-tier array could have SSD disks as Tier 0 and SAS disks as Tier 1. Automatic Storage Tiering is a technique used to automatically promote or demote data between storage tiers, based on actual application usage. Many storage vendors (e.g. HP with 3PAR Adaptive Optimisation (33) and EMC with its FAST technology (34)) nowadays implement automatic storage tiering in hardware.
- **Virtual SAN solutions** - For many years, local storage was not the best option for virtualised infrastructures, however due to technology advances and, in particular, the introduction of Solid State Disks, it can now be used as an effective and cheaper solution with respect to standard NAS or SAN enterprise solutions. Moreover, software vendors have introduced

functionality to use shared local storage into a fully-featured shared storage array, for example VMware Virtual SAN and HP StoreVirtual VSA.

2.2.2.5 Software and Hardware -Assisted Network Virtualisation

The Network Virtualisation process strongly involves the lower levels of the ISO/OSI protocol stack: virtual machines require L2 NICs to connect to virtual network segments; all the VMs in a segment need to connect to one or more (virtual) switches that manage different VLANs.

Two main approaches are commonly used to implement virtualisation at the edge of the network: software-assisted and hardware-assisted virtualisation.

Software-assisted network virtualisation

In software-assisted network virtualisation, communication capabilities are provided by the hypervisor through vSwitches, according to the *Edge Virtual Bridging* (EVB) specifications. More specifically, Edge Virtual Bridging is the term for a range of new technologies and protocols that are being standardised in terms of coordination and management of virtualised architectures at the edge of the network. A vSwitch is a software component managed by the hypervisor that, in turn, manages both the traffic flows from and to VMs that are running on a physical server. EVB technologies are embraced within the IEEE 802.1Qbg standardisation project (35). The two most common approaches included in EVB and currently used in commercial available technologies are:

- Virtual Ethernet Bridge (VEB),
- Virtual Ethernet Port Aggregator (VEPA).

External communications (i.e. the communication between a VM and an external node) are managed by both VEB and VEPA in the same way: packets are sent through the physical interface of hosting node to reach external network. This allows the traffic to be handled by an external physical switch and, consequently, to be monitored, managed and secured using all the tools available to the physical switch. The difference between VEB and VEPA is related to the management of internal communication (i.e. the communication between VMs running on the same physical host).

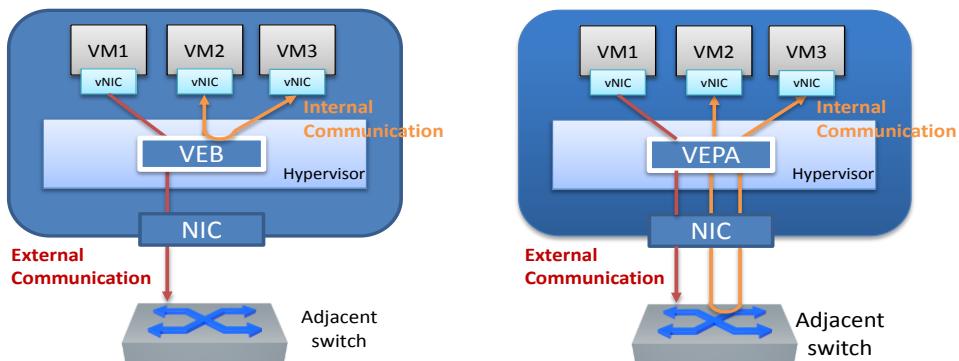


Figure 11: VEB vs. VEPA

Using the first approach, internal communications are managed directly by the *VEB* that resolves the L2 destination address of the target machine and avoids sending traffic through external switches. Consequently, the internal traffic is managed only by software, and, for this reason, it is not captured by the external network devices: this makes network traffic monitoring difficult and, at the same time, delegates to the host the network address resolution overhead, affecting the performance. On the contrary, *VEPA* forces the traffic between local VMs to pass through the adjacent real switch. Therefore, using this approach the traffic can be easily monitored and secured, reducing the node overhead. On the other hand, the internal traffic uses the physical port, with impacts to bandwidth and latency as a result.

Hardware-assisted network virtualisation

The disadvantage of a software-assisted approach is that, when multiple guests run on the host and the network traffic volumes are high, the virtual switch can be a potential bottleneck. To avoid this, multiple NICs should be used in the host, adjusting the virtual switch connected to each NIC such that the network bandwidth used by the guest can be distributed. However, this method is not particularly efficient for some tasks, such as placing guests dynamically and moving a guest to another host using live migration. To address these limitations Intel has developed its VT-c suite of technologies.

Single Root I/O Virtualisation (SR-IOV) enables a single PCI Express (PCIe) network adapter to appear to the hypervisor as multiple special-purpose network adapters. These special-purpose network adapters, termed Virtual Functions (VF), are only available for direct presentation to VMs. By providing a VF directly to a VM, the hypervisor's virtual switch is no longer required to process network traffic. This hypervisor bypass increases network throughput, lowers latency, and reduces overall CPU utilisation.

Network adapters that feature SR-IOV are comprised of one Physical Function (PF) and multiple VFs per port. The PF is responsible for the management and configuration of its associated VFs. On the host server, the administrator configures a PF to present a defined number of VFs.

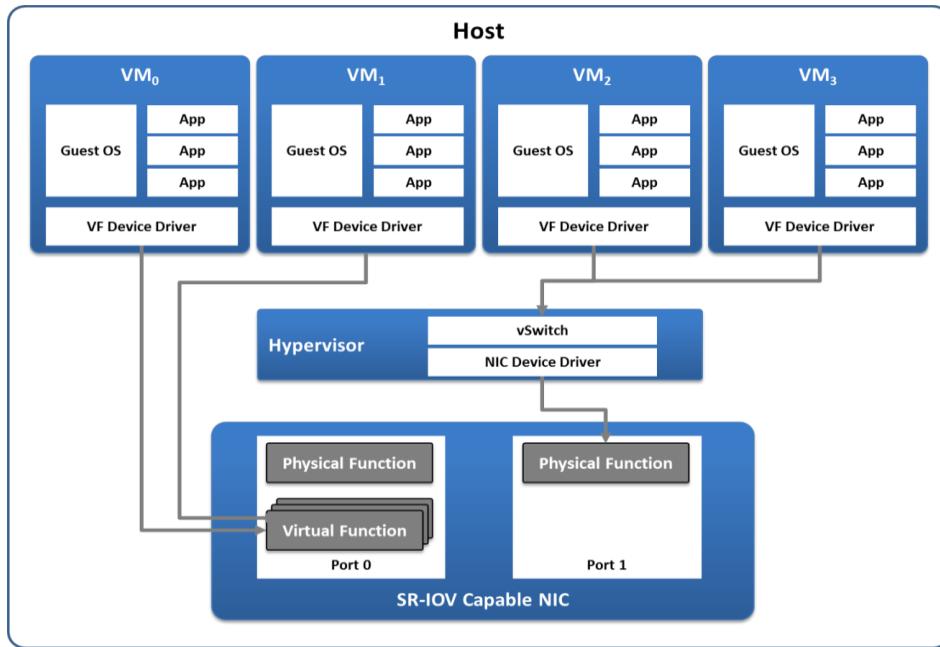


Figure 12: SR-IOV PF and VF conceptual overview

Virtualisation technology for Directed I/O (**VT-d**) developed by Intel is implemented in I/O devices and provides support for virtualisation of I/O transactions. It helps the VMM to better utilise hardware by improving application compatibility and reliability, and providing additional levels of manageability, security, isolation, and I/O performance. VT-d is primarily implemented in a chipset, and not in the CPU itself. In emulation based I/O, the intermediate software layer controls all the I/O between the VMs and the device. The data gets transferred through the emulation layer to the device and vice versa (36).

Virtualisation technology for Connectivity (**VT-c**) is a collection of input/output (I/O) virtualisation technologies primarily concerned with I/O. VT-c is complementary to but independent of VT-d. The key technologies are:

- I/O Acceleration Technology for the Reduction of CPU Loads – For network applications the key technology is Intel's Data Plane Development Kit (DPDK);
- Virtual Machine Device Queues (VMDq) improve traffic management within the server by offloading traffic sorting and routing from the hypervisor's virtual switch to an Intel Ethernet Controller for the reduction of system latency;
- Virtual Machine Direct Connect (VMDc) is implemented using the PCI-SIG standard called Single Root I/O Virtualisation (SR-IOV) which allows partitioning of a single Ethernet Server Adapter port into multiple virtual functions. Administrators can use these virtual ports to create multiple isolated connections to virtual machines for the improvement of network I/O throughput.

2.2.2.6 Data Plane Development Kit (DPDK)

One of the most important issues which must be tackled in NFV is the plane performance for VNFs. In fact, even if the commercial vSwitches offers good

performance, they are generally not comparable with real network device. To enable VNFs to be efficiently deployed and provide the performance that support their requirements the internal mechanisms for communication management within hypervisors are being improving.

One approach that is being widely adopted is **Intel's Data Plane Development Kit (Intel DPDK)**. It is a set of libraries and drivers for fast packet processing on x86 platforms that can improve packet-processing performance by up to ten times. DPDK support, which actually depends on the processor, is integrated in all recent Intel Atom and Xeon processors.

In order to accelerate the adoption of DPDK and its usage in NFV deployments, Intel also released a DPDK-enabled version of the popular OpenvSwitch, called Intel DPDK vSwitch (37). **Open vSwitch** (38) is an open source virtual switch that supports distribution across multiple physical servers. It can be integrated with multiple Linux-based hypervisors (including Xen, XenServer, KVM and VirtualBox) and supports different features, like STP, NIC bonding with source MAC load balancing, IPv6 support, standard 802.1Q VLAN tagging and trunking, tunnelling protocols (GRE, VXLAN, IPsec), monitoring capabilities of internal VM communication via NetFlow or sFlow, QoS control, OpenFlow protocol and multi-table forwarding pipeline, and user-space forwarding engine options, and so forth.

Open vSwitch architecture is composed by a small portion of in-kernel code, a kernel module called *openvswitch_mod.ko*, which implements the part of the behaviour of switch that interacts with the *ovs-vswitchd* demon, running in user-space. These modules implement the switching logic. Moreover, there is also another module, called *ovsdb-server*, which behaves as a lightweight database containing information regarding the configuration parameters of the switch and it is queried by the *ovs-vswitchd* module. There are also other modules that provide interfaces which are useful for configuring the system both locally and remotely.

Coupling OpenvSwitch and Intel DPDK acceleration technology, **Intel DPDK vSwitch** has been developed with the aim of realising a virtual switching platform with high performance capabilities, reducing network access time of the VM traffic and the computation overload on the hypervisor. This specific solution is based on QEMU and is part of an open source project called *Packet Processing* (39).

The *Intel DPDK vSwitch* has been realised through modification of the Open vSwitch kernel forwarding module (data plane) by building the switching logic directly on top of the DPDK library: it significantly improves the switching throughput. Intel DPDK vSwitch currently provides four different communication methods between the virtual machine and the host (*each one optimised for a specific communication application*) with the purpose to optimise the copy operations due to the VMs' communication. This product, which is freely available, is currently focused on fast L2 switching, with more advanced features (like dynamic flows, tunnel support and multiple table support) coming in later releases.

2.2.3 Cloud Environments and Controllers

Cloud management platforms are integrated tools that provide management of cloud environments. These tools incorporate self-service interfaces, provisioning of system images, enabling metering and billing, and providing some degree of workload optimisation through established policies. Through the self-service interface (e.g. based on OCCI) the user can request virtual infrastructure. This request is issued to a Cloud Controller, which provisions this virtual infrastructure somewhere on available resources within the DC. The Cloud Controller provides the central management system for cloud deployments as shown in Figure 13.

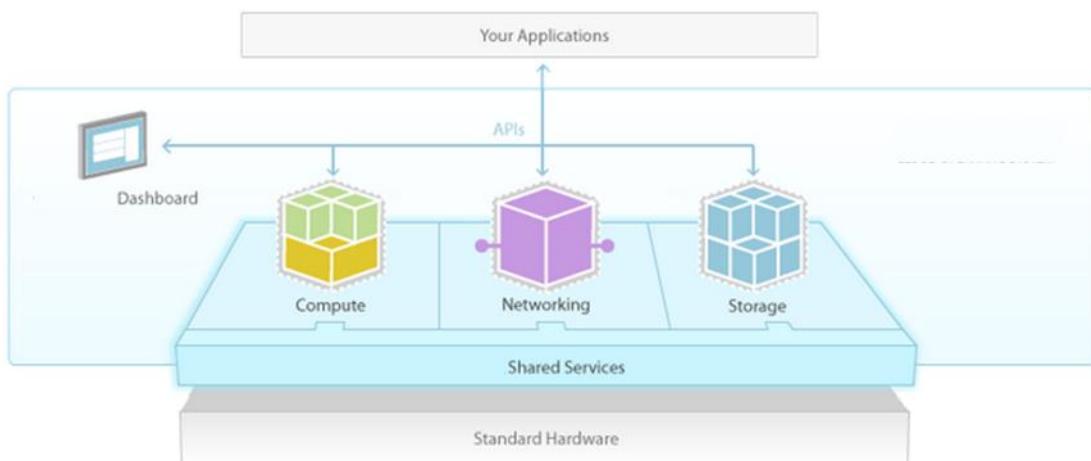


Figure 13: Cloud Management System Deployments

The most popular cloud management platforms include open source solutions such as OpenStack, CloudStack and Eucalyptus and commercial solutions from Microsoft and VMware. This section provides an overview of some of these solutions, on the Cloud Controller component. In the T-NOVA context, the Cloud Controller is a key component that needs to deliver end-to-end provisioning of virtual infrastructure, to enable full control over it and also to provide a detailed and real-time view of the infrastructure load.

2.2.3.1 OpenStack



OpenStack is a cloud OS that controls large pools of compute, storage, and networking resources throughout a DC, all managed through a dashboard that gives administrators control while empowering their users to provision resources through a web interface (40; 40). As an open source solution, OpenStack is developed and supported by a global collaboration of developers and cloud computing technologists. The project seeks to deliver solutions for all types of clouds by being simple to implement, scalable, and feature rich. The technology consists of a series of interrelated projects delivering various components for a cloud infrastructure solution. All OpenStack source code is available under an Apache 2.0 license.

OpenStack has a modular design that enables integration with legacy and third-party technologies. It is built on a shared-nothing, messaging-based architecture with modular components, each of which manages a different service; these services, together to instantiate an IaaS Cloud. The primary component of the cloud operating environment is the Nova compute service. Nova compute orchestrates the creation and deletion of compute/VM instances. Nova is designed to operate as much as possible as hypervisor-agnostic. It works with open source libraries such as libvirt. Similar to other OpenStack components, Nova is based on a modular architectural design where services can be co-resident on a single host or, more commonly, on multiple hosts. The core components of Nova include the following:

- The nova-api accepts and responds to end-user compute API calls. It also initiates most of the orchestration activities (such as running an instance) as well as enforcing some policies.
- The nova-compute process is primarily a worker daemon that creates and terminates VM instances via hypervisor APIs (XenAPI for XenServer/XCP, libvirt for KVM or QEMU, VMwareAPI for vSphere, etc).
- The nova-scheduler process keeps a queue of VM instance requests and for each request it determines where the VM instance should run (specifically, which compute node it should run on).
- The Nova service itself does not come with a hypervisor, but manages multiple hypervisors, such as KVM or ESXi. Nova orchestrates these hypervisors via APIs and drivers. For example, Hyper-V is managed directly by Nova and KVM is managed via libvirt, while Xen and vSphere can be managed directly or through management tools such as libvirt and vCenter for vSphere, respectively.

2.2.3.2 Eucalyptus

 **Eucalyptus** (Elastic Utility Computing Architecture Linking Your Programs To Useful Systems) is an open-source Cloud that provides on-demand computing instances and shares the same APIs as Amazon's EC2 cloud. Eucalyptus was designed as a highly-modular framework in order to enable extensibility with minimal effort (41). The Cloud Controller (CLC) in Eucalyptus acts as the Cloud entry-point by exposing and managing the virtualised resources. The CLC offers a series of web services oriented towards resources, data and interfaces (EC2-compatible and Query interfaces). In addition to handling incoming requests, the CLC acts as the administrative interface for cloud management and performs high-level resource scheduling and system accounting. The CLC accepts user API requests from command-line interfaces like euca2ools or GUI-based tools like the Eucalyptus Management Console and manages the underlying compute, storage, and network resources.

2.2.3.3 Cloudstack

 **Apache CloudStack** is open source software designed to deploy and manage large networks of virtual machines, as a highly available, highly scalable Infrastructure as a Service (IaaS) cloud computing

platform (42). CloudStack is used by a number of service providers (e.g. BT) to offer public cloud services, and by many companies to provide an on-premises (private) cloud offering, or as part of a hybrid cloud solution. CloudStack is a turnkey solution that includes the entire "stack" of features most organisations want with an IaaS cloud: compute orchestration, Network-as-a-Service, user and account management, a full and open native API, resource accounting, and a first-class User Interface (UI).

CloudStack is a framework that allows pooling of computing resources in order to IaaS cloud services that can be used to provide IT infrastructure such as compute nodes (hosts), networks, and storage as a service to the end users on demand. CloudStack Management Server is the main component of the framework, consisting of managing resources such as hosts, storage devices and IP addresses. The Management Server runs on a dedicated host in a Tomcat container and requires a MySQL database for persistence. The Management Server controls allocation of VMs to hosts and assigns storage and IP addresses to VM instances. This component also controls or collaborates with the hypervisor layers on the physical hosts over the management network and thus controls the IT infrastructure.

2.2.3.4 VMware vCloud Suite



VMware's vCloud Suite - is a comprehensive, integrated cloud platform for building and managing cloud environments (43). Tools for cloud management are delivered through VMware vCenter Server, a centralised and extensible platform for managing virtual infrastructure. The tools included in the vCenter Server framework support: configuration of ESX servers and VMs, performance monitoring throughout the entire infrastructure, using events and alerts. The objects in the virtual infrastructure can be securely managed with roles and permissions.

2.2.4 Network Resource Virtualisation and Management

Virtualising the Network Infrastructure refers to the environment that supports the coexistence of multiple Virtual Networks (VNs) on the same physical substrate, also realising different isolated domains of nodes characterised by a specific topology that can be managed as real networks. In the T-NOVA architecture those nodes are Virtual Machines (VMs) that host the VNFs. VMs are connected to VLANs that can be within a single DC or distributed over different DCs. In this last case, tunnelling protocols are needed in order to encapsulate the VLAN L2 frames in L3 transport networks. In the T-NOVA architecture the inter-DC connectivity is provided by the Transport Network Manager (TNM), whose capabilities and functionalities are discussed in Section 4.7.

This section provides an overview of the common Tunnelling Protocols which can be of interest to T-NOVA, followed by a review of the major SDN initiatives of interested finally some common open source NaaS frameworks are reviewed.

2.2.4.1 Tunnelling Protocols

As mentioned above, a single physical server may host a number of different VNF services that need to be connected to different VLANs. Moreover, each of these

VLANs may span several DCs interconnected via L3 networks; all the VMs in a segment have to be connected to a virtual switch that can manage different VLANs.

The most important standardisation activities carried out on VLAN specification is 802.1Q. This standard however does inherently support the expansion of VLANs over L3 technologies. The continuity of L2 segments (i.e. VLANs) among different DCs is a requirement for the T-NOVA architecture. In order to preserve the L2 segments continuity amongst the NFVI-Point of Presence (NFVI-PoP), tunnelling protocols (heavily used in today's cloud services) will be exploited.

In the following subsections a brief introduction to IEEE 802.1Q is presented and the three most common tunnelling protocols are discussed namely VxLAN (44), Network Virtualization using Generic Routing Encapsulation (NVGRE) (45) and Stateless Transport Tunneling (STT) (46).

IEEE 802.1Q and L2 Virtualisation

IEEE 802.1Q is the networking standard that supports virtual LANs (VLANs) on an Ethernet network. The standard defines a system of VLAN tagging for Ethernet frames and the accompanying procedures to be used by bridges and switches in handling these frames. The standard also contains provisions for a quality of service prioritisation scheme (commonly known as IEEE 802.1p) and defines the Generic Attribute Registration Protocol.

Network segments, which are VLAN-aware (i.e., IEEE 802.1Q conformant) may include VLAN tags. Traffic on a VLAN-unaware (i.e., IEEE 802.1D conformant) segment of the network will not contain VLAN tags. When a frame enters the VLAN-aware segment of the network, a tag is added to represent the VLAN membership of the frame's port or the port/protocol combination, depending on whether port-based or port-and-protocol-based VLAN classification is being used. Each frame must be distinguishable as being within exactly one VLAN. A frame in the VLAN-aware portion of the network that does not contain a VLAN tag is assumed to be flowing on the native (or default) VLAN.

The standard was developed by IEEE 802.1, a working group of the IEEE 802 standards committee, and continues to be actively revised with notable revisions including IEEE 802.1ak, IEEE 802.1Qat and IEEE 802.1Qay.

In T-NOVA, 802.1q VLANs can be established within a NFVI-PoP, e.g. to facilitate communication among Virtual Network Function Components (VNFCs) of the same service.

L3 tunnelling protocols

While L2 virtualisation seems adequate within a single L2 topology, transporting L2 frames via a L3 network (e.g. a wide-area transport network interconnecting data centres) mandates the use of tunnelling protocols.

The aim of a tunnelling protocol is to virtualise (abstract) the physical network topology and bring functionality like isolation of multiple tenants, isolation of overlapping address space between multiple tenants, expanded VLAN/tenant ID address space, and enhanced VM mobility by providing L2 services over an L3

network (L2 over L3). In T-NOVA, the use of a tunnelling protocol is considered essential in order to interconnect VNFCs dispersed among remote NFVI-PoPs.

The three commonly used L3 tunnelling protocols are:

- **VXLAN** - A Layer 2 overlay scheme over a Layer 3 network. It uses MAC Address-in-User Datagram Protocol (MAC-in-UDP) encapsulation to provide a means to extend Layer 2 segments across the data centre network. VXLAN is a solution to support a flexible, large-scale multitenant environment over a shared common physical infrastructure. The transport protocol over the physical data centre network is IP plus UDP (44).
- **NVGRE** - Network virtualisation method that uses encapsulation and tunnelling to create large numbers of virtual LANs (VLANs) for subnets at layer 2 that can extend across dispersed data centres) at layer 3 . The purpose is to enable multi-tenant and load-balanced networks that can be shared across on-premises and cloud environments. NVGRE was designed to solve problems caused by the limited number of VLANs that the IEEE 802.1Q specification enables, which are inadequate for complex virtualised environments, and make it difficult to stretch network segments over the long distances required for dispersed data centres (45),
- **STT** - Proposed by Nicira, it is written from a software centric view point rather than from a network centric view point. The main advantage of the STT proposal is its ability to be implemented in a software switch while still benefitting from NIC hardware acceleration. STT uses a 64-bit network ID rather than the 24 bit IDs used by NVGRE and VXLAN. STT is particularly useful when some tunnel endpoints are in end-systems, as it utilises the capabilities of standard network interface cards to improve performance (46),

Each protocol has a different set of advantages and disadvantages. Table 4 presents the main strengths and weaknesses for each protocol.

Table 4: Common VLAN Tunnelling Protocols

Item	VxLAN	NVGRE	STT
Proposed/used by	VMware, Cisco, Broadcom, Red Hat	Microsoft, HP, Intel, Broadcom	Nicira, VMware
Encapsulation	UDP	GRE	TCP
Standard	No	No	No
Overhead (additional header information)	54 bytes	46 bytes	80 bytes of new header for the first segment of this packet, 62 for each following segment
Tenant space (network identifier length)	24-bit	24-bit	64-bit

OpenFlow	Yes (OF v1.4)	No?	No?
OVS	Yes	Yes	Yes
Hardware-based TCP Segmentation Offload (TSO) support	No	No	Yes

2.2.4.2 Software Defined Network Controllers

A key abstraction of the SDN paradigm is the separation of the network control and forwarding planes. Conceptually, in SDN networks, resources are treated as a dynamic collection of arbitrarily connected forwarding devices with minimal intelligence. The control logic is implemented on top of a so-called SDN controller. The controller is a logically centralised entity which is responsible for a set of tasks, including the extraction and maintenance of a global view of the network topology and state, as well as the instantiation of forwarding logic appropriate to a given application scenario. In practice the controller manages connections to all substrate switches using a southbound protocol such as OpenFlow, and installs, modifies and deletes forwarding entries into the forwarding tables of the connected switches by using protocol specific control messages.

While it is possible to implement single purpose controllers, e.g. for L2 forwarding or routing, available SDN controller implementations typically provide an extendable software platform on top of which SDN applications may be developed and deployed. Such a controller framework offers easy to use (northbound) APIs to the functionality provided by the SDN substrate. Further, it may include helper functions that provide, for example topology discovery or flow statistics collection. As a result an SDN controller may be regarded as a layer between the SDN substrate and the SDN application layer, which implements the logic for concrete network services (see Figure 14). Typically, SDN controllers are executed on commodity server hardware. While conceptually SDN controllers are centralised, in real world deployments the controller functionality may be distributed across multiple devices to ensure scalability and failure resilience.

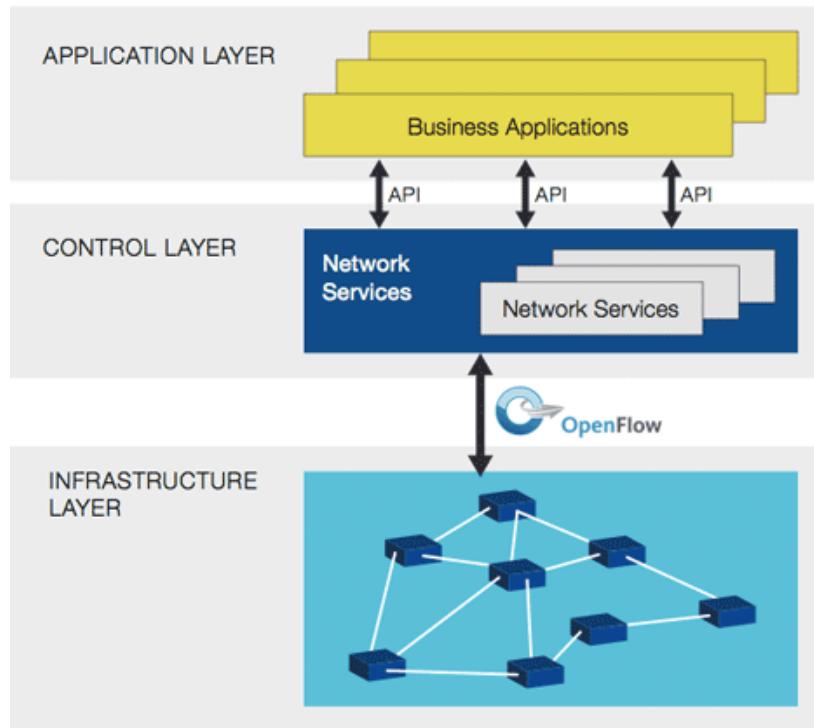


Figure 14: Open Networking Foundation Software-Defined Network Architecture

The NOX controller was the first widely available OpenFlow controller (47). NOX was originally developed by Nicira and released as open-source software. Due to its early availability and its simplicity NOX quickly became the de-facto reference design for OpenFlow controllers. As a result it has been used to test new OpenFlow features, novel controller ideas and it has been employed extensively in research and feasibility studies. NOX applications – called modules – are implemented using the C programming language. NOX is event based; each module essentially consists of a collection of callback functions, triggered by the arrival of specific OpenFlow protocol messages. A spin-off of NOX called POX (48) enables the use of Python for programming modules. While NOX/POX is extremely versatile it is not primarily aimed for production use, as it is not optimised for performance and stability and lacks resilience features.

Other controller frameworks aimed at deployment in production environments, include Beacon (49), Maestro (50) and FloodLight (51), all of which are implemented in Java. FloodLight is the open source basis for Big Switch's commercial OpenFlow controller. OpenDayLight (52) is currently the newest and also largest SDN controller platform. It is backed by the Linux Foundation and developed by an industrial consortium, which includes Cisco, Juniper and IBM, among many others. OpenDayLight includes numerous functional modules which are interconnected by a common service abstraction layer. Further, OpenDayLight provides a flexible northbound interface using Representation State Transfer APIs (REST APIs), and includes support for the OpenStack cloud platform. Table 5 summarises the main features of existing SDN controllers:

Table 5: Key features of common SDN controllers

Controller	Developer	Open Source	Language	Openflow support	Openstack support
NOX	Nicira	Yes	C++ / Python	v1.0	No
POX	Nicira	Yes	Python	v1.0	No
Maestro	Rice University	Yes	Java	v1.0	No
Beacon	Stanford University	Yes	Java	v1.0	No
Floodlight	Big Switch Networks	Yes	Java	v1.0	Quantum plug-in
ONOS	Open Networking Lab	Yes	Java		
Ryu	NTT	Yes	Python	v1.0-v1.4 & Nicira extensions	Neutron plug-in (Havana and Grizzly)
Nodeflow	CISCO	Yes	Javascript		
Trema	NEC	Yes	C & Ruby	v1.0	Quantum plug-in
OpenDayLight	Linux Foundation	Yes	Java	v1.0, v1.3	Neutron plug-in
Iris	ETRI	Yes	Java	v1.0.1-v1.3.2	
MUL	Kulcloud	Yes	C	v1.0, v.1.3	
Jaxon	Independent developers	Yes	Java		
JunosV Contrail	Juniper	No		No	Yes

Another framework that is attracting attention is **OpenContrail** led by Juniper Networks. Actually it is more than a SDN controller: it is a modular project that provides an environment for network virtualisation and published northbound APIs. In particular, the network virtualisation is provided by means of a set of building blocks and high level policies; it integrates an SDN controller to support network programmability and automation, and a well-defined data model to describe the desired state of the network; an analytics engine is designed for very large scale ingestion and querying of structured and unstructured data. It also provides an extensive REST API to configure and gather operational and analytics data from the system.

2.2.4.3 NaaS platforms

Network service delivery and management models remain an area of on-going evolution, and are additionally being continually revised in tandem with the constantly evolving needs of the R and E community. The network as a service concept represents an interesting service model from which T-NOVA can benefit. Network as a Service (NaaS) is a business model for delivering network services virtually over any network on a pay-per-use basis. It is not a new concept. However, its development has been hindered by some of the same concerns that have affected also other cloud computing services, such as high availability or service level agreements. In the following section a brief review of the NaaS platforms is presented.

Open Network as a Service (OpenNaas)

The NaaS model has been instantiated in the OpenNaas easy prototyping and proof casing of NaaS concepts. OpenNaas is an open-source framework, which provides tools for managing the different resources present in any network infrastructure. The software platform was created in order to offer a neutral tool to the different stakeholders comprising an Open Access Network (OAN). It allows them to contribute and benefit from a common NaaS software-oriented stack for both applications and services. It is based on a lightweight, abstracted, operational model, which is decoupled from actual vendors' specific details, and is flexible enough to accommodate different designs and orientations. In fact, the OpenNaas framework provides tools to implement the logic of an SDN-like control and management plane on top of the lightweight abstracted model. The manner in which it is designed allows the deployment of VNFs within it. The elements loaded in OpenNaas contains a model which stores the information about the resource, and a set of capabilities that allows to access to the data of the model.

Figure 15 depicts the layered architecture of the framework, with the platform layer, the resource abstraction layer with the NaaS manageable units, and the upper layer, where the network intelligence resides, as well as the integration of the framework with third-party components. Besides, the resource abstraction, the core platform concepts are also depicted. Different OpenNaas deployment examples can be found in the following list of European projects extending the OpenNaas framework: OFERTIE (53), CONTENT (54), and SODALES (55). Furthermore, authors in (56) used OpenNaas in order to build a first proof-of-concept pilot for the VNF creation and management.

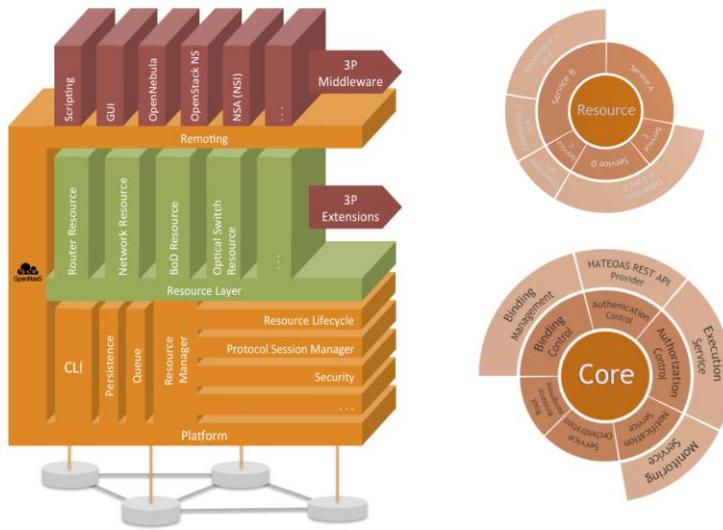


Figure 15: OpenNaaS Architecture (left), NaaS Resource Abstraction (right)

OpenStack Neutron

OpenStack Neutron (57), historically known as Quantum, is an OpenStack project focused on delivering Networking as a Service (NaaS). It is designed to address deficiencies in “baked-in” networking technology found in cloud environments, as well as the lack of tenant control (in multi-tenant environments) over the network topology and addressing, which makes it hard to deploy advanced networking services.

Neutron provides a way for organisations to make it easier to deliver networking as a service in the cloud and provides REST APIs to manage network connections for the resources managed by other OpenStack services.

It is designed to implement a “plugin” mechanism that will provide an option for network operators to enable different technologies via the Neutron API making it technology agnostic.

Neutron provides native multi-tenancy support (isolation, abstraction and full control over virtual networks), letting tenants create multiple private networks and control the IP addressing on them, and exposes vendor-specific network virtualisation and SDN technologies.

As a result of API extensions, administrators and users have additional control over security and compliance policies, QoS monitoring and troubleshooting, the ability to build sophisticated networking topologies, as well as the ability to easily deploy advanced network services, such as a firewall, L2-in-L3 tunnelling, end-to-end quality of service support intrusion detection or VPN.

The core Neutron API includes support for Layer 2 networking and IP Address Management (IPAM), as well as an extension for a Layer 3 router construct that enables routing between Layer 2 networks and gateways to external networks. It is based on a simple model of virtual networks, subnet, and port abstractions to describe networking resources. Network is an isolated layer-2 segment, analogous to a VLAN in the physical networking world. More specifically, it is a broadcast domain reserved for the tenant that created it or explicitly configured as shared. Neutron

includes a growing list of plugins that enable interoperability with various commercial and open source network technologies, including routers, switches, virtual switches and SDN controllers.

Starting with the Folsom release, Neutron is a core and supported part of the OpenStack platform. However, it is a standalone and autonomous service that can evolve independently to OpenStack.

OpenDaylight Virtual Tenant Network (VTN)

OpenDaylight Virtual Tenant Network (VTN) provides multi-tenant virtual network on an SDN controller (58). Traditionally physical networks have been configured as silos for each department within an organisation (or for each customer) by a service provider. This has resulted in significant and unnecessary hardware investments and operating expenses due to underutilised, redundant network equipment required to implement this scheme.

VTN addresses this problem by providing an abstraction that enables the complete separation of the logical plane from physical plane of the network. This allows users to design and deploy virtual networks for their customers without needing to know the physical network topology or underlying operating characteristics. The VTN also allows the network designer to construct the virtual networks using common L2/L3 network semantics.

VTN allows the users to define the network with a look and feel of conventional L2/L3 network. Once the network is designed on VTN, it is automatically mapped onto the underlying physical network, and then configured on the individual switches leveraging an SDN control protocol. The definition of the logical plane makes it possible not only to hide the complexity of the underlying network but also to better manage network resources. It achieves a reduction in the reconfiguration time of network services and minimising network configuration errors.

Open DOVE

Open DOVE (Distributed Overlay Virtual Ethernet) is a network virtualisation platform that provides isolated multi-tenant networks on any IP network in a virtualised DC (59). DOVE provides each tenant with a virtual network abstraction providing layer-2 or layer-3 connectivity and the ability to control communications using access control policies. Address dissemination and policy enforcement in DOVE is provided by a clustered directory service. It also includes a gateway function to enable virtual machines on a virtual network to communicate with hosts outside the virtual network domain.

Users interact with Open DOVE to create and manage virtual networks through the Open DOVE Management Console (DMC), which provides a REST API for programmatic virtual network management and a basic graphical UI. The DMC is also used to configure the Open DOVE Gateway to provide connectivity to non-virtualised networks.

The Open DOVE Connectivity Server (DCS) supplies address and policy information to individual Open DOVE vswitches, which implement virtual networks by encapsulating

tenant traffic in overlays that span virtualised hosts in the data centre. The DCS also includes support for high-availability and scale-out deployments through a lightweight clustering protocol between replicated DCS instances. The Open DOVE vswitches serve as policy enforcement points for traffic entering virtual networks. Open DOVE uses the VxLAN encapsulation format but implements a scalable control plane that does not require the use of IP multicast in the data centre.

The DOVE technology was originally developed by IBM Research and has also been included in commercial products.

Flowvisor

FlowVisor is the ON.LAB network slicer, which allows multiple tenants to share the same physical infrastructure (60). A tenant can be either a customer requiring his own isolated network slice; a sub-organisation that needs its own slice; or an experimenter who wants to control and manage some specific traffic from a subset of endpoints. FlowVisor acts as a transparent proxy between OpenFlow switches and various guest network operating systems. It supports network slicing and allows a tenant or an experimenter to control and manage some specific traffic from a subset of end points. This approach enables multiple experimenters to use a physical OpenFlow network without interfering with each other.

FlowVisor enables network virtualisation by dividing a physical network into multiple logical networks ensuring that each controller touches only the switches and resources assigned to it. It also partitions bandwidth and flow table resources on each switch and assigns those partitions to individual controllers.

FlowVisor slices a physical network into abstracted units of bandwidth, topology, traffic and network device CPUs. It operates as a transparent proxy controller between the physical switches of an OpenFlow network and other OpenFlow controllers and enables multiple controllers to operate the same physical infrastructure, much like a server hypervisor allows multiple operating systems to use the same x86-based hardware. Other standard OpenFlow controllers then operate their own individual network slices through the FlowVisor proxy. This arrangement allows multiple OpenFlow controllers to run virtual networks on the same physical infrastructure.

FlowVisor, originally developed at Stanford University, has been widely used in experimental research and education networks to support slicing where multiple experimenters get their own isolated slice of the infrastructure and control it using their own network OS and a set of control and management applications. FlowVisor has been deployed on a Stanford production network and sponsors, such as GENI, Internet2, NEC and Ericsson, have been contributing to it and using it in their research labs. The SDN research community considers FlowVisor an experimental technology, although Stanford University has run FlowVisor in its production network since 2009. FlowVisor lacks some of the basic network management interfaces that would make it enterprise-grade. For example it currently does not have any CLI or Web-based administration console but requires users to make changes to the technology with configuration file updates.

OpenVirteX

OpenVirteX is a network hypervisor that can create multiple virtual and programmable networks on top of a single physical infrastructure (61). Each tenant can use the full addressing space, specify their own topology, and deploy the network OS of their choice. Networks can be reconfigured at run-time, and OpenVirteX can automatically recover from physical failures.

OpenVirteX is actually a network hypervisor that enables operators to provide networks whose topologies, management schemes, and use cases are under the full control of their tenants. More specifically OpenVirteX builds on OpenFlow as protocol and FlowVisor for design. In this respect they share some common properties i.e. act as proxies between tenants and the underlying physical infrastructure. Unlike FlowVisor however, OpenVirteX provides each tenant with a fully virtualised network featuring a tenant-specified topology and a full header space.

3 THE T-NOVA ORCHESTRATION LAYER

This section describes the Orchestration layer, starting with an overview of its main characteristics, challenges and framework (subsection 3.1); followed by a description of requirements associated with its FEs (subsection 3.2), and finally a description of its functional architecture (subsection 3.3).

3.1 Orchestration Layer Overview

NFV is an emerging concept, which refers to the migration of certain network functionalities, traditionally performed by dedicated hardware elements, to virtualised IT infrastructures where they are deployed as software components. NFV leverages commodity servers and storage to enable rapid deployment, reconfiguration and elastic scaling of network functionalities.

Decoupling the network functions software from the hardware creates a new set of entities, namely:

- **Virtual Network Functions (VNFs):** software-based network functions deployed over virtualised infrastructure;
- **Network Functions Virtualized Infrastructure (NFVI):** virtualised hardware that supports the deployment of network functions;
- **Network Service (NS):** chain of VNFs and/or Physical Network Functions (PNFs) interconnected through virtual network links (VLs).

Since VNFs, NFVIs, NSs and the relationships between them did not exist before the NFV paradigm, handling them requires a new and different set of management orchestration functions.

VNFs require more agile management procedures when compared with legacy PNFs deployed over dedicated appliances. Besides the traditional management procedures already in place for PNFs, in charge of BSSs/OSSs, such as customer management, accounting management and SLA management, VNFs require new management procedures, e.g. to automatically create, to update and/or to terminate VNFs and NSs. Furthermore, the automatic deployment and instantiation procedures associated with a specific VNF need to be in place as well as the monitoring and automatic scaling procedures during the service runtime phase.

Another challenge brought about by the NFV paradigm is the management of the virtualised infrastructure. In fact, one of the main advantages of virtualising the network functions is to enable the automatic adjustment of NFVI resources according to the network function demands. To achieve this, the VNF specific requirements, according to the contracted SLA, have to be mapped to the required virtualised infrastructure assets (compute – e.g. virtual and physical machines, storage and networking – e.g. networks, subnets, ports and addresses). The mapping procedures should also consider the network topology, connectivity and network QoS constraints, as well as function characteristics (e.g. some functions may require low

delay, low loss or high bandwidth). Since virtualised resources can be centralised in a single NFVI-PoP or distributed across several NFVI-PoPs, the management and orchestration entities will also have to decide what is the most appropriated NFVI-PoP or NFVI-PoPs to deploy the function.

Besides the VNFs and the NFVI-PoPs management challenges, new and more complex NSs will be provided based on the combination/chaining of several VNFs. Therefore, in addition to the managing and orchestrating of each VNF and of the associated NFVI-PoP, orchestration and management procedures also have to be defined at the service level. These will coordinate several VNFs, as well as their association through Virtual network Links (VLs). Moreover, since the NSs can also be composed by PNFs, the interconnections between these and the VNFs are also required. The NS composition includes the constituent VNFs, PNFs and VLs, in the VNF Forwarding Graph (VNFFG). Each NS can have one or more VNFFGs, if there are conditions to have alternatives in terms of path creation, which can be used as backups.

Figure 16 illustrates the entities introduced by the NFV paradigm, as well as their relationships.

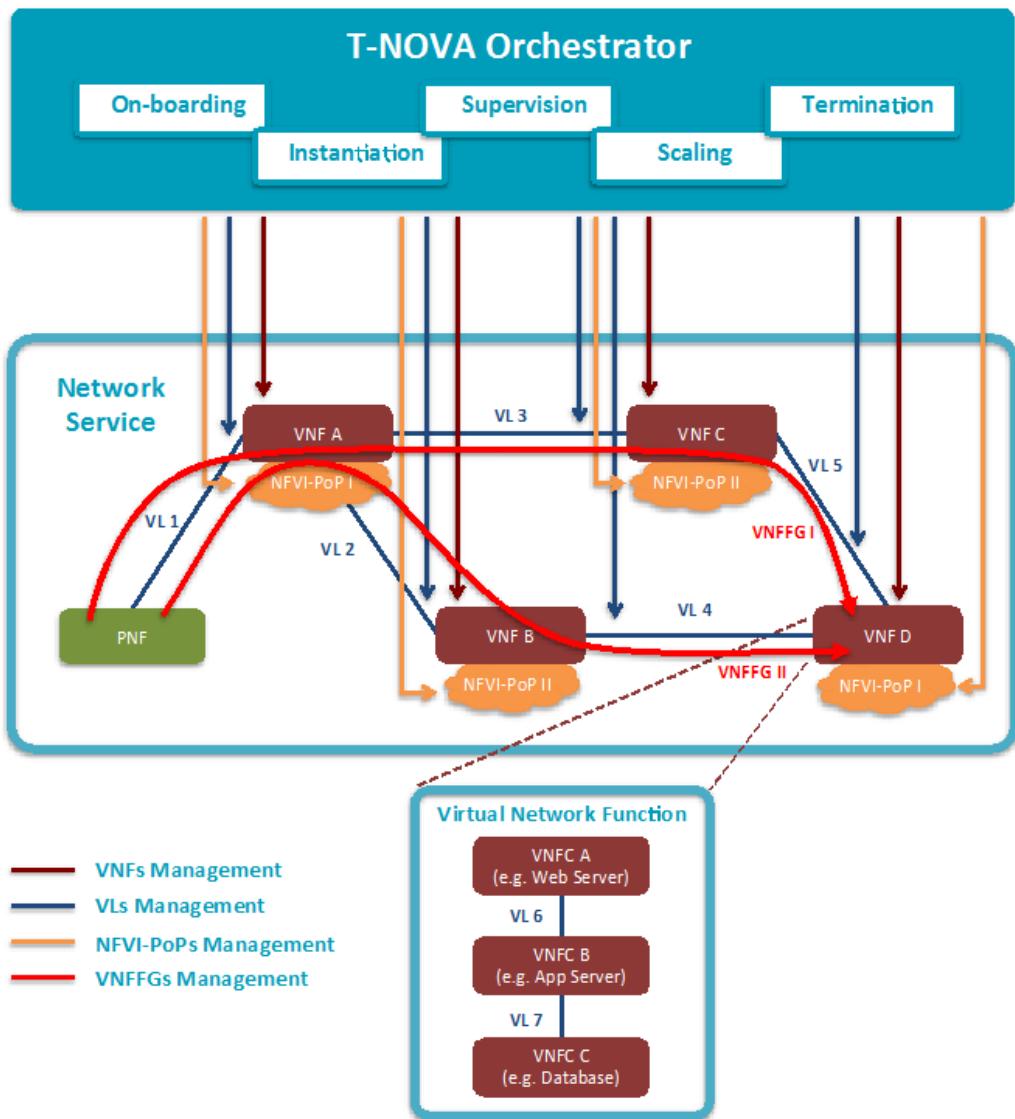


Figure 16: NSs & VNFs Complex Orchestration Overview

The NS presented in Figure 16 is composed by the following entities:

- Four VNFs: A, B, C and D;
- One PNF;
- Five VLs: 1 (interconnecting VNF A and PNF), 2 (interconnecting VNF A and VNF B), 3 (interconnecting VNF A and VNF C), 4 (interconnecting VNF B and VNF D) and 5 (interconnecting VNF C and VNF D).

The VNFs are deployed over two different NFVI-PoPs:

- NFVI-PoP I: supports VNF A and D deployments;
- NFVI-PoP II: supports VNF B and C deployments.

Two VNFFGs are illustrated:

- VNFFG I: delivers the NS through the PNF – VNF A – VNF C – VNF D networking path;

- VNFFG II: delivers the NS through the PNF – VNF A – VNF B – VNF D networking path.

Internally, the VNFs can be composed by one or more software components, also known as Virtual Network Function Components (VNFCs). Each VNFC is typically deployed in a single Virtual Machine (VM), although other deployment procedures can exist. As VNFs, VNFCs can be instantiated in a single NFVI-PoP or distributed across several NFVI-PoPs. The VNFCs interconnections are made through dedicated VLs. Figure 16 illustrates the internals of a specific (VNF D). The latter software components, namely web server (VNFC A), application server (VNFC B) and database (VNFC C), interconnected through VLs (VL6 and VL7).

On top of all these entities (e.g. NS, VNF, VNFC, VL, NFVI-PoP, etc) stands the orchestrator, which has responsibility for managing the complexity associated with the NSs and VNFs lifecycle management (e.g. on-boarding/deployment, instantiation, supervision, scaling, termination), including the internals of the VNFs (not illustrated in the figure).

In summary, the T-NOVA Orchestrator platform is focused on addressing two of the most critical issues in NFV:

1. Automated deployment and configuration of NSs/VNFs;
2. Management and optimisation of networking and IT resources for VNFs accommodation.

To address the complex management processes related with the NSs and VNFs, the Orchestrator is split in two main FEs:

1. NFV Orchestrator (NFVO): manages the virtualised NSs lifecycle procedures, including the networking links that interconnect the VNFs;
2. VNF Manager (VNFM): manages the VNFs lifecycle procedures.

The T-NOVA Orchestrator will also be able to deploy and monitor T-NOVA services by jointly managing WAN resources and cloud (compute/storage) assets (DCs). Indeed, the T-NOVA Orchestrator goes beyond traditional cloud management, since its scope is not restricted to a single DC; it needs to jointly manage WAN and distributed cloud resources in different interconnected DCs in order to couple the basic network connectivity service with added-value NFs.

Further details regarding these T-NOVA Orchestrator entities and functionalities are provided in the following subsections. The VNF related concepts and architectural components are discussed extensively in Deliverable D2.41 (D2.41) (62).

3.2 Orchestrator requirements

As already outlined in subsection 3.1, the T-NOVA Orchestrator is composed by two main building blocks: the NFVO and the VNFM.

The NFVO orchestrates the subset of functions that are responsible for the lifecycle management of Network Services (NSs). In addition, it is also responsible for the resource orchestration of the NFVI resources across:

- a single VIM, corresponding to a single NFVI-PoP, and/or
- multiple VIMs, corresponding to multiple NFVI-PoPs, by using a specialized VIM designated by TNM.

The VNFM is the functional block that is responsible for the lifecycle management of the VNFs.

The deployment and operational behaviour of the Orchestrator is captured in deployment templates, where the most important for this subsection are the Network Service Descriptor (NSD), the Virtual Network Function Descriptor (VNFD). Other templates are also used, e.g., Virtual Link Descriptor (VLD), and the VNF Forwarding Graph (VNFFGD), which will be further detailed in subsection 3.3.

This subsection details the Orchestrator requirements that have been identified after a research study involving several sources, e.g. use cases defined in D2.1 (63), ETSI ISG NFV requirements (64), ITU-T requirements for NV (10), as well as excerpts of relevant parts of the ETSI ISG MANO architecture and associated FEs (8).

The list of requirements for each FE may be found in Annex A, where 35 requirements have been identified for the NFVO and 11 for the VNFM. However, it should be noted that none of these requirements imposes any specific solution at the implementation level, which will be performed in WP3/4.

Taking into account that the list of requirements is quite extensive, the entire set of requirements has been classified and divided into types as indicated in the remaining part of the current subsection.

3.2.1 NFVO requirements types

Network Services under the responsibility of the NFVO, are composed by VNFs and, as such, are defined by their functional and behavioural specification. In this context, the NFVO coordinates the lifecycle of VNFs that jointly realise a NS. This coordination includes managing the associations between the different VNFs that make-up part of the NS, and when applicable between VNFs and PNFs, the network topology of the NS, and the VNFFGs associated with the NS.

The operation of NSs defines the behaviour of the higher Orchestration layer, which is characterised by performance, dependability, and security specifications. The end-to-end network service behaviour is the result of combining individual network function behaviours as well as the behaviours of the composition mechanisms associated with the underlying network infrastructure layer, i.e. the IVM layer.

In terms of deployment and operational behaviour, the requirements of each NS are carried in a deployment template, the NSD, and stored during the NS on-boarding process in the NS catalogue, for future selection once the instantiation of the service takes place. The NSD fully describes the attributes and requirements necessary to implement a NS, including the service topology, i.e. constituent VNFs and the relationships between them, VLs, VNFFGs, as well as NS characteristics, e.g. in terms of SLAs and any other information necessary for the NS on-boarding and lifecycle management of its instances.

As the NS is the main responsibility of the NFVO, the **NS lifecycle** constitutes the most relevant technical area regarding the NFVO classification in terms of requirements.

As indicated below, the other requirement types are related with the **VNF lifecycle** management with respect to the actions and procedures taken by the NFVO, which also includes the second FE that constitutes part of the Orchestrator, together with the NFVO: the VNFM. The actions and procedures associated with the VNFM's behaviour, and in particular those related to the VNF lifecycle, will be further discussed in subsection 3.2.2.

Regarding the remaining requirement types, it should be noted that there is one type related to the NFVO, which handles the **management of the resources** located in the VIM and in the TNM; another one related with the **policy management**; and another one, specific to the T-NOVA system, which is concerned with the most relevant **interactions with the Marketplace**, the layer immediately above the Orchestration layer.

Finally, there are still two further types that relate to NS lifecycle operations: **connectivity handling** and the **monitoring process**. A decision was taken to create separate groups for these two (sub)types in order to emphasize the importance they play in the overall operation of the Orchestrator.

3.2.1.1 NS Lifecycle

A Service Provider (SP) may choose one or more VNFs to compose a new NS, by parameterising those VNFs, selecting a SLA, etc. within the context of the T-NOVA system. The NFVO is then notified of the composition of this new NS, by the reception of a request that includes a NSD, which is validated in terms of description.

In a similar process, when a Customer subscribes to a NS, the Marketplace notifies the NFVO, which instantiates the NS according to its NSD description, agreed SLA and the current status of the overall infrastructure usage metrics. Upon a successful instantiation, the Orchestrator notifies the Marketplace, thus triggering the accounting process of the subscribed NS as well as of the customer.

After these steps the NFVO becomes responsible for NS lifecycle management, where lifecycle management refers to a set of functions required to manage the instantiation, maintenance and termination of a NS.

3.2.1.2 VNF Lifecycle

The NFVO performs its capabilities by using the VNFM operation in what concerns the handling of the VNF lifecycle. Although the VNFM is the FE in charge of the management of the VNF lifecycle, as further described in subsection 3.2.2, some operations require the intervention of the NFVO.

The requirement type specified in the current subsection refers precisely to those parts of the VNF lifecycle management that are performed by the NFVO.

In this context, **Function Providers** (FPs) publicise their VNFs in the **Network Function Store** (NF Store). This implies the use of a VNFD describing the

infrastructure (computation, storage, network infrastructure and connection) needed for the VNF to be instantiated later on by a request sent to the Orchestrator.

After a validation of the VNFD, the NFVO publicises the VNF to the Marketplace as being ready to be part of a NS. Associated with the VNFD, there may be potentially a VM image that will make part of the deployment of such VNF.

As the FP provides newer versions this process is repeated. If and when the FP wishes to withdraw the VNF, the reverse process is executed taking into consideration the current status of NS exploiting the under deletion VNF.

3.2.1.3 Resource Handling

The NFVO is the Orchestrator FE that performs the resource handling of the subset of Orchestrator functions that are responsible for global resource management governance.

In terms of scope, the following domains and associated IT virtualised resources are managed by the NFVO: **Compute**, i.e. virtual processing CPUs and virtual memory; **Storage**, i.e. virtual storage; and **Network**, i.e. virtual links intra/interconnecting VNFs within the Data Centre Network (DCN). In T-NOVA, the NFVO also manages the resources of the TNM network domain.

The governance described above is performed by managing the between the VNF instances and the NFVI resources allocated to those VNF instances and by using the Infra Resources catalogue as well as information received from the VIM and from the TNM.

According to the characteristics of each service (agreed SLA) and the current usage of the infrastructure (computation, storage infrastructure and connectivity), there is an optimal allocation for the required infrastructure.

This optimal infrastructure allocation will be the responsibility of an allocation algorithm (or a set of algorithms) that will be defined, in WP3.

3.2.1.4 Monitoring Process

One of the key aspects of the T-NOVA project is not only the ability to optimally allocate infrastructures for a NS, but also to react, **in real time**, to the current performance of a subscribed NS, so that the agreed SLA is maintained. To accomplish these two aspects, it is crucial that a meaningful set of infrastructure (computational, storage, infrastructure and connectivity) usage metrics be collected.

NS metrics must be defined together with the SLA(s) to be provided with every NS instantiation.

It is expected that the data to be collected will be significant with a high frequency of change, so adequate strategies will have to be designed to support collecting large volumes of data.

As such, during the NS lifecycle, the NFVO may monitor the overall operation of a NS with information provided by the VIM and/or by the TNM, if such requirements were captured in the NS deployment template.

Such data may be used to derive usage information for NFVI resources being consumed by VNF instances or groups of VNF instances. For instance, the process may involve collecting measurements about the number of NFVI resources consumed by NFVI interfaces, and then correlating NFVI usage records to VNF instances.

Beyond the infrastructure usage metrics sets of NS usage metrics, need to be defined upon service composition, in order to allow tracking of the agreed SLA and to determine if it is being maintained or not.

These metrics are more service oriented than infrastructure oriented, and are built on top of infrastructure usage metrics. For instance, a metric such as "the current number of simultaneous sessions" is something that the infrastructure cannot measure, but the "current maximum network latency" is something available at the infrastructure level, which might make sense at the service level as well. The choice between which metrics to track is made by the Marketplace, at service composition time.

The collection of these measurement metrics may be reported to external entities, e.g. the Customer, the SP or the FP, via the Marketplace, if such requirements were captured in the NS deployment template.

In addition, this information may be compared with additional information included in the on-boarded NS and VNF deployment templates, as well as with policies applicable to the NS that can be used to trigger automatic operational management of the NS instance, e.g. automatic scaling of VNF instances that are part of the NS.

3.2.1.5 Connectivity Handling

The NFVO has an abstracted view of the network topology and interfaces to the underlying VIMs and TNMs in order to handle connectivity services by performing the management of the NS instances, e.g., create, update, query, delete VNFFGs.

Connectivity management must be handled over the same domains as those indicated for resource handling.

3.2.1.6 Policy Management

Policies are defined by conditions and corresponding actions/procedures, e.g. a scaling policy may state execution of specific actions/procedures if the required conditions occur during runtime. Different actions/procedures defined by the policy can be mutually exclusive, which implies a process of selection of a particular action/procedure (or set of actions/procedures) to be executed either automatically or manually.

In the context of T-NOVA, once declared, a policy may be bound to one or more NS instances, VNF instances, and NFVI resources. Policy management always implies some degree of evaluation for the NS instances and VNF instances, e.g., in term of policies related with affinity/anti-affinity, lifecycle operations, geography, regulatory rules, NS topology, etc.

In addition, policy management also refers to the management of rules governing the behaviour of Orchestrator functions, e.g., management of NS or VNF scaling operations, access control, resource management, fault management, etc.

Associated with the policy management terminology is the concept of policy enforcement, i.e. policies are defined by certain entities and are then enforced in other entities, which may in their turn enforce them in additional entities.

In the T-NOVA context, policies may be defined by external entities, e.g. the Customer, the SP or the FP, and are then enforced into the NFVO, via the Marketplace. In its turn, the NFVO may enforce them into the VNFM.

Policy enforcement may be static or on-demand.

3.2.1.7 Marketplace-specific interactions

The Marketplace is the T-NOVA layer that interfaces with external entities, e.g., Customers, SPs and FPs. In the T-NOVA global architecture, it interacts with the Orchestration layer through an interface whose requirements are defined in subsection 3.4.

The deployment and behaviour of the Marketplace imposes requirements that the Orchestration must fulfil in order to offer those external entities an entire set of functionalities, which are defined in D2.41 (62).

The request made by the Marketplace for those requirements as well as the correspondent responses from the Orchestrator are, most of the time, implicit in the current description of the Orchestrator requirements.

However, for some of those requirements that are based within D2.1 (63), e.g. publishing the outcome of the NS instantiation, publishing NS metrics, or reporting usage metrics, it was decided to create a separate group in order to highlight their processing mechanisms.

For instance, the various kinds of metrics described above may be used by business-oriented processes residing in the Marketplace, namely to start and stop tracking of the usage a NS for billing purposes.

3.2.2 VNFM requirements types

The deployment and operational behaviour requirements of each VNF is captured in a deployment template, the VNFD, and stored during the VNF on-boarding process in the VNF catalogue as part of a VNF Package, for future use. The deployment template describes the attributes and requirements necessary to realise such the VNF and captures, in an abstracted manner, the requirements to manage its lifecycle.

The VNFM performs the lifecycle management of a VNF based on the requirements included in this template. As such, the **VNF lifecycle** constitutes the most relevant type in the VNFM classification of requirements in relation to the procedures taken in this global process.

As also decided for the NFVO, there is still a further type that constitutes, in fact, an area of operation that belongs to the VNF lifecycle: the **monitoring process**. Once

again, the reason behind the creation of a separate group for this (sub)type is related to emphasising the importance of its rule in the Orchestrator's operation.

3.2.2.1 VNF Lifecycle

The VNFM is responsible for the VNF lifecycle management, where lifecycle management refers to a set of functions required to manage the instantiation, maintenance and termination of a VNF.

3.2.2.2 Monitoring Process

During the lifecycle of a VNF, the VNF Management functions may monitor Key Parameter Indicator (KPIs) of a VNF, if such KPIs were captured in the deployment template. The management functions may use this information for scaling operations. Scaling may include changing the configuration of the virtualised resources (scale down, e.g., add CPU, or scale up, e.g., remove CPU), adding new virtualised resources (scale out, e.g., add a new VM), shutting down and removing VM instances (scale in), or releasing some virtualised resources (scale down).

So, every VNF will usually provide its own usage metrics to the VNFM, which will be, in general, specific to the function the VNF provides, although they might be based on the infrastructure on top of which the VNF has been deployed.

The treatment of the information collected during the VNF monitoring process is very similar to the one described for the NS process and may result in reports being sent external entities, via the Marketplace, and/or to trigger automatic operational management of the VNF instance, e.g. automatic scaling.

3.3 Functional Orchestrator Architecture

This subsection describes the Orchestrator reference architecture, including its functional entities as well as external interfaces.

3.3.1 Reference Architecture

The Orchestrator reference architecture, as well as the interfaces with the external Functional Entities (FEs) is depicted in Figure 17. In detail, the orchestrator interacts with the Marketplace, which is the T-NOVA domain responsible for accounting, SLA management and business functionalities. Besides the Marketplace, the Orchestrator also interfaces with the IVM, and in particular with the VIM, for managing the data centre network/IT infrastructure resources, as well as with the TNM for WAN connectivity management. Finally, the Orchestrator interacts with the VNF itself, which in the T-NOVA scope is located in the IVM domain, to ensure its lifecycle management.

Internally, the T-NOVA Orchestrator consists of two main components and a set of repositories. One of the core elements is the NFVO, acting as the front-end with the Marketplace and orchestrating all the incoming requests towards the other components of the architecture. Further details relating to the NFVO and the associated incoming requests are available in subsection 3.3.2.1. To support the

NFVO operation procedures, a set of repositories is identified in order to store the description of the available VNFs and NSs (VNF Catalogue and NS Catalogue), the instantiated VNFs and NSs (NS & VNF Instances), as well as the available resources in the virtualised infrastructure (Infrastructure Resources Catalogue). Further details about the orchestrator repositories are provided in subsection 3.3.2.3. Finally, the NFVO also interacts with the other core element, the VNF Manager (VNFM), responsible for the VNF-specific lifecycle management procedures, as described in subsection 3.3.2.2.

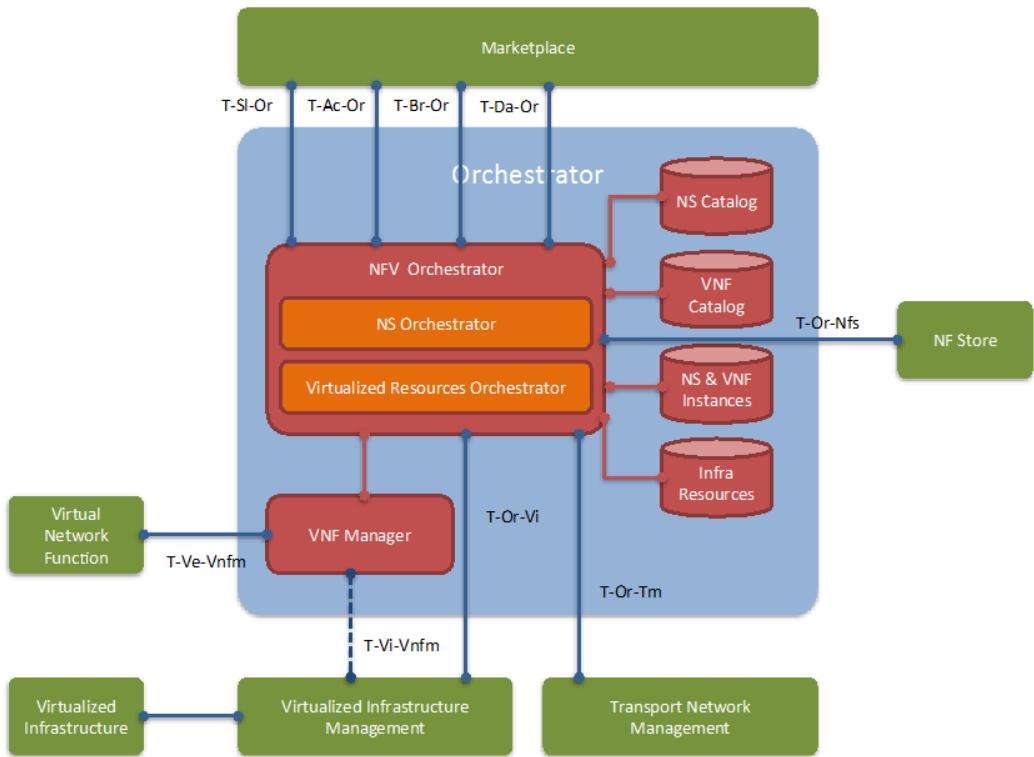


Figure 17: T-NOVA Orchestrator Reference Architecture

3.3.2 Functional entities

This subsection describes the functional entities of the Orchestrator architecture.

3.3.2.1 Network Function Virtualisation Orchestrator (NFVO)

The main function of the NFVO is to manage the virtualised NSs lifecycle and its procedures. Since the NSs are composed by VNFs, (PNFs, VLs and VNFFGs, the NFVO is able to decompose each NS into these constituents. Nevertheless, although the NFVO has the knowledge of the VNFs that compose the NS, it delegates their lifecycle management to another dedicated FE of the Orchestrator domain, designated by VNFM.

A description of the main deployment templates must be taken into account when determining the best connectivity paths to deliver a service is provided:

- a VNFFGD is a deployment template that describes a topology of the NS or a portion of the NS, by referencing VNFs and PNFs as well as VLs that used for

interconnection. In addition to the VLs, whose descriptor is described below, a VNFFG can reference other information elements in the NS such as PNFs and VNFs. A VNFFG also contains a Network Forwarding Path (NFP), i.e. an ordered list of Connection Points forming a chain of NFs, along with policies associated to the list,

- a VLD is a deployment template which describes the resource requirements that are needed for establishing a link between VNFs, PNFs and endpoints of the NS, which could be met by choosing an option between various links that are available in the NFVI. However, the NFVO must first consult the VNFFG in order to determine the appropriate NFVI to be used based on functional (e.g., dual separate paths for resilience) and other needs (e.g., geography and regulatory requirements).

In addition to the **orchestration of the virtualised service level operations**, which allows the abstraction of service specificities from the business/operational level – in this case the T-NOVA Marketplace – the NFVO also **manages the virtualised infrastructure resource level operations** as well as the **configuration/allocation of transport connections** when two or more distinct DCs are involved. Hence, it coordinates the resource reservation/allocation/removal to specific NSs and VNFs according to the availability of the virtualised infrastructures, also known as data centres.

To address the two main functionalities above mentioned, the NFVO is architecturally split in two modules, namely the Network **Services** Orchestrator (NSO) and the Virtualised **Resources** Orchestrator (VRO), further described below.

Network Service Orchestrator

The NSO is one of the components of the NFVO with the responsibility for managing the NS lifecycle and its procedures. More precisely, the following tasks fall under the responsibility of the NSO:

- **NSs and VNFs on-boarding:** management of Network Services deployment templates, also known as NS Descriptors and VNF Packages, as well as of the NSs instances topology (e.g., create, update, query, delete VNF Forwarding Graphs). On-boarding of a NS includes the registration in the NS catalogue therefore ensuring that all the templates (NSDs) are stored, see NS on-boarding procedure detailed in subsection 5.2.1;
- **NS instantiation:** trigger instantiation of NS and VNF instances, according to triggers and actions captured in the on-boarded NS and VNF deployment templates. In addition, management of the instantiation of VNFs, in coordination with VNFMs as well as validation of NFVI resource requests from VNFMs, as those may impact NSs, e.g. scaling process, see NS instantiation procedure detailed in subsection 5.2.2;
- **NS update:** support NS configuration changes of various complexity such as changing inter-VNF connectivity or the constituent VNFs;
- **NS supervision:** monitoring and measurement of the NS performance and correlation of the acquired metrics for each service instance. Data is obtained from the IVM layer (performance metrics related with the virtual network links

interconnecting the network functions) and from the VNFM (aggregated performance metrics related with the VNF, see NS supervision procedure detailed in subsection 5.2.3);

- **NS scaling:** increase or decrease of the NS capacity according to per-instance and per-service auto-scaling policies. The NS scaling can imply either increasing/decreasing of a specific VNF capacity, create/terminate new/old VNF instances and/or increase/decrease the number of connectivity links between the network functions;
- **NS termination:** release of a specific NS instance by removing the associated VNFs and associated connectivity links, as well as the virtualised infrastructure resources, (see NS termination procedure detailed in subsection 5.2.5).

In addition to these lifecycle related procedures, the NSO also performs policy management and evaluation for the NS instances and VNF instances, e.g., policies related with scaling.

Figure 18 provides an illustration about the NSO interactions within the T-NOVA Orchestrator and with the remaining T-NOVA external entities:

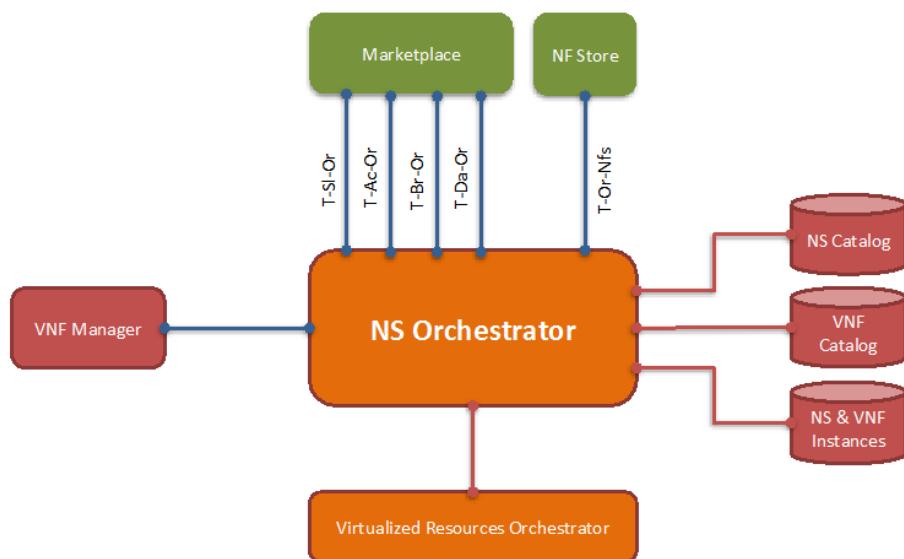


Figure 18: NS Orchinator (Internal & External) Interactions

From the external perspective, it interacts with the Marketplace for operational and business management purposes as follows:

- Exchange provisioning information (e.g., requests, modifications/updates, acknowledgements) about the NSs (through the T-Da-Or interface);
- Provides the orchestrator with information on each NS instance SLA agreement. In turn he orchestrator sends SLA-related metrics to the Marketplace (through the T-SI-Or interface);
- Deliver to the Marketplace usage accounting information with respect to VNFs and NSs (through the T-Ac-Or interface);

- Provides the orchestrator with information about the NSs composition. The orchestrator delivers to the Marketplace information about the available VNFs (through the T-Br-Or interface).

Internally, the NSO has the following communication points:

- **NS Catalogue:** collects information about the NSs (NSD), including the set of constituent VNFs, interconnecting network links (VLD) and network topology information (VNFFGD);
- **VNF Catalogue:** stores the VNFD during the on-boarding procedures;
- **NS and VNF Instances:** stores information about the NS instances status;
- **Virtualised Resources Orchestrator (VRO):** exchanges management actions related to virtualised resources and/or connections, either within the data centre scope (e.g. compute, storage and network) and/or on the transport network segment;
- **Virtual Network Function Manager (VNFM):** exchange lifecycle management actions related with the VNFs.

Virtualised Resources Orchestrator

The Virtualised Resources Orchestrator (VRO) is the resource layer management Functional Entity of the NFVO main block. It is responsible for the following actions:

- Coordinate resource reservation/allocation/removal and establish the placement for each VM that composes the VNF (and the NS);
- Interact with the WAN elements for connectivity management actions;
- Validate NFVI resource requests from VNFMs, as those may impact the way the requested resources are allocated within one NFVI-PoP or across multiple NFVI-PoPs. Whether the resource related requests comes directly from the VNFM or from the NFVO is implementation dependent;
- Manage the relationship between the VNF instances and the NFVI resources allocated to those VNF instances;
- Collect usage information of the NFVI resources;
- Collect performance information about the network links interconnecting the VNFs;
- Collect performance about the virtualised infrastructure resources supporting NSs.

The following virtualised resources are managed by the VRO:

- **Compute:** virtual processing CPUs and virtual memory;
- **Storage:** virtual storage;
- **Network:** virtual links intra/interconnecting VNFs within the DCN.

Figure 19 provides an illustration with further details about the VRO interactions within the T-NOVA Orchestrator and with the remaining T-NOVA external entities:

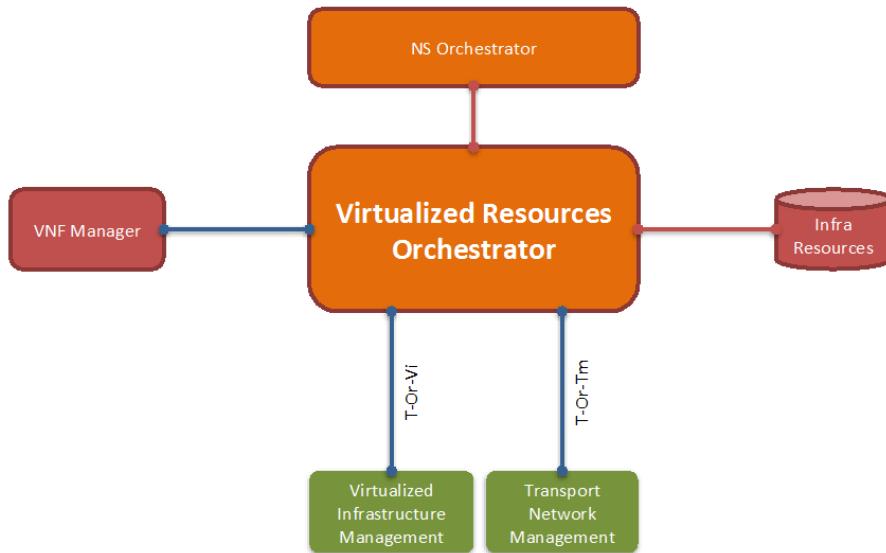


Figure 19: Virtualised Resources Orchestrator (Internal & External) Interactions

From an external perspective, it interacts with the VIM and the TNM for the following purposes:

- **Virtualised Infrastructure Manager:** to enforce resource reservation/allocations/removal and to collect monitoring information about the virtual links interconnections of the VNFs, through the T-Or-Vi interface;
- **Transport Network Manager:** enforces resource/connectivity decisions allocations/removals and to collect monitoring information about the transport network elements, through the T-Or-Tm interface.

Internally, the VRO interacts with the following blocks:

- **Network Services Orchestrator:** exchanges resource reservation/allocation/removal management actions related with a specific NS, for all the constituent VNFs;
- **Infrastructure Resources catalogue:** queries and stores information about the virtualised and non-virtualised infrastructure resources;
- **Virtual Network Function Manager:** exchanges resource reservation/allocation/removal management actions, in the case the resource management is handled by the VNFM.

3.3.2.2 Virtual Network Function Manager (VNFM)

The VNFM is responsible for the lifecycle management of the VNF. Each VNF instance is assumed to have an associated VNFM. A VNFM may be assigned the management of a single VNF instance, or the management of multiple VNF instances of the same type or of different types. The Orchestrator uses the VNFD to create instances of the VNF it represents, and to manage the lifecycle of those instances. A VNFD has a one-to-one correspondence with a VNF Package, and it fully describes the attributes and requirements necessary to realize such a VNF. NFVI resources are assigned to a VNF based on the requirements captured in the VNFD (containing resource allocation

criteria, among others), but also taking into consideration specific requirements accompanying the request for instantiation.

The following management procedures are within the scope of the VNFM:

- **Instantiate:** create a VNF on the virtualised infrastructure using the VNF on-boarding descriptor, as well as the VNF feasibility checking procedure, see VNF instantiation procedure detailed in subsection 5.1.2;
- **Configure:** configure the instantiated VNF with the required information to start the VNF. The request may already include some customer-specific attributes/parameters;
- **Monitor:** collect and correlate monitoring information for each instance of the VNF. The collected information is obtained from the IVM layer (virtualised infrastructure performance information) and from the VNF (service specific performance information), see VNF monitoring procedure detailed in section 5.1.3;
- **Scale:** increase or decrease the VNF capacity by adding/removing VMs (out/in horizontal scaling) or adding/removing resources from the same VM (down/up vertical scaling), see VNF scale-out procedure detailed in subsection 5.1.4;
- **Update:** modify configuration parameters;
- **Upgrade:** change software supporting the VNF;
- **Terminate:** release infrastructure resources allocated for the VNFs, see VNF termination procedure detailed in subsection 5.1.5.

Figure 20 provides an illustration with further details on the VNFM interactions within the T-NOVA Orchestrator and with the remaining T-NOVA external entities:

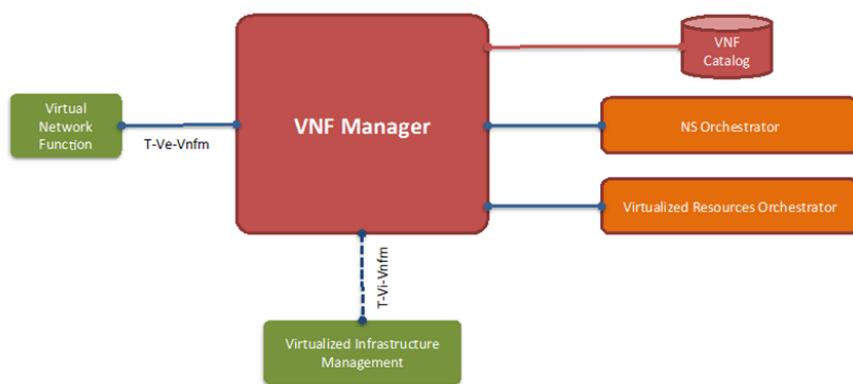


Figure 20: VNF Manager (Internal & External) Interactions

From the external perspective, it interacts with the VNF and with the VIM with the following purposes:

- **Virtual Network Function (VNF):** configures VNF specific information and receives VNF related monitoring information (through the T-Ve-Vnfm interface);

- **Virtual Infrastructure Management (VIM):** collects monitoring information about the virtualised infrastructure resources allocated to the VNF (through the T-Vi-Vnfm interface).

Internally, the VNFM interacts with the following components:

- **Network Services Orchestrator (NSO):** receive VNF instantiation requests for a specific NS and provide VNF monitoring information;
- **VNF Catalogue:** collects information about the VNFs internal composition (VNFD), including the VNF Components (VNFCs), software images (VMs) and management scripts;
- **Virtualised Resources Orchestrator (VRO):** exchanges resource reservation/allocation/removal management actions, in cases where the management is handled by the VNFM.

3.3.2.3 Repositories and Catalogues

To support the T-NOVA Orchestrator lifecycle management operations, the following catalogues are defined:

- NSs Catalogue (NS Catalogue);
- VNFs Catalogue (VNF Catalogue);
- NSs and VNFs Instances Repository;
- Infrastructure Resources Repository.

NS Catalogue

Represents the repository of all the on-boarded NSs in order to support the NS lifecycle management:

- **NS Descriptor (NSD):** contains the service description template, including SLAs, deployment flavours, references to the virtual links (VLDs) and the constituent VNFs (VNFFG);
- **Virtual Link Descriptor (VLD):** contains the description of the virtual network links that compose the service (interconnecting the VNFs);
- **VNF Forwarding Graph Descriptor (VNFFGD):** contains the NS constituent VNFs, as well as their deployment in terms of network connectivity.

VNF Catalogue

Represents the repository of all the on-boarded VNFs in order to support its lifecycle management:

- **VNF Descriptor (VNFD):** contains the VNF description template, including its internal decomposition in VNFCs, deployment flavours and references to the VLDs;
- Software images of the VMs located in the IVM layer.

NS & VNF Instances

Represents the repository of all the instantiated NSs and VNFs, which can be created/updated/released during the lifecycle management operations.

Infrastructure Resources

Represents the repository of available, reserved and allocated NFVI-PoP resources, also including the ones related to the WAN segment.

3.3.3 External Interfaces

In this section the external interfaces of the Orchestrator are described. However it is important within the perspective of the T-NOVA architecture to understand the context in which the term interface is used as is its relationship to reference points a common architectural locus used within the networking domain

In network terms a reference point is an abstract point in a model of network or protocol. This reference point essentially serves to partition functions or configurations and so assists in the description of a network model as well as serving as a point of interoperability between different parts of the network (65). In a networking context, an interface may or may not be associated with any given reference point. An interface typically represents a protocol level connection which may or may not be mapped to a reference point.

This strict delimitation between the definition of reference points and interfaces in the context of NFV and SDN given the hybridisation of networking and IT technologies can be challenging, i.e. in the network domain, this framework is strictly defined, and it is therefore normal practice to retain the use of the term reference point, while in the IT domain, there is a more flexible demarcation between technologies leading to a degree of hybridisation. As a consequence in the IT domain the term interface is used in a more flexible manner to encompass reference points also.

While strictly speaking the separation of the terms should be technically maintained the approach adopted in this deliverable is to utilise a broader and more flexible definition of interfaces and reference points given the expected one-to-one mapping of reference points and interfaces in the context of the proposed T-NOVA architecture. Additionally interfaces in the T-NOVA system may not necessarily be tied specifically to a protocol but rather act as point of information exchange through APIs. Hence within the context of this deliverable interfaces are envisioned to encompass both the architectural characteristics of interfaces and references points given fusion of the IT and networking domains.

Having clarified the use of the term, the description of the Orchestrator's external interfaces will start to be provided by means of a very short reference on security, which is a common area that affects all the interfaces. It will be followed by an introduction to the interface requirements that are presented in Annex A.2 in a tabular format.

Regarding the common issue, and considering the most generic scenarios in which the roles described in D2.1 (63) are played by distinct entities all the external interfaces being described in this section must support at least a minimum degree of security. The decision on the exact degree of security for each implemented interface will be taken later in the project's timeline.

3.3.3.1 Interface between the Orchestrator and the Network Function Store

The interface between the Orchestrator and the Network Function Store (NF Store) serves two purposes:

- For the NF Store, to **notify the Orchestrator** about new, updated and withdrawn VNFs;
- For the Orchestrator, to **retrieve from the NF Store** and store in the VNF Catalogue **the VNFD and VMs images** that need to be instantiated to support that VNF.

This “two-phase” interaction between the Orchestrator and the NF Store, instead of just one in which the NF Store could pass the Orchestrator the VNF Descriptor and VM images, allows for the optimisation of resources on both sides of the interface. On the NF Store side this is just a notification to the Orchestrator, and on the Orchestrator’s side, the download of the VM images is only carried out when the VNF is instantiated preventing unnecessary use of resources. Uploading of the VNFD to the VNF catalogue is executed at the start of the VNF on-boarding process.

3.3.3.2 Interface between the Orchestrator and the Marketplace

The interface between the Orchestrator and the Marketplace serves the following purposes:

- **Provide available VNFs:** involves SP browsing and selection of VNFs, as well as composition of market services by the Marketplace, followed by a request to the Orchestrator;
- **Publish a new network service:** related to the request for the storage of information related to a new service by the Marketplace, included in the provision of the NSD, see subsection 3.2. This process is also called **NS on-boarding** by the Orchestrator FEs;
- **Request for a Network Service:** after a Customer’s or a SP subscription of a service, a subsequent request from the Marketplace is generated, which includes in the NSD all the VNFs the NS to be deployed needs, as well as all the VMs those VNFs need in the VNFD, the available infrastructure and its current usage;
- **Change configuration of a deployed network service** upon a request from the Marketplace;
- **Provide network service state transitions:** notification provided by the Orchestrator to the Marketplace;

- **Provide network service monitoring data:** notification provided by the Orchestrator to the Marketplace;
- **Terminate a provisioned network service:** upon a request from the Marketplace when there is an explicit solicitation.

3.3.3.3 Interface between the Orchestrator and the VIM

The interface between the Orchestrator and the VIM serves the following purposes:

- **Allocate/release/update resources:** upon a request from the Orchestrator to (re)instantiate, update the configuration of, or release a resource (VM or connection within the same DC);
- **Reserve/release resources:** upon an expected future need from the Orchestrator to instantiate or release a reserved resource (VM or connection in the same DC). This requirement makes sense in scenarios where allocating resources from scratch is complex or too time consuming for the purpose in mind. Reserved resources may have lower prices than effective allocated ones and become faster to allocate when time comes;
- **Add/update/delete SW image:** whenever a new, update or removal of a VM image is needed in the process of allocating, updating or removing a new VNF/VNFC instance;
- **Retrieve infrastructure usage data to NSO:** information provided by the VIM to the Orchestrator, NSO FE, so that optimal allocation of NS instances is possible and an adequate level of metrics can be reported to the Marketplace, if allowed by information included in the NSD;
- **Retrieve infrastructure usage data to VNFM:** information provided by the VIM to the Orchestrator, VNFM FE, so that optimal allocation of VNF instances is possible and an adequate level of metrics can be reported, via NSO, to the Marketplace, if allowed by information included in the VNFD;
- **Retrieve infrastructure resources metadata to VRO:** information provided by the VIM to the Orchestrator, VRO FE, so that optimal allocation of NS instances is possible, according to the characteristics of the supporting infrastructure (e.g., the availability of specialized components, such as Graphical Processing Units (GPUs) or Digital Signal Processors (DSPs), as well as the maximum number of vCPUs or Giga-bytes of RAM, which will influence the allocating algorithm for determining the most appropriate resources);
- **Manage VM's state:** information provided by the VIM to the Orchestrator, VNFM FE, so that atomic operations, such as redeployment/withdrawal of an entire VNF, on the allocated VMs are feasible (depending on the implementation approach, these operations can also be done by the IVM layer).

3.3.3.4 Interface between the Orchestrator and the Transport Network Management

The interface between the Orchestrator and the Transport Network Management serves the following purposes:

- **Allocate/release/update transport connection:** upon a request from the Orchestrator to (re)instantiate, update the configuration of or release a transport connection (between two distinct DCs);
- **Reserve/release transport connection:** upon an expected future need from the Orchestrator to instantiate or release a transport connection (between two distinct DCs). This requirement makes sense in scenarios where allocating connections from scratch is complex or too time consuming. Reserved connections may have lower prices than effective allocated ones and become faster to allocate when time comes;
- **Retrieve transport connection usage data to NSO:** information provided by the TNM to the Orchestrator, NSO FE, so that optimal allocation of transport connections between two or more distinct DCs is possible and an adequate level of metrics can be reported, together with VNF and NS level metrics, to the Marketplace;
- **Retrieve transport connection metadata:** information provided by the TNM to the Orchestrator, VRO FE, such that the optimal allocation of transport connections between two or more distinct DCs is made possible, according to the characteristics of the supporting infrastructure e.g., maximum number of vLinks allowed, maximum bandwidth, etc.;
- **Manage transport connection state:** information provided by the TNM to the Orchestrator, NSO FE, so that atomic operations, such as redeployment/withdrawal of an entire VNF within different DCs are feasible (depending on the implementation approach, these operations can also be executed by the IVM layer).

3.3.3.5 Interface between the Orchestrator and the VNF

The interface between the Orchestrator and the VNF serves the following purposes:

- **Instantiate/terminate VNF:** sent by the VNFM as a request, whenever an instance of a NS of which the VNF is a component is to be launched or removed. Removal of a VNF instance can only be done if there is no NS instance using that VNF.
- **Retrieve VNF instance run-time information:** sent by the VNFM, so that VNF SLA metrics can be checked and the SLA can be fulfilled;
- **Configure a VNF:** sent by the VNFM, so that open configuration parameters can be fulfilled later or changed after the VNF instance is already running;
- **Manage VNF state:** sent by the VNFM, so that the Orchestrator is able to start, stop, suspend already running VNF instances;

- **Scale VNF:** sent by the VNFM, so that VNF scaling is feasible. All the VNF scaling information is available in the VNFD. Virtualised resources are available through the VRO.

4. THE T-NOVA IVM LAYER

4.1 INTRODUCTION

T-NOVA's Infrastructure Virtualisation and Management (IVM) layer provides the requisite hosting and execution environment for VNFs. The IVM incorporates a number of key concepts that influence the associated requirements and architecture for the layer. Firstly the IVM supports separation between control and data planes and network programmability. The T-NOVA architecture leverages SDN for designing, dimensioning and optimising control- and data-plane operations separately, allowing capabilities from the underlying hardware to be exposed independently. Secondly the IVM is based around the use of clusters of commodity computing nodes in cloud computing configurations to support instantiation of software components in the form of VMs for NFV support, offering resource isolation, optimisation and elasticity. This configuration should support automated deployment of VNFs from the T-NOVA marketplace and dynamically expansion/resizing of VMs as required by SLAs. Building on physical IT and network resource domains the IVM provides full abstraction of these resources to VNFs. Finally the IVM must expose the necessary external and internal interfaces to support appropriate integration. The external interfaces provide connectivity with the T-NOVA Orchestration layer in order to execute requests from the Orchestrator and secondly to provide information on the infrastructure and VNF being hosted in order for the Orchestrator to make effective management decisions. The internal interfaces provide connectivity between the internal domains of the IVM to ensure the requests for the creation, deployment, management and termination of VNF services and their host VMs can be executed appropriately among the constituent infrastructure and control components.

For an architectural perspective the IVM is comprised of NFVI, VIM and TNM capabilities. The NFVI in turn is composed of Compute, Hypervisor and Network Domains. The VIM is comprised of compute, hypervisor and network control and management capabilities, while the TNM works as a single FE. All the various domains within the IVM implement northbound and southbound interfaces to provide management, control and monitoring of the composite infrastructure, both physical and virtualised. Secondly these interfaces provide the key integration capabilities within the overall T-NOVA system architecture.

The following sections describe the key objectives and characteristics of the IVM and its constituent components, along with their requirements. These requirements were then utilised together with T-NOVA D2.1 (63) and D2.21 (4) to define the architecture of IVM in a manner that addressed these requirements and the overall goals of T-NOVA. The architecture for T-NOVA is presented as an overall integrated architecture together with detailed descriptions of the architecture FEs and interfaces of the constituent domains.

4.2 OBJECTIVES AND CHARACTERISTICS OF THE T-NOVA IVM LAYER

The T-NOVA IVM is considered to comprise of a mixture of physical and virtual nodes and will be used to develop, implement and showcase T-NOVA's services. The IVM will be fully integrated with the T-NOVA Orchestrator to ensure that requirements for the deployment and lifecycle management of T-NOVA VNF services can be carried out in an appropriate and effective manner. The IVM should be sufficiently flexible to support a variety of use cases beyond those explicitly identified in T-NOVA (see D2.1 (63)). As mentioned previously, infrastructure virtualisation plays a key role in achieving this vision in T-NOVA. Virtualisation and management of the virtualised resources extends beyond the compute and storage to include network infrastructure in order to fully exploit the capabilities of the T-NOVA architecture. Virtualisation of the DC network infrastructure allows decoupling of the control functions from the physical devices they control. In this regard the T-NOVA will implement an SDN control plane for designing, dimensioning and optimising the control- and data-plane operations separately, allowing capabilities from the underlying hardware to be exposed independently.

In summary the key objectives for the T-NOVA IVM are as follows:

- Support separation of control and data plane and network programmability at least at critical locations within the network such as the network access/borders,
- Utilisation of commodity computing nodes in cloud configurations to support the instantiation of software components in the form of VMs for NFV support, offering resource isolation, optimisation and elasticity,
- Use of L2 Ethernet switched networks (subnets) to provide physical network connectivity between servers,
- Each server supports virtualisation and hosts a number of VMs (virtual appliances) belonging to their respective vNets. Virtual switch instances or real physical SDN-capable switches handle network connectivity among the VMs either on the same server or among the servers co-located in the same DC,
- Interconnection of L2 subnets inside and outside DC's boundaries via a L3 network (IP routers). This inter data centre connectivity is provisioned through appropriate WAN ingress and egress points.
- Virtualisation of compute and network resources allows the T-NOVA system to dynamically expand/resize VMs. This accommodates for dynamic scaling of sudden spikes in the workload; the instantiation of network elements as VMs into clusters of nodes facilitates horizontal scaling (hosting of many VM instances into the same cluster) and vertical scaling (automatic re-sizing of VM instances according to function requirements and traffic load) (see T-NOVA requirements/use cases – D2.1 (63)).

4.3 T-NOVA IVM LAYER REQUIREMENTS

The requirements capture process focused on identifying the desired behaviours of the IVM. The requirements identified focus on the entities within the IVM, the functions that are performed to change states or object characteristics, monitoring of state and the key interactions with the T-NOVA Orchestration layer. None of these requirements specifies how the system will be implemented. Implementation details are left to the appropriate tasks in WP3/4 as the implementation-specific descriptions are not considered to be requirements. The goal of the requirements was to develop an understanding of what the IVM needs, how it interacts with Orchestration layer, its relationship to the overall T-NOVA architecture described in D2.21 (4). Additionally the use cases included in D2.1 (63) were also considered and cross-referenced with IVM requirements where appropriate.

The initial phase of eliciting requirements included:

- Reviewing available documentation including early and final drafts of (63) and (66),
- Reviewing the high level T-NOVA architecture that was developed by Task 2.2 to gather information on how the users and service providers will perform their tasks such as VNF deployment, scale out etc., and to better understand the key characteristics of the T-NOVA system that will be required to realise user goals including those at a system level.

The adopted approach was generally in-line with the Institute of Electrical and Electronics Engineer (IEEE) guidelines for requirements specification. A similar process was used in Tasks 2.1 and 2.2. Requirements were primarily anchored to the existing T-NOVA use cases and the interactions with Orchestrator both in terms of the actions and requests that Orchestrator would expect the IVM to execute. Additionally the data/information that is required by the Orchestrator to successful deploy and manage VNF services were considered. Identified requirements were primarily functional in nature since they were related to the behaviour that the IVM is expected to exhibit under specific conditions. In addition ETSI's NFV Virtualisation Framework requirements were also considered, in order to ensure approach scope and coverage for the requirements that have been specified. The following are the key categories of requirements that were considered:

- Portability,
- Performance,
- Elasticity,
- Resiliency,
- Security,
- Service Continuity,
- Service Assurance,
- Operations and Management,
- Energy Efficiency.

Using a system engineering approach the high level architecture for the IVM was previously described in (4). Each component of the overall system was specified in

terms of high-level functional block and the interactions between the functional blocks are specified as interfaces. This approach identified the following functional blocks:

- Virtualised Infrastructure Management (VIM),
- Transport Network Management (TNM),
- Infrastructure Elements, consisting of Computing, Hypervisor and Networking.

The requirements presented in the following section are related to these functional blocks and were developed using the previously described methodology. These requirements were used as a foundational input into the development of the overall IVM architecture and its constituent functional blocks, which is presented in subsection 4.4.

A detailed specification of the requirements for each module within the scope of the T-NOVA IVM architecture can be found in Annex B. A total of 70 requirements were identified and documented relating to the VIM, NFVI (compute, hypervisor, DC network) and TNM. It should be noted that requirements that relate to basic expected behaviours of the various domains components have been excluded in order to focus on requirements that are specifically needed by the T-NOVA system. Analysis of these requirements has identified the following conclusions for each architectural module.

4.3.1 Virtual Infrastructure Manager

The VIM is required to manage both the IT (compute and hypervisor domains) and network resources by controlling the abstractions provided by the Hypervisor and Infrastructure network domains. It also implements mechanisms to efficiently utilise the available hardware resources in order to meet the SLAs of the VNFs and NSs. The VIM is also required to play in a key role in the VNF lifecycle management. Additionally, the VIM is required to collect infrastructure utilisation/performance data and to make this data available to the Orchestrator in order to generate usage/performance statistics. The specifics of how the metrics are provisioned and processed at both the VIM and Orchestrator layers can vary and will typically be implementation specific. The details of the T-NOVA implementation will be determined in WP3/4. To accomplish these goals the VIM needs the following capabilities:

- The Network Control capability in the VIM requires SDN features to manage the infrastructure network domain within an NFVI-PoP;
- Hardware abstraction in the Compute domain for efficient management of resources; However, the abstraction process should ensure that platform specific information relevant to the performance of VNFs is available for resource mapping decisions;
- Virtual resource management in the Hypervisor domain to provide appropriate control and management of VMs;
- Strong integration between these three sub-domains through appropriate interfaces;

- Integration with the Orchestrator via well-defined interfaces to provide infrastructure related data to the Orchestrator and to receive management and control requests from Orchestrator for execution by the VIM.

4.3.2 Transport Network Management

The Transport Network Management is expected to provide the connectivity to NSs allocated in more than one NFVI-PoP. Connectivity should take form of VLAN to WAN connections through ingress and egress points at each NFVI-PoP involved in the NS service. This connectivity has to be provided in a configurable manner (i.e. supports a high level of customisation). Moreover, to setup this connectivity, cooperation between the TNM and the NFVI Network domain is needed in order to allocate the traffic over the inter-DC and intra-DC networks in an appropriate manner.

4.3.3 NFVI Compute

The NFVI Compute domain should be able to provide an appropriated performance level for the VNFs that are been deployed in terms of performance and utilisation of the infrastructure resources. Moreover, the compute nodes and the hypervisor should work in an integrated and performant manner. The compute domain should collect metrics on the performance of the physical resources and make them available over a suitable interface to the Orchestrator. Finally, the T-NOVA Compute domain should have the capability, if required by a network service, to support heterogeneous compute resources, such as Graphical Processing Unit (GPUs), Field Programmable Gate Array (FPGAs), Multi-Integrated Cores (MICs) etc.

4.3.4 NFVI Hypervisor

The NFVI Hypervisor domain should be able to implement hardware resource abstraction, virtual resource lifecycle management mechanisms which are coordinated by the Orchestrator via the VIM, and to provide to the VIM monitoring information while having minimal impact on the VNF workload performance. Additional details on the collection, processing and utilisation of metrics in the T-NOVA system can be found in subsection 5.3.

4.3.5 NFVI DC Network

The NFVI DC Network domain should implement an SDN approach to provide network virtualisation capabilities inside a NFVI-PoP (creation of multiple distinct domains over one single physical network using VLANs), network programmability through the separation between Control Plane (CP) and Data Plane (DP), and, at the same time, it should support transport tunnelling protocols of L2 packets over L3 networks, to assist the TNM in setting up the communication between different NFVI-PoPs. It should also be able to gather performance data and send them to the VIM Network Control module.

4.4 T-NOVA IVM Architecture

As mentioned above, the T-NOVA IVM layer comprises of three key architectural components namely the NFVI, the VIM and the TNM.

The high-level architecture, which has previously been described in D2.21 (4), was designed to align with the ETSI MANO architecture featuring corresponding components to the NFVI and the VIM. However, the addition of the TNM is a T-NOVA specific feature.

The approach adopted in the design and elucidation of the IVM focused on the functional characteristics of the overall IVM architecture and its sub domains. Careful consideration was given to decoupling the functional characteristics from implementation-oriented designs. This allowed us to focus on what the IVM needs to do rather to avoid the inclusion of implementation-orientated functionality. A good example of where this approach generated challenges was with the VIM architecture where there was a tendency to gravitate towards technology solutions as a means to easily encapsulate functional needs. However careful consideration of the key inputs was important in fully decoupling functional needs from implementation details to ensure that T-NOVA IVM architecture remains technology-agnostic but at same time provides appropriate guidance and structure to the activities in WP3/4.

The key inputs that were considered during the architecture design process are the following:

- D2.1 (Use case and requirements) (63),
- D2.21 (subsection 3.3.3) (4),
- DGS NFV-INF 001 v0.3.8 - Infrastructure Overview (67),
- DGS NFV-INF 003 v0.3.1 - Architecture of the Compute Domain (68),
- DGS NFV-INF 004 v0.3.1 - Architecture of the Hypervisor domain (69),
- DGS NFV-INF 005 v0.3.1 - Infrastructure network domain (5),
- DGS NFV-INF 007 v0.3.1 - Interfaces and Abstractions (70),
- DGS NFV-MAN 001 v0.6.3 - Management and orchestration (8),
- DGS NFV-REL 001 v0.1.3 - Resiliency Requirements (71),
- DGS NFV-SWA 01 v0.2.0 - VNF Architecture (7).

The IVM architecture has been defined in accordance to a systems design process which was used to identify the components, modules, interfaces, and data necessary for the IVM in order to satisfy the requirements outlined in the previous subsection and those described in D2.1 (63) and D2.21 (4). Figure 21 shows the overall architecture of the VIM, as discussed so far.

4.4.1 External Interfaces

The key external interfaces for the IVM are outlined in Table 6. These interfaces primarily deal with the connection between the IVM and the T-NOVA Orchestrator;

however there is also an external interface between the TNM and the transport network.

The interfaces between the Orchestrator and VIM support a number of key functions within T-NOVA. The functions supported by the interfaces can be categorised as either management or control. As shown in the IVM architecture in Figure 21, two specific interfaces have been identified, mapping to the interfaces identified in the ETSI MANO architecture.

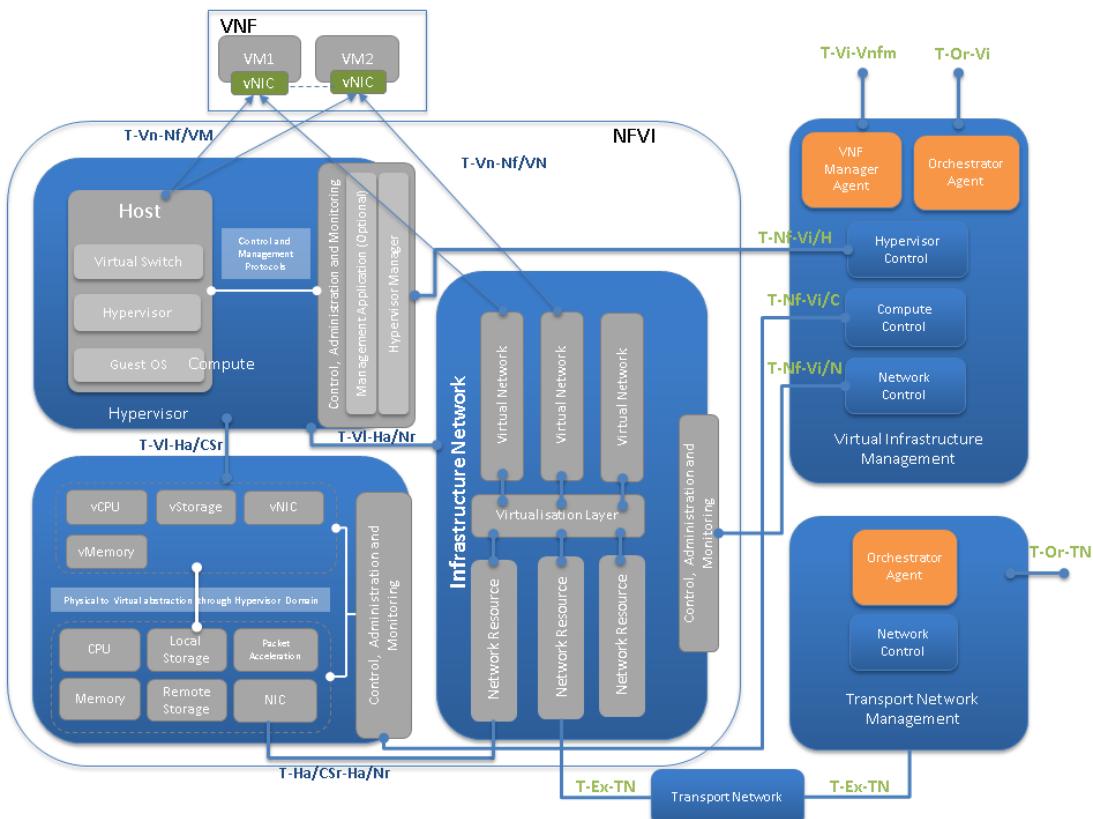


Figure 21: T-NOVA infrastructure virtualisation and management (IVM) high level architecture

The first interface is the VNFM – VIM Interface (**T-Vi-Vnfm**) and is responsible for the exchange of infrastructure monitoring information either through explicit request by the Orchestrator or through periodic reporting initiated by the VIM. The types of data exchanged over this interface include detail information on the status, performance and utilisation of infrastructural resources (such CPU, storage, memory, etc.). Data will also encompass networking information relating to a specific VNF such as NIC level network traffic from the hosting VM or inter VM network traffic, if a VNF is deployed across more than one VM.

Finally VNF performance data will also be exchanged over this interface. Collectively the data will be used by the VNF Manager within the T-NOVA Orchestrator to track VNF service performance by comparison with specific KPIs in order to ensure SLA compliance.

The second interface identified is the NFV Orchestrator – VIM interface (**T-Or-Vi**). This interface is responsible for handling requests from the NFV Orchestrator with respect

to the full lifecycle of a NS. Typical examples of requests sent over this interface would include, for example, parts of the on-boarding, scaling and termination procedures of a NS. This interface will be used by the NFV Orchestrator to send resource related commands/information to the VIM such as resource reservation/allocation or configuration definitions of VMs (e.g. HEAT templates in an OpenStack Cloud environment or network requirements such as the specification of the interconnections between VNF instances, i.e. network topology). Specific types of monitoring information will also be exchanged over this interface such as data related to the network connections between NS instances either within a data centre or within intra data centre connections that are physically dispersed. This interface is also used by the VIM to report back to the NFV Orchestrator the outcome of all received requests.

The Transport Network Manager provides management capabilities of network connectivity between NFVI-PoPs. The NFV Orchestrator – Transport Network Interface (**T-Or-TN**) interface support requests from the NFV Orchestrator to provide connectivity to either SDN Controlled or non SDN control transport networks (such as IP or MPLS based networks) typically for inter DCs (MAN or WAN). These networks are non-virtualised in nature.

The TNM Interface – External networks (**T-Ex-TN**) is the explicit network connection to the transport network. The implementation of this interface will vary based on the protocol the network is using. More than one interface may also be implemented if connectivity to different types of transport networks is required.

Table 6: External Interfaces of the T-NOVA IVM

T-Nova Name	T-NOVA Reference	ETSI ISG NFV Framework Reference Point	Reference Point Type	Description and Comment
Virtual Network Function Management-VIM Interface	T-Vi-Vnfm	Vi-Vnfm	Management Interface	This interface is responsible for the exchange of infrastructure monitoring information either through explicit request by the Orchestrator or through periodic reporting initiated by the VIM. The types of data exchanged over this interface include status, performance and utilisation of infrastructural resources

NFV Orchestrator– VIM Interface	T-Or-Vi	Or-Vi	Orchestration Interface	This interface allows the NFV Orchestrator to request/reserve and configure resources to the VIM and for the VIM to report the characteristics, availability, and status of infrastructure resources.
NFV Orchestrator– Transport Network Interface	T-Or-TN	-	Orchestration Interface	This interfaces the TNM with the NFV Orchestrator and is used to manage the set-up, tear down and monitoring of connections in transport networks.
Transport Network Interface– External networks	T-Ex-TN	Ex-Nf	Traffic Interface	This interfaces the TNM with existing transport networks (SDN-enabled or non-SDN-enabled) and are used to implement requests received from the Orchestrator via the Or-TN interface.

4.4.2 Internal IVM Interfaces

The key internal interfaces of the IVM as outlined in Table 7. The interface for NFVI management including its functional entities is provisioned via the T-Nf-Vi interface. It is this interface, which will be utilised to establish trust and compliance of the underlying infrastructure specifically the Hypervisor domain via the T-Nf-Vi/H implementation of the interface, the compute domain via the T-Nf-Vi/C interface and the network domain via the T-Nf-Vi/N interface. A full description of these interfaces is presented in Table 7. A possible deployment configuration for the VIM could be provided running it within a hosted VM (it can be virtualised). For this specific configuration, the T-Nf-Vi management interface might be abstracted as a SWA-5 interface (see Figure 3). However, even if this configuration is possible, it is not desirable, due to security concerns and FE responsibilities. There are also reliability concerns regarding virtualising the VIM on the same infrastructure that it is managing. In a scenario where the hypervisor domain of the NFVI requires a restart, the VIM will lose its ability to operate and continue to manage the NFVI therefore the VIM should run on separated hardware platforms.

One of the interfaces that are internal to the NFVI is the SWA-5 interface², which is used for resources, such as a virtual NIC, a virtual disk drive, virtual CPU, etc. Examining Figure 21, this interface involves both the T-Vn-Nf/VN and T-Vn-Nf/VM. It is not intended for use as a management interface; hence a VNF should not use SWA-5 to manage the NFVI. This interface is primarily intended to logically fence off responsibilities, but is also intended for security considerations. In fact, reasonable steps must be taken to prevent unauthorised access, from within a VM, from attacking the underlying infrastructure and possibly shutting down the entire domain, including all other adjacent VMs.

Table 7: Internal interfaces of the IVM

T-Nova Name	T-NOVA Reference	ETSI NFV Framework Reference Point	INF Reference Point	Reference Point Type	Description and Comment
VIM-Network Interface	T-Nf-Vi/N	Nf-Vi	[Nf-Vi]/N	Management, Orchestration and Monitoring Interface	This interface is used for the management of Infrastructure Network domain resources.
VIM-Hypervisor Interface	T-Nf-Vi/H		[Nf-Vi]/H	Management, Orchestration and Monitoring Interface	This interface is used for the management of the Hypervisor domain resources.
VIM – Compute Interface	T-Nf-Vi/C		[Nf-Vi]/C	Management and Orchestration Interface	This interface is used for the management of Compute domain resources.
Hypervisor – Network Interface	T-VI-Ha/Nr	VI-HA	[VI-Ha]/Nr	Execution Environment	This interface is used to carry execution information between the Hypervisor and the Infrastructure Network domains.
Hypervisor -Compute Interface	T-VI-Ha/CSr	VI-Ha	[VI-Ha]/CSr	Execution Environment	This interface is used to carry execution

² SWA-5 corresponds to VNF-NFVI container interfaces: This is a set of interfaces that exist between each VNF and the underlying NFVI thus SWA-5 describes the execution environment for a deployable instance of a VNF (7).

					information between the Compute and the Hypervisor domain.
Compute–Network Interface	T-Ha/CSr-Ha/Nr	VI-Ha	Ha/CSr-Ha/Nr	Traffic Interface	This interface is used to carry execution information between the Compute and the Network domain.
Virtual Machine–VNFC Interface	T-Vn-Nf/VM	Vn-Nf	[Vn-Nf]/VM	VNF Execution Environment	This interface is used to carry execution environment information for each VNFC instance.
Virtual Network–Virtual Network Interface	T-Vn-Nf/VN		[Vn-Nf]/VN	VNF Execution Environment	This interface is used to carry execution environment information between VNFC instances.

4.5 NFVI and NFVI-PoP

The execution environment for VNFs is provided by the NFVI deployed in various NFVI-PoPs. The NFVI-PoP acts single geographic location i.e. a DC where a number of NFVI-nodes are located. A NFVI PoP is responsible for providing the infrastructural building blocks to host and execute VNF services deployed by the T-NOVA system in a particular location. The NFVI comprises of the IT resources in the form of the Compute and Hypervisor domains and network resources in the form of Network domain, as shown in Figure 21. The NFVI can utilise these domains in a manner that supports extension beyond a single NFVI-PoP to multiple NFVI-PoPs as required to support the execution of a given NS.

The NFVI-PoP is expected to support the deployment of VNFs in a number of potential configurations. These deployments will range from a single VNF deployed at a single NFVI-PoP, to multiple VNFs from different VNF providers in a multi-tenant model at one NFVI-PoP. Additionally, the NFVI may need to support VNFs deployed at more than one NFVI-PoP to instantiate the required NS. Interconnectivity between these PoPs is provisioned and managed in the case of T-NOVA by the TNM module, which is similar in function to the WAN Controller in the ETSI MANO architecture (8) (see subsection 4.7).

The network access capacity required at a particular NFVI-PoP will depend on the network service workload type, the number and capacity of the VNFs instantiated on the NFVI. The management and orchestration of virtualised resources should be able to handle NFVI resources in a single NFVI-PoP as well as when distributed across multiple NFVI-PoPs. Management of the NFVI is provided by the VIM through domain interfaces (T-Nf-Vi) as shown in Figure 21. The VIM also provides the intermediate interfaces between the Orchestrator and the NFVI (T-Or-Vi and T-Vi-VNFM). The NFVI will execute requests from the Orchestrator relating to the lifecycle management of VNFs such as deployment scale in/out, scale up/down and termination.

The following sections describe the architecture and the respective internal components of the NFVI, namely the compute, hypervisor and network domains. The interfaces required to implement an overall functional architecture for the T-NOVA NFVI system are also described.

4.5.1 IT Resources

The T-NOVA IT Resources encompasses the compute and hypervisor domains of the NFVI. These domains have their origins in traditional enterprise IT environments and more recently in the deployment of cloud computing environments. In order to support the development of NFV architectural approaches in carrier grade environments, IT resources and capabilities have been embraced in these environments to support the deployment of VNFs. However the functionality, capabilities and how these IT resources are composed within virtualised network architectures need to be carefully considered. The enterprise origins of these technologies often have inherent gaps in capability such as line-rate packet processing performance limitations. These gaps can influence architectural decisions and may require innovative solutions to address any identified gaps for VNF service deployment. The following sections discuss the compute and hypervisor domain architecture considerations and the proposed approach in the context of the T-NOVA system architecture.

4.5.1.1 Compute Domain

The Compute Domain is one of three domains constituting the NFVI and consists of servers, NICs, accelerators, storage, racks, and any associated physical components within the rack related to the NFVI, including the networking Top of Rack (ToR) switch. The Compute domain may be deployed as a number of physical nodes (e.g. Compute and Storage Nodes) interconnected by Network Nodes (devices) within an NFVI-PoP.

Traditionally the compute environment within the telecoms domain has been heterogeneous based around a variety of microprocessor architectures such as MIPS, PowerPC, SPARC, etc. with tight coupling between the microprocessor and the software implementation. Many traditional telecommunication systems are built in C/C++ technology with high interdependence on the underlying processing infrastructure and a specific instruction set.

As the first generation of VNFs have appeared in the marketplace based around adaption of specific software to a version that can run on virtualised X86 environments some performance difficulties have been encountered. While virtualisation decouples software and hardware from a deployment point of view, it does not do it from a development point of view. Selection of an appropriate cross compiler for the target platform (e.g. X86) may address some of the issues. However in order to achieve optimal performance, a proper redesign of the software may be required to ensure appropriate use of specific capabilities, like for example hyper threading in X86 processors. The specific application may also need to make use of software libraries to improve the performance of certain actions such as packet processing.

The compute domain architecture should have the capability to support distributed virtual appliances that can be hosted across multiple compute platforms as required by specific SLAs of VNFs services. Moreover storage technologies and management solutions are included in the domain and show a large degree of variability in terms of different technologies; scalability and performance (see subsection 2.2). Depending on the workloads and use-cases the choice of storage technology is likely to be specific to certain workloads.

Another important objective of the compute domain is to expose hardware statistics of the compute node with high temporal resolution. The VIM communicates directly to the compute domain and through the hypervisor to access all the hardware metrics, which can be static or dynamic in nature.

Subsection 5.3 describes requirements for exposing hardware characteristics (i.e. metrics) for planning/provisioning and high temporal resolution monitoring/deployment of VNFs. Interfaces to pass metrics to the VIM are described in the NFVI domains and interfaces (NFV Infrastructure Architecture).

Static metrics expose compute node characteristics which do not change or change slowly (e.g. once a day). These metrics ultimately act as a first order filter for selecting/provisioning a node for deploying a VNF. Static metrics are obtained from reading OS and ACPI tables. The Advanced Configuration and Power Interface (ACPI) specification provides an open standard for device configuration and power management by the operating system. Additional metrics may be stored in local structures provisioned by the vendor or administrator. For example compute node performance index, energy efficiency index, geographic location, specific features enabled/supported, security level, etc.

An Orchestrator can identify a candidate platform based on static metrics, however actually instantiate a VNF additional dynamic metrics will be required, e.g. CPU utilisation, memory, I/O headroom currently available etc. These metrics could be provided on a per-query basis or the compute node could proactively update hypervisor domain at regular intervals.

Heterogeneous Compute Architectures

A VNF developed for a target compute architecture needs to be fully optimised and validated prior to rollout. This process will also need to be repeated on a per

compute architecture basis. While the initial focus has been on X86 compute architectures, recently there has been interest in the use of co-processors such GPUs or FPGAs to accelerate certain VNF workloads: some NFV workloads can experience performance benefits by having access to different processing solutions from a variety of silicon vendors including network processors and general-purpose co-processors. The move towards more heterogeneous cloud computing environments is starting to gain attention, as standard X86 processors may have performance limitations for certain workloads tasks e.g. high speed packet processing. This has led DC equipment vendors to investigate the use of alternative compute architectures to enhance their offerings. In defining heterogeneous compute domain architectures for T-NOVA, we divided devices into two main categories:

- Devices which can only operate in conjunction with a host CPU, like GPUs, multi-integrated cores (MIC) and Micron's Automata processor;
- Devices which can operate in a stand-alone fashion, like FPGAs and FPGA SoCs (although FPGAs and FPGA SoCs can also act as devices attached to a CPU-controlled system).

For the first class of devices we can derive a compute node architecture, where the compute node is complemented by a co-processor, which can be any of the four technologies mentioned above (in the FPGA and FPGA SoC cases, they will, act as slave devices to the processor). The extent to which the accelerator resources themselves are virtualised is left to each specific implementation, though such a solution is known to improve the performance of the accelerator hardware. It must be noted that such a solution is only available for GPUs (e.g. nVidia's GRID), but not for FPGAs or the automata processor. This general architecture leaves a lot of the implementation choices open. For example the interconnection of the CPU and the co-processor could be implemented either over PCIe or over a direct link like Quick Path Interconnect (QPI) or division of the memory between the CPU and the co-processor. In any scenario, the system must be able to adhere to the requirements for the compute nodes as outlined down in Annex B.

The second class of devices is based around an FPGA SoC, which is an FPGA that integrates one or more processor cores in the same silicon die. Devices like these are available from all major FPGA vendors. In this case, the processing system on the FPGA SoC runs a Hypervisor on which OS' and applications are executed. To a large extend the same considerations as in the previous scenario apply, both in terms of interconnection of components and virtualisation of accelerator resources. The important difference here is the degree of integration, since the whole heterogeneous compute node resides within one physical device.

From an external interface perspective the heterogeneous compute nodes do not differentiate themselves from the standard compute node. Thus, there is an interface to the hypervisor, an interface to the controller for the virtualised network infrastructure and finally an interface to the VIM.

However, supporting heterogeneous devices in the compute domain will require appropriate changes to be made to several areas of the T-NOVA architecture. For instance, a VNF that is to be deployed to a heterogeneous compute node may need

to be specifically created for this compute architecture. Additionally, the deployment of the container of the associated VNFD needs to take into account different relevant factors (e.g. location of compute nodes with the appropriate resources). Finally, data collected in the VIM will need to reflect the resources available in the heterogeneous node and their occupancy. This trade-off between deployment flexibility and performance will probably need to be assessed on a case by case basis.

Key Components of the Compute Domain

The main components of the Compute domain's architecture are:

- **CPU and Accelerator:** A general-purpose compute architecture is considered based on commercial x86 server clusters. Additionally co-processors cards/FPGAs are also considered for application specific workloads or functions such as packet processing. As outlined in subsection 2.2 the CPU nodes will incorporate technologies to support virtualisation of the actual CPU such as VT-x. Connections to I/O devices will use technologies such as VT-d. Specific co-processors include acceleration chip for classification, Crypto, DPI/Regular Expression, Compression/Decompression, Buffer management, Queue management, Work scheduler, Timer management, Traffic management, address translation);
- **Network Interfaces:** The network interface could either be a NIC which connects to the processor via PCIe or the network interface capability may be resident on-board the server. Provisioning of virtualised network connectivity and acceleration will use technologies such as VT-c.
- **Storage:** Storage encompasses large-scale storage and non-volatile storage, such as hard disks and solid-state disk (SSD) which can be with locally attached or networked in configurations such as SAN. For some purposes, it is necessary to have visibility of the different storage hierarchy level (Cache Storage, Primary Storage, Secondary Storage, Cold Storage or Archived Storage) each one characterised by specific levels of latency, costs, security, resiliency and feature support. However, for many applications, the different forms of storage can be abstracted, especially when one form of storage is used to cache another form of storage. These caches can also be automated to form a tiering function for the storage infrastructure.

Collectively these technologies enable the hypervisor to abstract the physical resources into virtual resources which can be assembled into VMs for hosting VNFs. It should be noted that a single Compute Platform can support multiple VNFs.

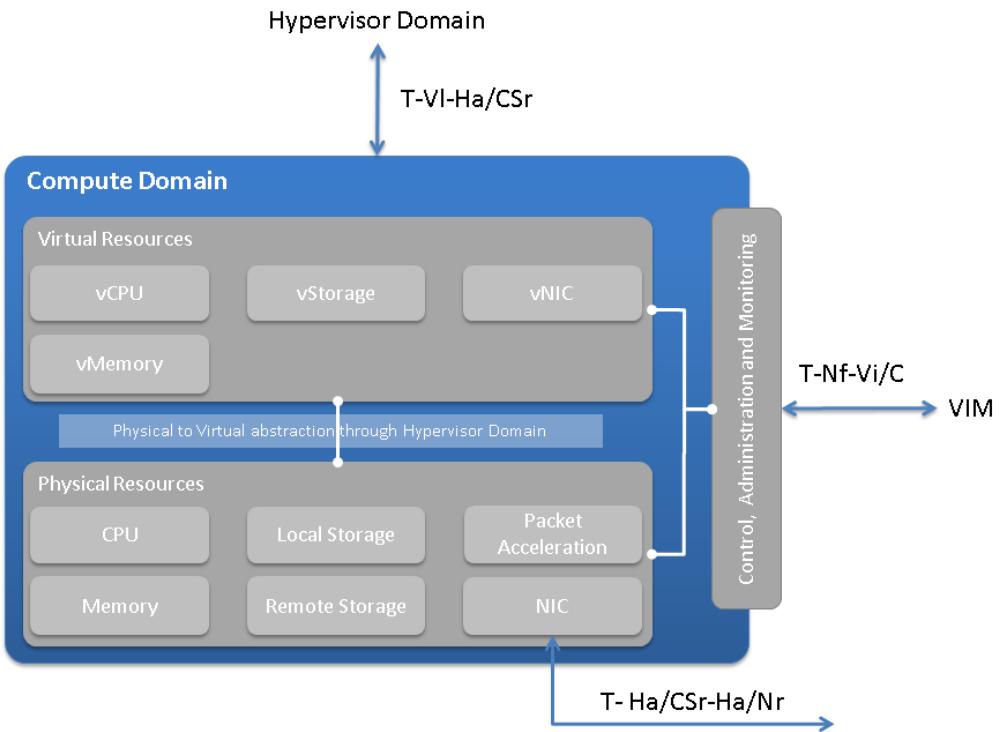


Figure 22: Compute Domain High Level Architecture

Compute Domain Interfaces

The compute domain presents three external interfaces:

- The ***T-Nf-Vi/C*** - used by the VIM to manage the compute and storage portion of the NFVI. It is the reference point between the management and orchestration agents in compute domain and the management and orchestration functions in the virtual infrastructure management (VIM);
- The ***T-[Vi-Ha]/CSr*** interface is the interface between the compute domain and the hypervisor domain. It is primarily used by the hypervisor/OS to gain insight into the available physical resources of the compute domain;
- The ***T-HA/CSr-Ha/Nr*** interface is used to carry execution information between the Compute and the Network domain.

Orchestration and management of the NFVI is strictly implemented via the **T-Nf-Vi** interfaces. The implementation of the interface must match the requirements outlined in Annex B in addition to having the general characteristics of being dedicated and secure. This interface is utilised to establish trust and compliance between the VIM and the underlying compute infrastructure. The interface is exposed by management agents of the compute node and allows both control and monitoring of the compute domain. With regard to monitoring, agents are installed both at the host OS (to measure physical resources) as well as the guest OSs (to measure virtualised resources associated with a specific VNFC). The latter metrics are of particular interest to T-NOVA operations, since they provide an indication of the resources consumed by a VNFC instance and are directly used for service monitoring.

Application performance such as SLA compliance depends on a variety metrics such as resource and system level metrics. The ability to measure application performance and consumption of resources plays a critical role in operational activities such as customer billing. Furthermore, statistical processing of VNFC metrics will be exploited to indicate a particular malfunction. Metrics to be collected at both physical compute node and VM include CPU utilisation, memory utilisation, network interface utilisation, processed traffic bandwidth, number of processes, etc.

4.5.1.2 Hypervisor Domain

The hypervisor domain is the part of the T-NOVA architecture that provides the virtualised compute environment to VNFs. Since the hypervisor domain embraces different types of hosts, with different Guest OSs and/or hypervisors, it is important to manage interoperability issues appropriately. Issues relating to the virtualisation of VNFs on technologies from different vendors need to be carefully considered.

The primary goal of the hypervisor domain is therefore to manage the heterogeneity of technologies from different vendors, thus providing an interoperable cloud environment to the VNFs. In that sense, the hypervisor domain provides an abstraction layer between the VIM (which controls, monitors and administrates the cloud) and the VNFs resources. The high level architecture of the hypervisor domain is shown in Figure 23.

Looking at a single host, the hypervisor module provides virtual resources by emulating different components, like CPUs, NICs, memory and storage. This emulation can be extended to include complete translation of CPU instructions sets; so that the VM believes it is running on a completely different hardware architecture with respect to the one it is actually running on. The environment provided by the hypervisor is functionally equivalent to the original machine environment. This emulation is carried out in cooperation with the Compute domain. The hypervisor module manages slicing and allocation of the local hardware resources to the hosted VMs.

It also provides the NICs to the VMs and connects them to a virtual switch in order to support both internal and external VM communication. A suitable memory access driver is integrated into the virtual switch that interconnects VMs with each other.

The virtual switches (vSwitches) are also managed by the hypervisor, which can instantiate and configure one or more vSwitches for each host. They are logical switching fabrics reproduced in software.

The integration of vSwitches and hypervisors is an area of specific focus due to its significant influence on the performance and on the reliability of VMs, especially in the case of VNFs. The various aspects and issues related to the integration of vSwitches with hypervisors are discussed in subsection 2.2.

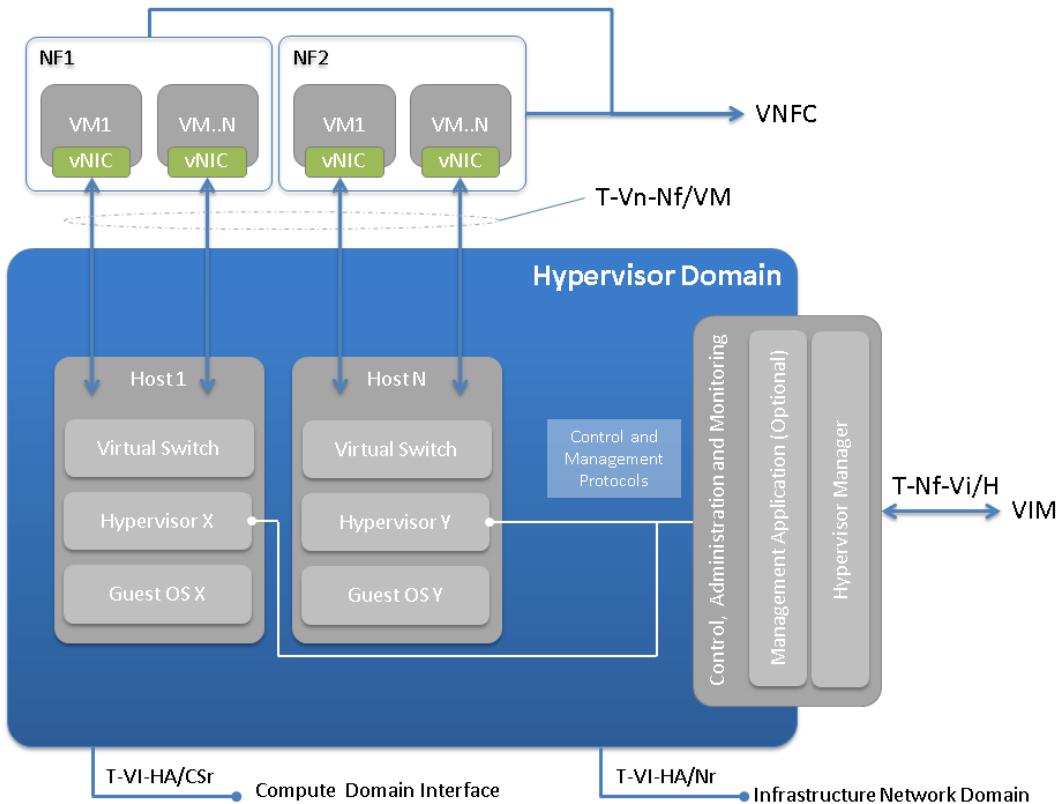


Figure 23: Hypervisor domain architecture

The Control, Administration and Monitoring module is essentially responsible for the control functionality for all the hosts within the cloud environment, abstracting the whole cloud. The main goal of this module is to provide a common and stable layer that will be used by the VIM to monitor, control and administrate the VNFs over the T-NOVA cloud. Moreover, as previously described it provides a unified the VIM and is used to control the lifecycle of the VNFs. This supports various operations on the VMs (or VNFs) such as provisioning, creation, modification of state, monitoring, migration and termination.

Since different hypervisors provide different interfaces, the Control, Administration and Monitoring (CAM) module needs to support heterogeneous hypervisors, managing virtual resources on different vendors' hypervisor at the same time. This particular task is accomplished by the hypervisor manager.

4.5.2 Infrastructure Network Domain

The T-NOVA network infrastructure comprehends the networking domain of the NFVI, i.e. the different virtualised network resources populating the NFVI as shown in Figure 24. The Network domain within the NFVI considers virtual resources composing virtual networks as the functional entity. Those virtual networking resources are devoted to provide connectivity to the different virtualised compute resources, which has been presented in previous section.

The T-NOVA architecture, and thus the network domain controlled by the VIM, leverages SDN for optimising network operations. Both the Control and Data Planes

are separated. The network domain builds a full abstraction of the actual resources included in the physical substrate and then creates vLinks between VMs (composing vNets), which are provisioned in order to satisfy the requirements of the different VNFs.

The main objectives of the network (aforementioned) resources are to provide connectivity between VMs which can run on the same server, on different servers within the same DC, or outside the same DC boundaries. (In the latter case, a co-operation with the TNM module is required). Within the T-NOVA IVM, this is directly translated into the creation of virtual networks that interconnect a set of compute resources which are providing the execution substrate to VNFs.

Virtual networks must be dynamically programmed in order to ensure network slicing, isolation, and ultimately connectivity in the T-NOVA multi-tenant scenario. Each vNet is dedicated to a specific VNF service, and provides connectivity between the different hosts serving the VNF service. Elasticity of the vNet is strictly required in order to guarantee that the corresponding VNF services can be properly scaled-up or –down. A virtualised control plane (SDN-like) will be responsible for controlling each one of these virtual networks (refer to subsection 4.6.2).

Basically, the network domain performs abstraction of the physical network devices themselves and then creates a set of virtual slices in an on-demand fashion. The architecture basically contains the southbound components, with the different resource agents and the abstracted models, with the upper part of the network domain contains the basic virtualisation capabilities, responsible for creating and composing the virtual networks.

The network domain contains two basic interfaces: (i) one to the VNF (T-Vn-Nf/VN), and (ii) the other to the basic VIM controller (T-Nf-Vi/N). A full description of the interfaces can be found in Table 7.

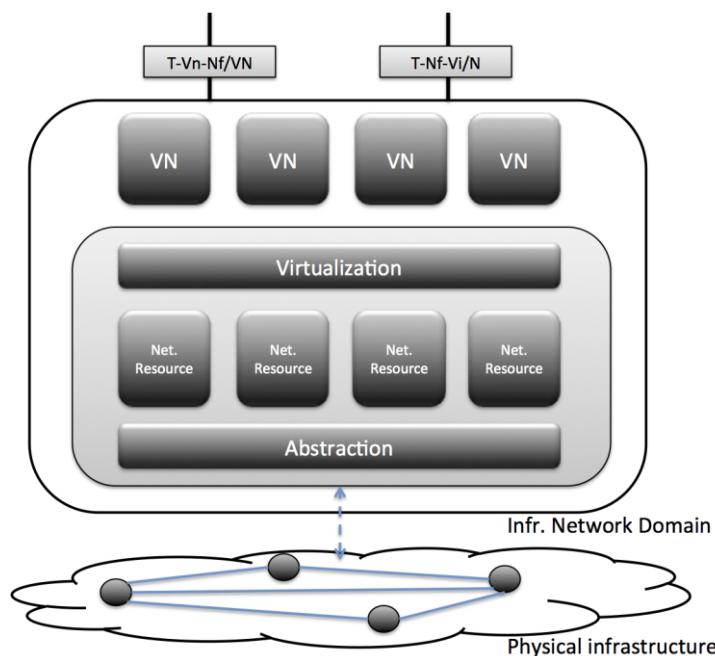


Figure 24: High level architecture of the Infrastructure Network

4.6 Virtualised Infrastructure Management

Within the T-NOVA IVM architecture the VIM is the functional entity that is responsible for controlling and managing the NFVI compute, storage and network resources within the NFVI. The VIM general is expected to operate in one operator's infrastructure domain (e.g., NFVI-PoP). However as many operators now have data centres distributed on a global basis, scenarios will arise where the VIM may operate in more than one NFVI-PoP to support either the architecture requirements for VNF services and/or operator business needs. Alternatively multiple VIMs may operate across operator data centres providing multi NFVI-PoPs that can operate independently or cooperatively as required under the control of an Orchestrator.

While a VIM, in general, can potentially offer specialisation in handling certain NFVI resources, in the specific context of the T-NOVA system the VIM will handle multiple resources types as shown in Figure 25. The VIM acts as the interface between the T-NOVA Orchestrator and the available IT-Infrastructure abstracted by the NFVI. The control components are at the heart of the VIM, encompassing the following elements:

- The algorithms and logic for control, monitoring and configuration of their related domain;
- An interface or API server to offer the implemented logic and collected information's in an abstracted way to other components;
- An interface to control and access the virtualised infrastructure.

The interfaces of the API servers from each control component in the VIM are furthermore aggregated in the Orchestrator Agent and the VNF Manager Agent to deliver a unified interface to the upper layers of the T-NOVA components via the T-Vi-Vnfm and T-Or-Vi interfaces. This architecture allows interaction with the upper layers with a higher level of abstraction giving the T-NOVA Orchestrator the layers with a higher level of abstraction giving the T-NOVA orchestrator the flexibility, to configure a particular part of the infrastructure or to collect infrastructure related data. The VIM also exposes southbound interfaces (as shown in Figure 25Figure 26) to the infrastructure resources (Hypervisor/Compute/Network) of the NFVI which enable control and management of these resources. A summary of the key north bound VIM interfaces can be found in Table 7.

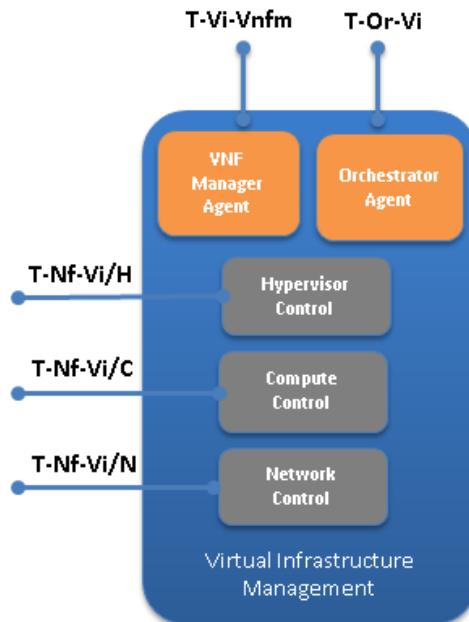


Figure 25: T-NOVA VIM high level architecture

The following are the key set functions identified that must be performed by T-NOVA VIM based on general requirements identified by ETSI for a VIM within the MANO architecture (8).

- Resource catalogue management,
- Orchestrating the allocation/upgrade/release/reclamation of NFVI resources, and managing the association of the virtualised resources to the physical compute, storage, networking resources,
- Supporting the management of VNF Forwarding Graphs (create, query, update, delete), e.g., by creating and maintaining Virtual Links, virtual networks, sub-nets, and ports,
- Management of the NFVI capacity/inventory of virtualised hardware resources (compute, storage, networking) and software resources (e.g., hypervisors),
- Management of VM software images (add, delete, update, query, copy) as requested by other T-NOVA functional blocks (e.g., NFVO),
- Collection and forwarding of performance measurements and faults/events information relative to virtualised resources via the northbound interface to the Orchestrator (T-Or-Vi),
- Management of catalogues of virtualised resources that can be consumed from the NFVI. The elements in the catalogue may be in the form of virtualised resource configurations (virtual CPU configurations, types of network connectivity (e.g., L2, L3), etc.), and/or templates (e.g., a virtual machine with 2 virtual CPUs and 2 GB of virtual memory).

The high level architecture for the T-NOVA VIM architecture reflects these key functions.

4.6.1 IT Resource Management and Control

In the T-NOVA system we distinguish between IT and visualised network resources. Also from a management and control perspectives this categorisation is clearly visible in the architectural design of the VIM. In fact, on the one hand, the VIM provides to the Orchestration layer a unified access point to all infrastructural resources at an abstracted level, but, on the other hand, internally the control modules are explicitly split into Compute and Hypervisor Control managing the IT resources, whereas the Network Control module manages the network resources. This architectural choice allows the T-NOVA system to manage them according to different requirements and needs (in terms of performance, time constraints, and so forth). The following subsections discuss the respective management and control needs of the hypervisor and compute resources within the VIM and their relationship to the NFVI.

4.6.1.1 Hypervisor Management

The hypervisor control function is responsible for providing high level control and configuration capability that is independent of the technology implementation within the hypervisor domain. The interface to the hypervisor domain (**T-Nf-Vi/H**) provides the necessary level of abstraction to the specifics of the underlying hypervisor. The hypervisor control component provides the basic commands like start, stop, reboot etc. and offers these commands through an API server to the VIM. Specific commands related to a particular hypervisor implementation may also be supported on case by case basis through the same API server allowing finer performance tuning. Additionally the hypervisor controller can implement a query API that can be used to provide detailed information such as configuration details, version numbers etc.

The network configuration of a newly created VM is usually configured by a script that runs at boot-time or can be done manually after the VM has booted. The hypervisor control component will offer the capability to implement a network configuration during VM instantiation thus enabling a higher degree of automation which is important for service provider operations. The hypervisor controller is able to push onto the VM, provided the hypervisor supports the action, the desired network configuration before the first boot of the OS.

The reliability capabilities inside the hypervisor controller have an important role as custom configurations can be requested by the T-NOVA Orchestrator. Their primary role is to prevent the user of the API from placing the hypervisor in an inconsistent or error state leaving it unable to manage or respond to the VMs under its control. The module may also play a role in managing issues such as misconfiguration, compromised commands or hypervisor options that do not work well with the allocated hardware.

4.6.1.2 Computing Resources Management

A key functionality of the compute domain management will be the collection and processing of the monitoring metrics collected by both the physical compute nodes as well as the VMs (VNFCs). A dedicated monitoring manager is envisaged; to which monitoring agents will connect to communicate compute domain resource metrics.

At the monitoring manager, these metrics will undergo statistical processing in order to extract additional information such as fluctuation, distribution and correlation. This processing will provide useful information about the behaviour of each VNF component and will contribute towards the early detection of possible VNFC malfunctions. This will be the case e.g. if some measurements fall outside the normal VNF load curve (e.g. if CPU utilisation rises abnormally even though processed network traffic volume does not).

The placement of a VM on a compute resource is a critical task and the compute controller carries out this function using a placement scheduler. This scheduler will, if no further options are specified, make a decision based on the requirements of the infrastructure provider and place the VM in an automated fashion. To influence this decision making process, the scheduler will have a filter API that can be used via the Orchestrator agent and thus by the Orchestrator. The filter may have of details related to the desired SLA or specific hardware and software requirements. The main filter categories that influence the decision process by the scheduler are:

- Specific hardware requirements like CPU speed or type of disc,
- Specific software requirements like the host OS or the hypervisor,
- Current load and performance metrics of the compute node such as average CPU utilisation rate etc.,
- Financial considerations such as newest hardware or most energy efficient hardware.

A further core task of the compute controller is to provide specific management capabilities of the VMs for the Orchestrator especially where the operations overlap with hypervisor and network controller actions. Such tasks include:

- Creation and deletion of a VM,
- Rebuilding, suspend and pause a VM,
- Migrating a VM from one compute node to another compute node,
- Resizing a VM.

Creation of a VM requires close interaction with the base image repository that contains the basic unmodified OS images. In many cloud computing platforms, these base images are known as flavours.

A CLI capability is generally required within the compute controller in order to enable infrastructure administrators to carry out routine maintenance and administration tasks. For example, the administrators may need to migrate VMs on a physical compute node to another one as part of an infrastructure upgrade activity. Other potential action may include interaction with the scheduler and filters in order to modify the configuration of a VM or set of VMs to maintain an associated SLA for a VNF service running on the VMs.

4.6.2 Infrastructure Network Resources Management and Monitoring

The Network Control functional block within the VIM is responsible for configuring and managing the SDN-compatible network elements to provide an abstracted platform for running SDN applications (i.e. network virtualisation, load balancing, access control etc.).

In order to meet specific VNF services' requirements, the network elements, physical and virtual, need to be properly programmed by the Network Control function to ensure appropriate network slicing, isolation and connectivity in a multi-tenant environment. In this way, the network will be properly partitioned and shared among several vNets, each dedicated to a specific VNF service. In the T-NOVA architecture there is an explicit distinction between virtual and physical network control domains: the virtual network control domain is managed by the VIM, whereas the physical network control domain is managed by the TNM entity (discussed in next section).

The virtualisation of the Network Control is intended to address scalability and centralisation issues affecting the SDN controller in large network infrastructures. The proposed approach is to virtualise each instance of CP, enabling the distribution of the overall workload to multiple VM. In this regard, the SDN Control Plane can offer elasticity, auto-scaling and computational load balancing by exploiting cloud-computing capabilities.

In order to guarantee an efficient CP virtualisation, a SDN Control Plane Coordinator is expected to manage and monitor multiple CP instances. Moreover, it maintains a global consistent view of the network by means of a Distributed Cache among each running CP instance.

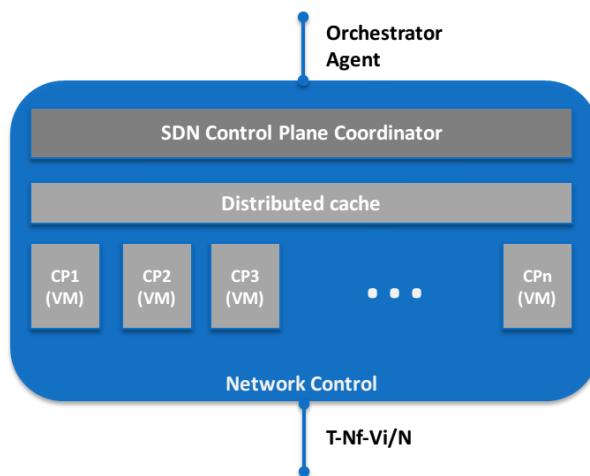


Figure 26: VIM Network Control Architecture

The Network Control component interfaces internally with the VIM Hypervisor and Compute components and externally with the Orchestrator layer, by accepting requests to deploy vNets based on certain topology and QoS requirements.

4.7 Transport Network Management

The ETSI specifications indicate that the NFVI is the totality of the NFVI-PoPs along with the transport network that interconnects them. In T-NOVA architecture, there is an explicit separation between those two domains and two different network domains have been identified: the former involves the SDN based network which is internal to an NFVI-PoP, whereas the latter involves the transport networks that interconnect NFVI-PoPs.

The TNM is the module of the IVM architecture whose main function is to manage the transport network, composed by PNFs, providing also the connectivity between different NFVI-PoPs, relying on existing WAN networks.

Those PNFs can be classified in two different categories:

- *SDN-enabled network elements* - physical devices that implement an SDN approach,
- *Legacy network element* - physical devices which do not support any SDN programmability feature.

The NFVO interfaces to the TNM through the T-Or-TN reference point (see Annex B, Table 28) supporting requests relating to the creation and management of virtual networks over different NFVI-PoPs: therefore, in order for the Orchestrator to request a virtual network connection between VNFs running in different DCs interaction with both virtual network resources (through the VIM) and physical networks among NFVI-PoPs (through the TNM) is required.

The TNM is invoked by the Orchestrator to setup the interconnection among Network Controllers (NCs) belonging to different NFVI-PoPs. In fact, within a VIM, potentially, multiple NCs are encompassed (e.g., if different virtual network partitioning techniques are used within the domain); in this case, the VIM is responsible for requesting virtual networks from each underlying NC and setting-up the interworking functionality between them. Thus, at the lowest level, network controllers have visibility to L2 network elements within the NFVI-PoP whereas, at a higher level, the VIM provides connectivity services to the Orchestrator in a suitable manner using the underlying resources.

The TNM is responsible for a number of key aspects related to connectivity services. These include the following:

- Management and control of existing PNFs;
- Monitoring of WAN resources and virtual links in order to provide the Orchestrator with useful statistics (such as jitter, RTT, delay, bandwidth, etc.) to make decisions about allocation of network resources;
- Management of virtual/physical links between NFVI-PoPs according to NFVO provisioning via configuration of:
 - SDN-enabled network elements, that enable network slicing techniques,

- Legacy network elements, relying on tunnelling protocols (e.g., VXLAN (44), NVGRE (45), STT (46)) in case of L3 PNFs or on native trunking/aggregation protocols in case of L2 PNFs (e.g. VLAN, Q-in-Q, etc.),
- Interfacing to the NFVO in order to accept provisioning requests and to submit monitoring information.

In the following sections the management and monitoring of network resources are discussed for both SDN-enabled and legacy network devices.

It is worth noting that the T-NOVA scope does not include elaboration on implementation of a full solution for legacy technologies. However, existing management solutions will be investigated in order to develop an understanding of how to support interfacing to the NFVO in order to achieve the provisioning of the required functions (i.e. configuration, tunnel establishment, QoS provision, failover support etc.).

4.7.1 Network Resources Management and Monitoring

The TNM plays a very important role within the IVM by providing the NFVO with an abstracted view of the network topology and resources, (i.e. link capacities, latency, etc.), for available WAN networks. It is common for large domains to be segmented into different administration domains in order to increase the efficiency of both management and monitoring. In this respect, T-NOVA expects that two types of transport network domains will be supported: (i) the *SDN Domain* which comprises SDN network elements (usually L2 devices) and (ii) the *Legacy Domain* which comprises L2/L3 network elements that do not support programmability, but support traffic engineering technologies (e.g. MPLS/IP).

4.7.1.1 SDN-enabled Network Elements

Today's WANs are becoming more complex and the introduction of SDN aligned approaches holds great potential for managing and monitoring network devices and the traffic which flows over them. The benefits are mainly related to automated network provisioning and to the flexibility in link deployment between different data centres.

From a T-NOVA perspective, the TNM has responsibility for controlling and monitoring the physical network devices which are SDN-enabled, with the purpose of providing WAN connectivity between different NFVI-PoPs while considering both SLAs required by VNFs and efficient management of cloud infrastructure resources.

In this context, the interaction with per-existent SDN will be needed to manage and monitor network resources to get required flexibility and customisation capabilities: TNM and VIM Network Control modules will need to be coordinated both by the Orchestrator in an appropriate manner, in order to setup VLANs among different virtual and physical SDN-enabled devices.

Although for the intra-DC networking the deployment of SDN technologies is becoming more common place, the adoption of SDN at the transport level and

especially at Layer 0 to 1, is still very much in its infancy (72), (73). When considering the transport layers we encompass technologies at layer 0 (DWDM, photonics) and layer 1 (Sonet/SDH and OTN). A key reason for the delay in SDN adoption in the transport network is the on-going transition from the analog to digital domain. The mechanisms for dealing with analog attributes in optical networks are vendor specific, and it is not possible for a generic controller to deal with the current myriad of vendor specific implementations. Nor is it possible for network operators to remove all of their transport equipment from their networks and replace it with a standardised optical hardware based around open standards. However, at higher layers (i.e. WAN) the adoption path is potentially more expeditious. Companies like Google and the Carrier Ethernet (MEF) and cloud business units of network operators have already adopted SDN solutions for their WANs (74).

For the purpose of the T-NOVA proof-of-concept demonstration the TNM development of SDN compatible devices, is out of scope as it is not part of the objectives of the project which are mostly focusing on the NFVI-PoP network management and control. However, at an architectural level it is thoroughly supported to ensure appropriate future proofing.

4.7.1.2 Legacy Network Elements

Managing and monitoring legacy network domains is a well understood and mature capability. A variety of standardised and proprietary frameworks have been proposed and implemented varying from commercial to open source solutions.

As outlined in subsection 2.2.4.2 the standard method for allowing network overlays over legacy network domain is the exploitation of L2 to L3 tunnelling mechanisms. Those mechanisms introduce the use of tunnelling protocols that allow the management aspects of each tunnel on an end-to-end basis. The most interesting tunnelling protocols, from a T-NOVA architecture perspective, (as discussed in subsection 2.2.4.2) are VxLAN, NVGRE and STT. In short these protocols allow the interconnection of NFVI-PoPs over L3 legacy network by encapsulating the NFVI network traffic (actually DC traffic) end-to-end. They require the setup of an endpoint for each connected DC, which is responsible for encapsulation and decapsulation of packets.

At a WAN level the architecture design of T-NOVA supports any type of legacy WAN technology (i.e. MPLS, Optical, Carrier Ethernet etc.) or SDN compatible, provided that the appropriate interfaces are developed. In this context, and for the sake of demonstrating the UC as discussed in D2.1, T-NOVA will exploit an IP/MPLS transport network and provide a simple implementation of TNM in order to support provisioning of vNETs in an end-to-end manner.

From a monitoring perspective, there are a number of frameworks ranging from passive to active and hybrid that allow the monitoring of legacy networks (75), (76). T-NOVA will employ such mechanisms in order to monitor adequately the status of the network and more importantly the status and resource usage of the established tunnels. Monitoring of the transport network resources will also be part of the considered TNM functionalities that will be implemented. Moreover, the monitoring

information will be conveyed to the NFVO as an input in the mapping and path computation mechanism. Historical monitoring data collection will also be collected to facilitate tracking of SLA breaches.

5 T-NOVA VNFs AND NSs PROCEDURES

This section illustrates the set of most common procedures associated with the deployment and management of VNFs (e.g. on-boarding, instantiation, monitoring, scaling, etc.) to illustrate the interactions between the T-NOVA Orchestrator and IVM architecture FEs that have been described in Sections 3 and 4. The flow diagrams presented in this section serve as a means to validate the architectures for the T-NOVA Orchestrator and IVM layers and their constituent architectural components. In addition, the flow diagrams also illustrate the interactions at the FE level and validate the purpose and capabilities of the interfaces that have been identified in subsections 3 and 4. As stated above, the sequence diagrams are intended to illustrate specifically the interaction of the entities of the Orchestration and the IVM layers, however some of the details of the internal actions of each module are not illustrated as these are implementation specific and depend on the technologies utilised.

While a conceptual exercise, the description and illustration of the key VNF deployment and management workflows provide a means to stress tests regarding the taken architectural decisions and capture necessary refinements prior to implementation related activities in WP3/4. Subsection 5.1 focuses on the VNF procedures, whereas subsection 5.2 is centred on the NS procedures.

5.1 VNF related procedures

To describe the VNF procedures, the following assumptions are made:

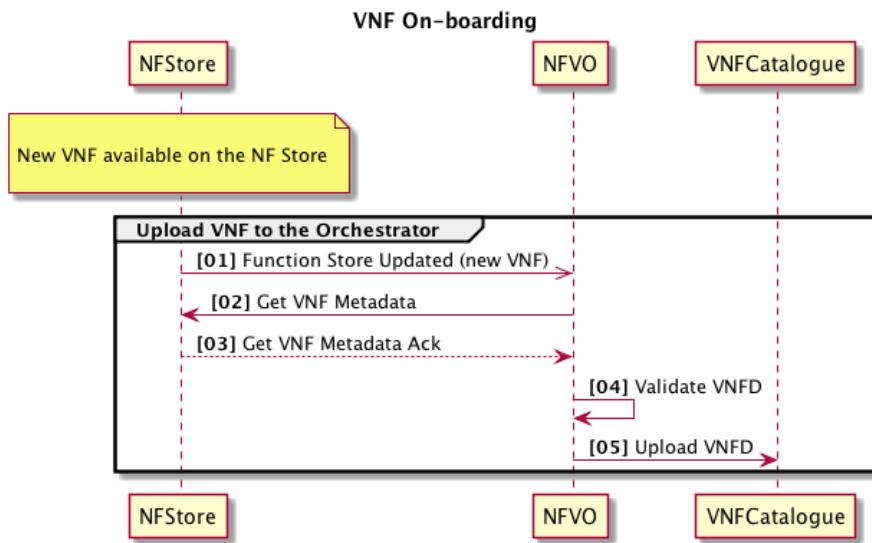
- The VNF is composed by one or more VNFC³s;
- Each VNFC has a dedicated VM;
- VNFCs are interconnected through Virtual Network Links;
- The VNF, as well as the constituent VNFCs, is instantiated within a single data centre, which implies that no scenarios involving the TNM are applicable.

The VNF details (e.g. deployment rules, scaling policies, and performance metrics) are described in the VNF Descriptor.

5.1.1 On-boarding

VNF on-boarding (Figure 27) refers to the process of making the T-NOVA Orchestrator aware that a new VNF is available on the NF Store.

³ A single VNF which is hosted by a single VM is called a Virtual Network Function Component (VNFC)

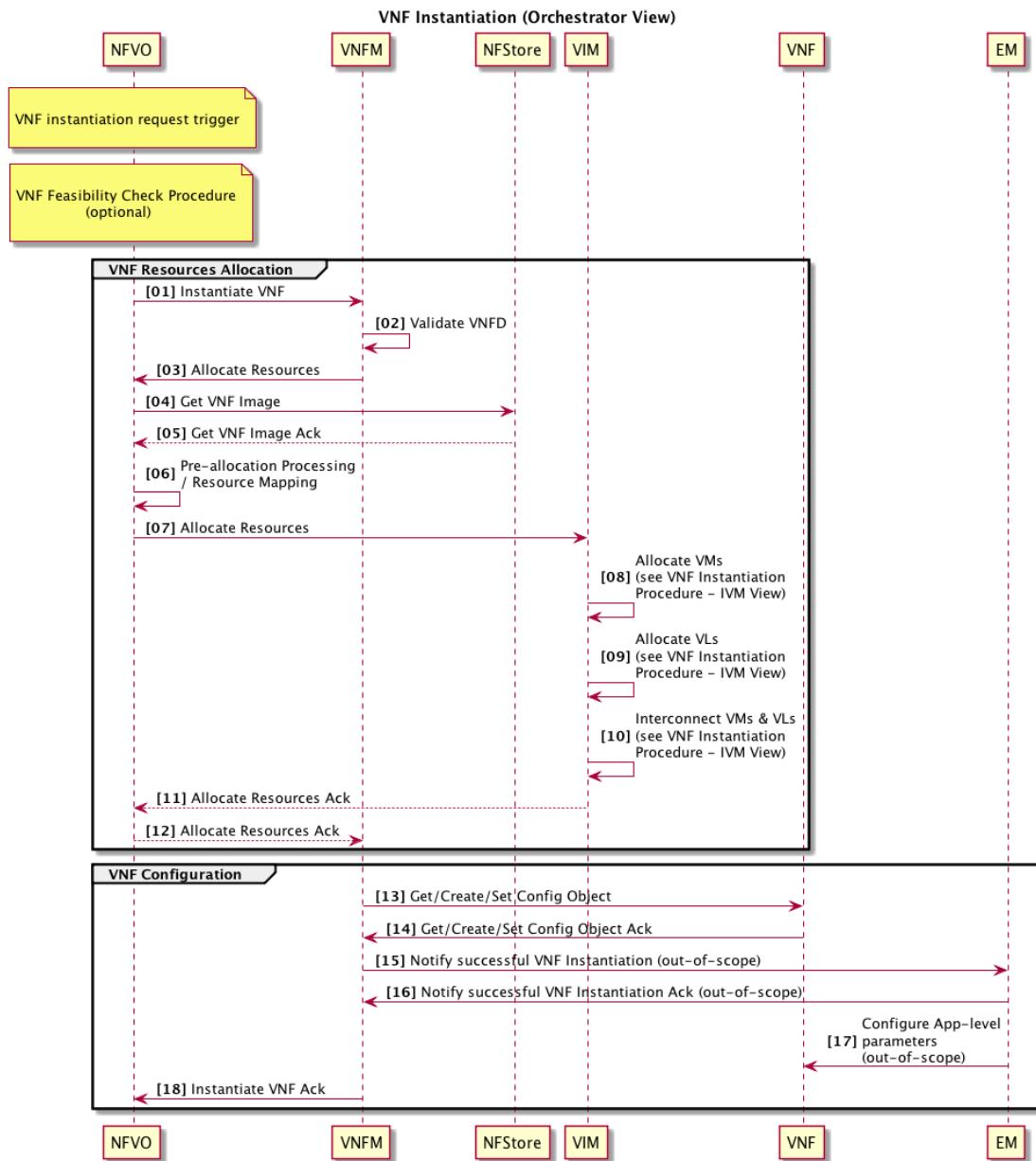
**Figure 27: VNF On-boarding Procedure**

Steps:

1. A new VNF is uploaded to the NF Store. As a result, the NF Store notifies the NFVO that a new VNF is available.
2. The NFVO requests the metadata (VNF Descriptor) of the new VNF from the NF Store.
3. The VNF Descriptor is provided to the NFVO.
4. The NFVO processes the VNFD to check if the mandatory elements are provided.
5. The NFVO uploads the VNFD to the VNFCatalogue.

5.1.2 Instantiation

VNF instantiation (Figure 28 and Figure 29) refers to the process of creating and provisioning a VNF instance. Figure 28 refers to the instantiation process from the perspective of the Orchestration Layer, whereas Figure 29 shows the instantiation process from the IVM layer point of view.

**Figure 28: VNF Instantiation Procedure (Orchestrator's View)****Steps VNF Instantiation – Orchestrator's View:**

1. NFVO calls the VNFM to instantiate the VNF, with the instantiation data.
 - Optionally, and before the instantiation request from the NFVO to the VNFM, a feasibility check could be made to ensure the required resources for the VNF are available (and reserved) at the virtual infrastructure (interacting with the VIM) layer.
2. The VNFM validates the request and processes it. This might include modifying/complementing the input instantiation data with VNFD data and VNF lifecycle specific constraints.
3. The VNFM then calls the NFVO for resource allocation.

4. The NFVO retrieves VNF image(s) from the NF Store.
5. NF Store delivers the VNF image(s) to the NFVO.
6. The NFVO executes any required pre-allocation processing work.
 - **VNF location selection:** The selection of where to locate a VNF instance could be based on the request, available resources, the nature of the VNF, the Network Service(s) in which the VNF instance is participating in as well as defined policies.
 - **Resource pool selection:** The resource pool to be used needs to be selected. Note that this is not the same as the VNF location. Multiple resource pools could exist in the same location or some VNFCs that are part of a VNF instance may need to be located remotely from the rest.
 - **Dependency checking:** Availability of all the required external dependencies from the required location need to be checked. If the VNF instance has any QoS requirements, it also needs to be verified if they can be met in the selected location. Note that the QoS requirements could be on compute or network resources, or on external services on which the VNF instance is dependent.
7. The NFVO requests the allocation of resources from the VIM (compute, storage and network) needed for the VNF instance (and delivers the VNF image(s)).
8. The VIM instantiates the required compute and storage resources from the infrastructure, for further details see VNF Instantiation Procedure – IVM View.
9. The VIM instantiates the internal connectivity network – a VNF may require dedicated virtual networks to interconnect its VNFCs (networks that are only used internally to the VNF instance), for further details see VNF Instantiation Procedure – IVM's View.
10. The VIM interconnects the instantiated internal connectivity network with the VNFCs, for further details see VNF Instantiation Procedure – IVM View.
11. Acknowledgement of completion of resource allocation back to NFVO.
12. The NFVO acknowledges the completion of the resource allocation back to VNFM, returning appropriate configuration information.
13. After the VNF is instantiated, the VNFM configures the VNF with any VNF specific lifecycle parameters (deployment parameters).
14. The VNF sends an acknowledgement to the VNFM that the configuration process is completed.
15. The VNFM notifies the EM (if present) of the new VNF, step outside the scope of T-NOVA.
16. The EM acknowledges the VNFM, step outside the scope of T-NOVA.

17. The EM configures the VNF with application-level parameters and acknowledges the VNFM, step outside the scope of T-NOVA.

18. The VNFM acknowledges the completion of the VNF instantiation back to the NFVO.

The diagram corresponding to steps 8-10 is indicated below.

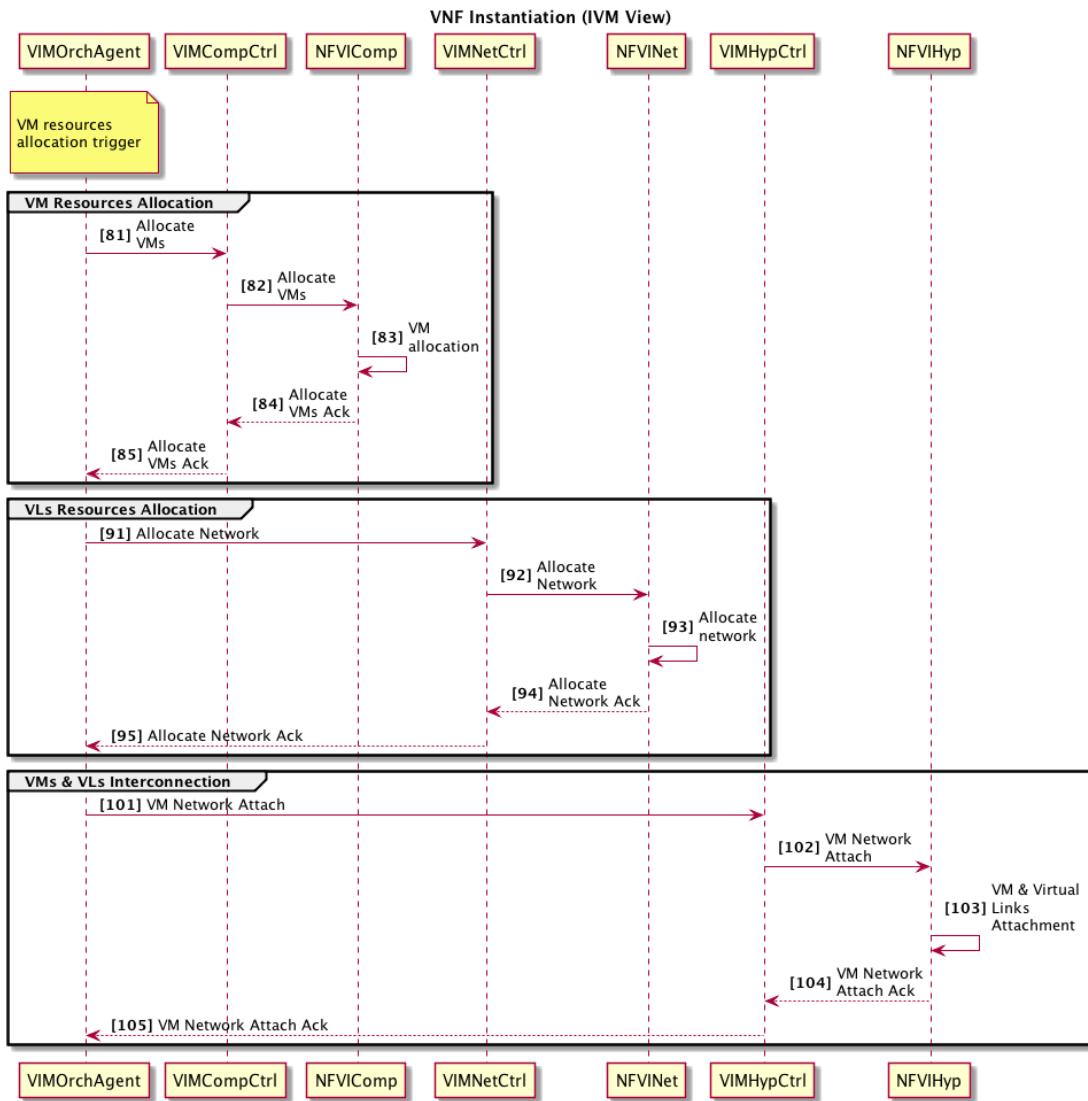


Figure 29: VNF Instantiation Procedure (IVM's View)



The specifics details of steps 8-10 are as follows:

- 8.1. The VIM Orchestrator Agent submits a request to the VIM Compute Control module to create new VMs, according to the VNF requirements.
- 8.2. The VIM Compute Control module:
 - Processes the request;
 - Analyses the required configuration;
 - Selects one or more suitable compute nodes to host the VMs;

- Sends request to allocate VMs to the selected nodes.
- 8.3. The selected NFVI Compute node(s) allocates the VMs.
- 8.4. The NFVI Compute nodes send back an acknowledgment to the VIM Compute Control module when they successfully boot.
- 8.5. The VIM Compute Control module sends back an acknowledgment to the VIM Orchestrator Agent.
- 9.1. The VIM Orchestrator Agent submits a request to the VIM Network Control module for the allocation of Network Resources.
- 9.2. The VIM Network Control module:
 - Processes the request;
 - Analyses the required configuration;
 - Sends a request for allocation of virtual network resources on the NFVI Network.
- 9.3. The NFVI Network:
 - Allocates the resources;
 - Sets up the virtual networks, by configuring the required interconnectivity between virtual switches.
- 9.4. The NFVI Network sends back an acknowledgment to the VIM Network Control module.
- 9.5. The VIM Network Control module sends back an acknowledgment to the VIM Orchestrator Agent.
- 10.1. The VIM Orchestrator Agent submits a request to the VIM Hypervisor Control module to attach the new VMs to the required virtual networks.
- 10.2. The VIM Hypervisor Control module sends the request to the hypervisors controlling the new VM hosting nodes.
- 10.3. The hypervisors of those nodes:
 - Configure the vSwitches in order to manage the VLANs connectivity necessary to support the VNF requirements;
 - Setup the interconnections among VMs and vSwitches.
- 10.4. The hypervisors send back acknowledgments to the VIM Hypervisor Control module.
- 10.5. The VIM Hypervisor Control module sends back an acknowledgment to the VIM Orchestrator Agent.

5.1.3 Supervision

VNF supervision from the Orchestrator's layer point of view (Figure 30) refers to the process of monitoring of the VNF, including the infrastructure specific parameters

collected and reported by the IVM, as well as the VNF application/service-specific parameters.

VNF supervision from the IVM's layer point of view (Figure 31) refers to the process of monitoring of the VIM, including the VM performance metrics, the VL performance metrics, and the physical machines performance metrics.

As far as the supervision procedure from the Orchestrator's layer point of view is concerned, the sequence is as follows:

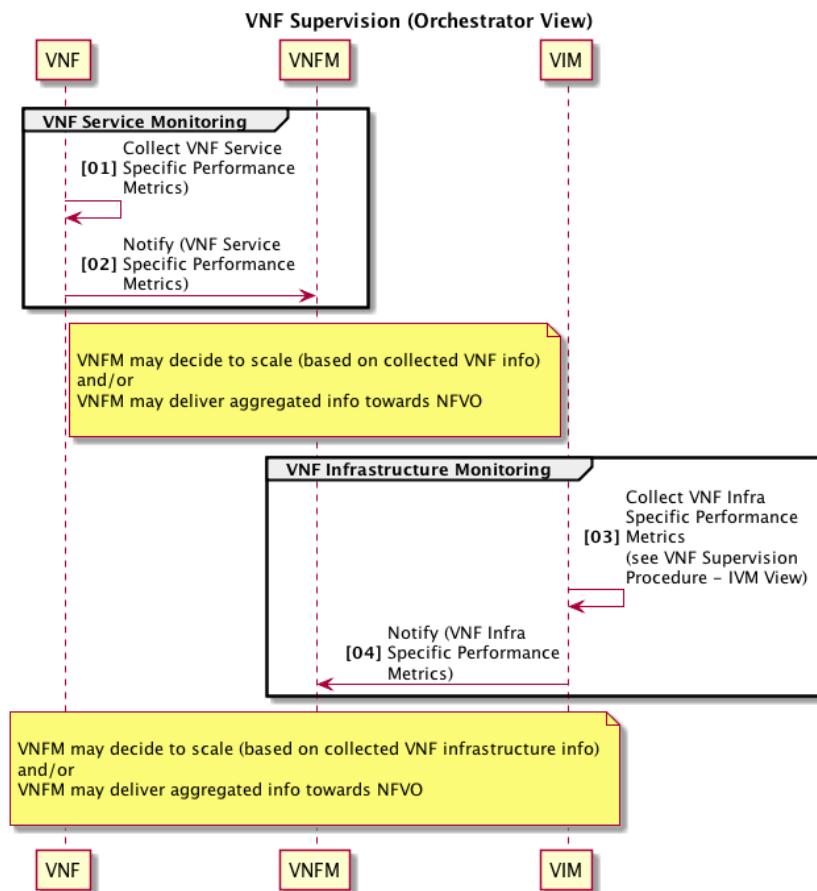


Figure 30: VNF Supervision Procedure (Orchestrator's View)



Steps (VNF Supervision – Orchestrator's View):

1. VNF collects performance metrics related with the VNF application/service.
2. VNF notifies the VNFM with the **VNF application specific metrics**:
 - As a result, the VNFM **may** decide to scale the VNF and/or provide aggregated monitoring information towards the NFVO.
3. VIM collects performance metrics related with the infrastructure allocated for the VNF, for further details see VNF Supervision Procedure – IVM View.
4. VIM notifies the VNFM with the **VNF infrastructure related performance metrics**.

As a result, the VNFM **may** decide to scale the VNF and/or provide aggregated monitoring information towards the NFVO. As far as the supervision procedure from the IVM's layer point of view is concerned, the sequence is as follows:

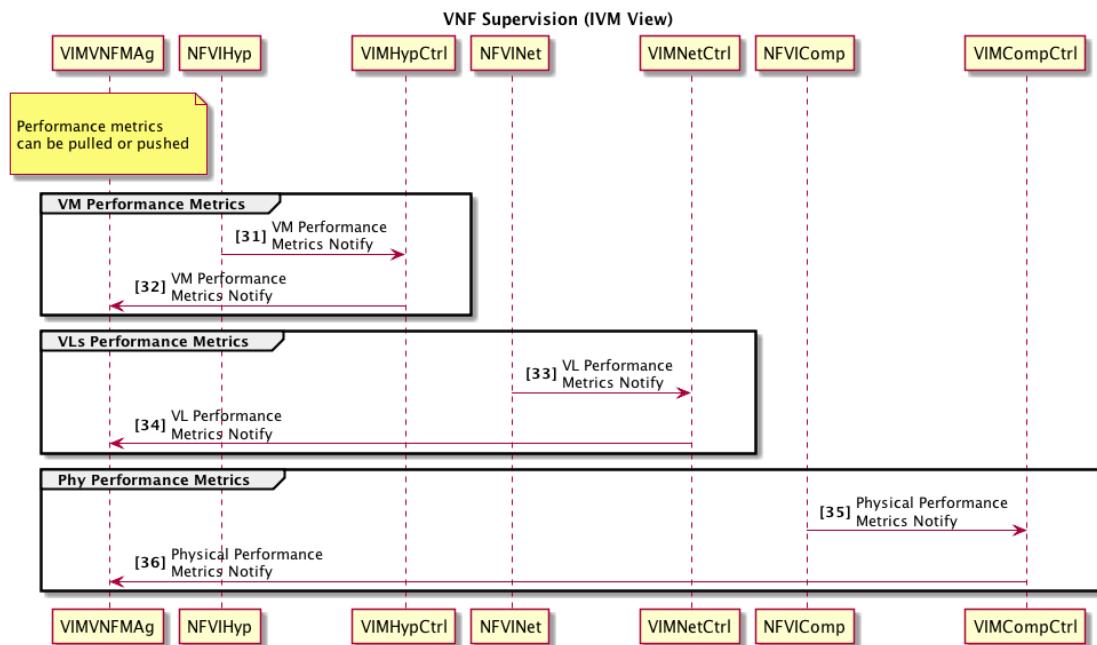


Figure 31: VNF Supervision Procedure (IVM's View)



Steps (VNF Supervision – IVM's View):

5.1. The NFVI Hypervisors:

- Collect VM performance metrics data;
- Send the data to the VIM Hypervisor Control module.

5.2. The VIM Hypervisor Control module sends the data to the VIM VNF Manager Agent.

5.3. The NFVI Network devices:

- Collect performance metrics data from virtual network links (VLs);
- Send the data to the VIM Network Control module.

5.4. The VIM Network Control module sends the collected data to the VIM VNF Manager Agent.

5.5. The NFVI Compute nodes:

- Collect the physical performance metrics data;
- Send the data to the VIM Compute Control module.

5.6. The VIM Compute Control module sends the data to the VIM VNF Manager Agent.

5.1.4 Scale-out

VNF scale-out refers to the process of creating a new VM to increase the VNF capacity with additional compute, storage, memory and network resources.

The scaling policies that indicate which/how/when VMs/VNFCs should be scaled are identified in the "VNF Deployment Flavour" attribute, which makes part of the VNF Descriptor (VNFD).

Figure 32 illustrates this case for a scaling-out: VNFC A is instantiated and a new VL is created to connect this new instance to the existing VNFC B instance. VNF scaling is further detailed on another deliverable of this project, D2.41 (62).

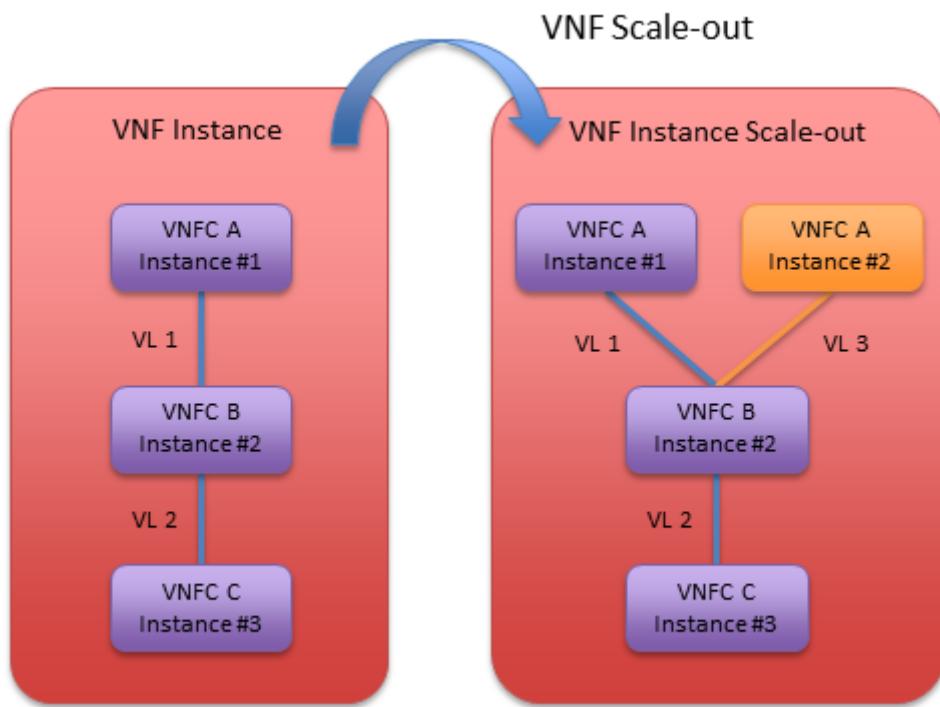


Figure 32: Scaling out a VNF

Figure 33 illustrates the VNF scale-out process where **it is the VNFM that decides to scale the VNF**, after receiving VNF application/service specific metrics from the VNF and VNF infrastructure related metrics from the VIM:

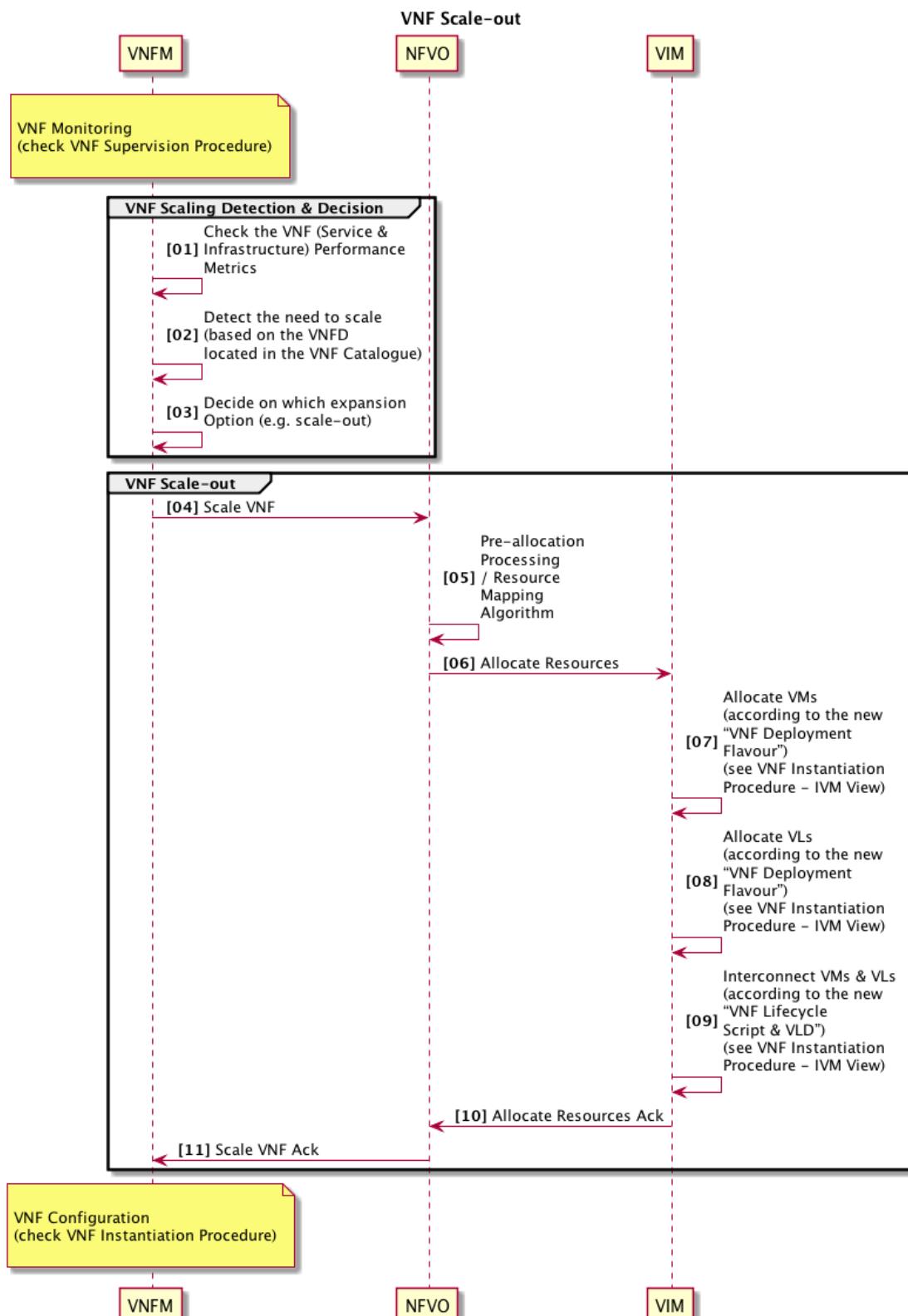


Figure 33: VNF Scale-out Procedure



Steps:

1. The VNFM collects performance metrics related with the VNF application/service (from the VNF) and with the infrastructure resources (from the VIM), for further information about the performance metrics collection, check the "VNF Supervision Procedure".
2. Based on the retrieved performance metrics and on the auto-scaling policies (included in the VNFD), the VNFM detects the need to scale.
3. The VNFM decides that the best option is to scale-out the VNF.
4. The VNFM requests the NFVO to scale-out the VNF by indicating the required resources for the new VM – matching a specific "VNF deployment flavour" from the VNFD stored in the VNF Catalogue.
 - NFVO may perform a VNF feasibility check where a resource reservation is made in the VIM (further information on the VNF Instantiation Procedure-Orchestrator's View).
5. The NFVO executes any required pre-allocation processing work, e.g. VNF location selection, Resource pool selection, Dependency checking, for further details see VNF Instantiation Procedure – Orchestrator's View.
6. The NFVO requests allocation of resources from the VIM (compute, storage and network) needed for the VNF instance (and delivers the VM image(s)).
7. The VIM instantiates the required compute and storage resources from the infrastructure (according to the new "VNF Deployment Flavour" attribute), for further details see VNF Instantiation Procedure – IVM's View.
8. The VIM instantiates the internal connectivity network – a VNF may require dedicated virtual networks links (VLs) to interconnect its VNFCs (networks that are only used as internal to the VNF instance), for further details see VNF Instantiation Procedure – IVM's View.
9. Thereafter the VIM interconnects the instantiated internal connectivity network with the VNFCs (according to the "VNF Lifecycle Script & VLD" attribute), for further details see VNF Instantiation Procedure – IVM's View.
10. Acknowledgement of completion of resource allocation is sent back to NFVO.
11. NFVO acknowledges the completion of the scale-out/resource allocation back to VNFM, returning appropriate configuration information.
 - Thereafter the VNFM proceeds with the VNF configuration procedures, as described in the "VNF Instantiation Procedure - Orchestrator's View".

5.1.5 Termination

VNF termination Figure 34 and Figure 35 refer to the process of releasing a VNF instance, including the network and VM resources allocated to it. Figure 34 refers to the termination process from the perspective of the Orchestrator's layer, whereas Figure 35 shows the termination process from the IVM internal point of view.

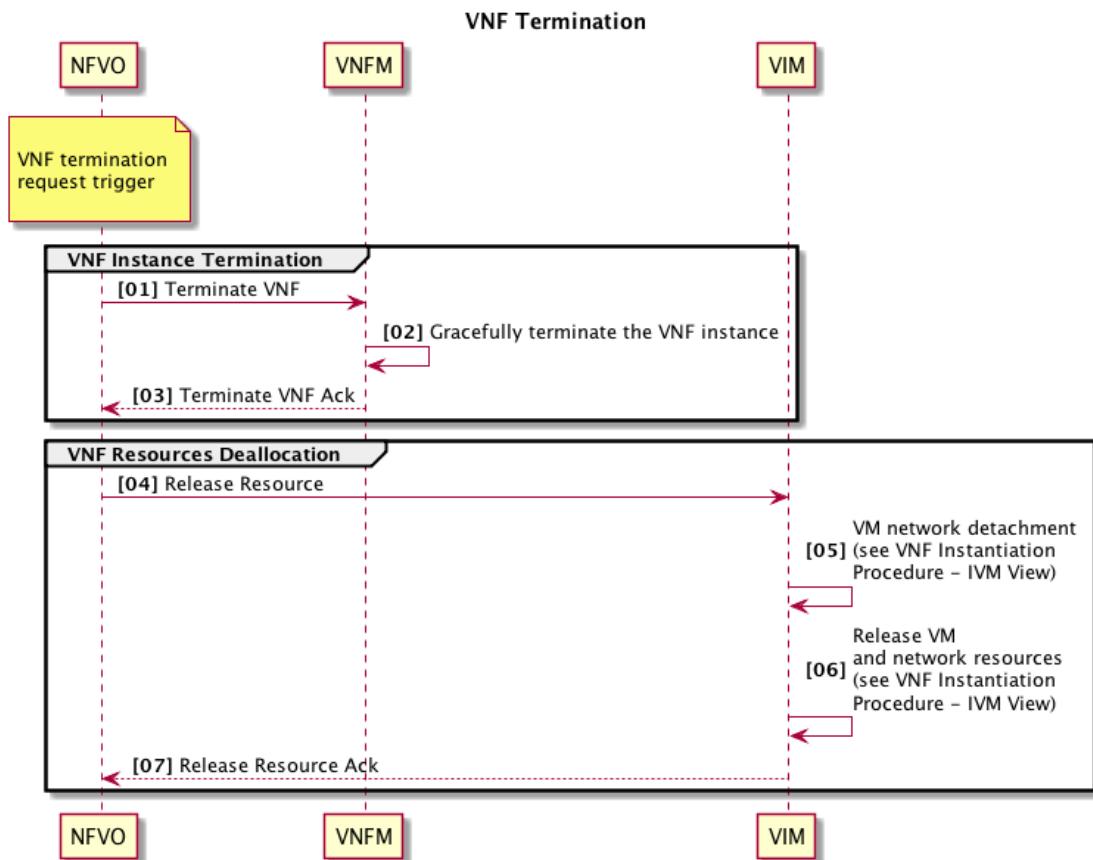


Figure 34: VNF Termination Procedure – Orchestrator’s View



Steps (VNF Termination Orchestrator’s View):

1. The NFVO calls the VNFM to terminate the VNF service. The VNF termination procedure can be triggered, for example, by the following actions:
 - Termination of the NS in which the VNF is instantiated;
 - Scale-in of the NS, requesting a specific VNF instance to be terminated;
 - Explicit request from the SP or the FP to remove the VNF.
2. The VNFM gracefully shuts down the VNF, i.e. without interrupting the NS that is being delivered, if necessary in coordination with other management entities. The VNF image(s) will be maintained on the NF Store (in order to be instantiated again in the future). The VNF catalogue is not affected by the VNF termination.
3. The VNFM acknowledges the completion of the VNF termination back to the NFVO.
4. The NFVO requests deletion of the VNF resources by the VIM.
5. Virtual network links (VLs) interconnecting the VMs are released, for further details see VNF Instantiation Procedure – IVM’s View.

6. VMs resources (compute, storage and memory) used by the VNF are released, for further details see VNF Instantiation Procedure – IVM's View.
7. An acknowledgement is sent indicating the success or failure of resource release back to NFVO.
 - The NFVO updates the infrastructure resources repository.

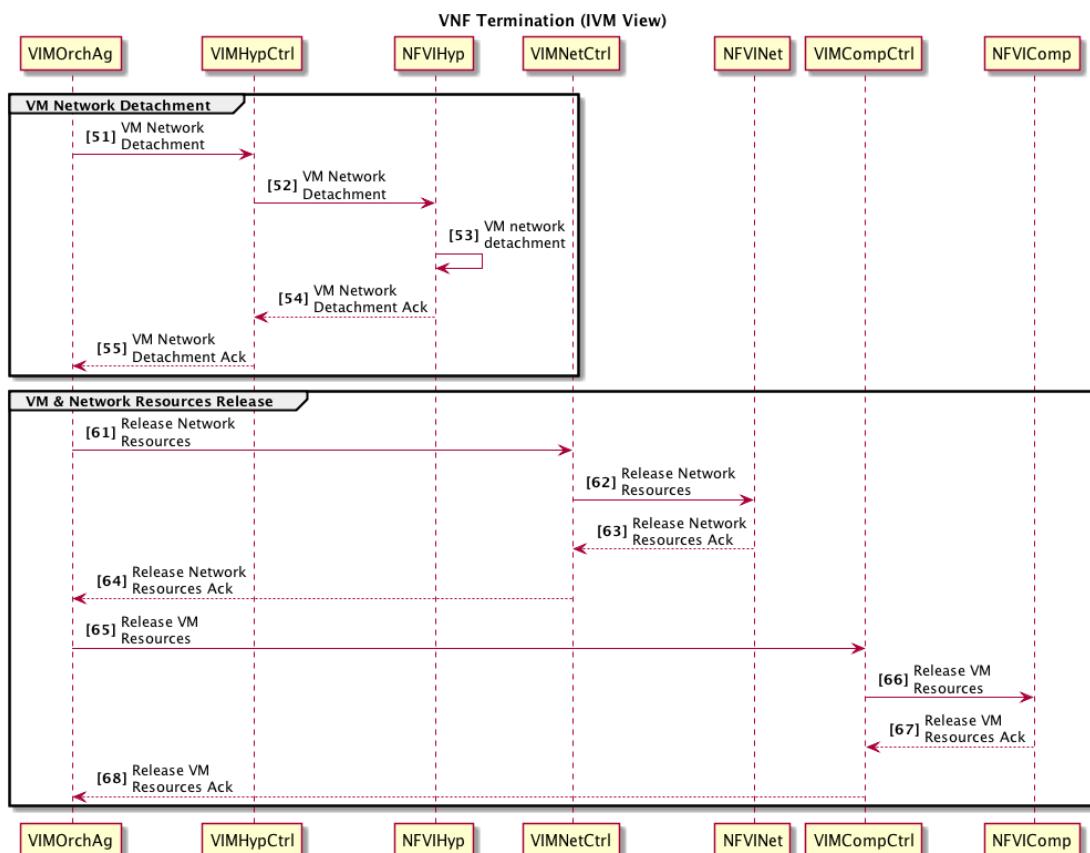


Figure 35: VNF Termination Procedure – IVM's View



Steps (VNF Termination – IVM's View):

- 5.1.The VIM Orchestrator Agent submits a request to the VIM Hypervisor Controller for detaching VM(s) from the virtual network;
- 5.2.The VIM Hypervisor Control module forwards the request to the NFVI Hypervisors involved;
- 5.3.The NFVI Hypervisors detach VM(s) from the network;
- 5.4.The NFVI Hypervisors send back an Acknowledgement to the VIM Hypervisor Control;
- 5.5.The VIM Hypervisor Control sends back an Acknowledgement to the VIM Orchestrator Agent;
- 6.1.The VIM Orchestrator Agent submits a request to the VIM Network Controller for releasing virtual network resources;
- 6.2.The VIM Network Control module forwards the request to the NFVI Network domain;

- 6.3. The NFVI Network Infrastructure **releases the network resources** and sends back an Ack;
- 6.4. The VIM Network Control sends back an Ack to the VIM Orchestrator Agent;
- 6.5. The VIM Orchestrator Agent submits a request to the VIM Compute Controller for releasing virtual compute resources;
- 6.6. The VIM Compute Control module forwards the request to the involved NFVI Compute nodes;
- 6.7. The NFVI Compute nodes **releases the compute resources** and sends back an Ack;
- 6.8. The VIM Compute Control sends back an Ack to the VIM Orchestrator Agent.

5.2 NS related procedures

To describe the NS procedures, the following assumptions are made:

- The NS is composed by one or more VNFs (in the following procedures, two VNFs – VNF1 and VNF2 – compose the NS);
- VNFs composing the NS are interconnected through Virtual Network Links (if VNFs run on the same DC) or through Non-virtual/legacy Network Links (if VNFs run on different DCs) (in the following procedures, VNF1 runs on DC1 and VNF2 runs on DC2);
- The NS constituent VNFs can be implemented in a single DC or spread across several DCs;
- Besides VNFs, PNFs can also be part of the NS (in the following procedures, PNF1 is interconnected with VNF1).

The NS details (e.g. deployment rules, scaling policies, performance metrics, etc) are described in the NSD, e.g. VNF Forwarding Graph for detailing the VNFs interconnections.

5.2.1 On-boarding

NS on-boarding (Figure 36) refers to the process of submitting a NSD to the NFV Orchestrator in order to be included in the catalogue.

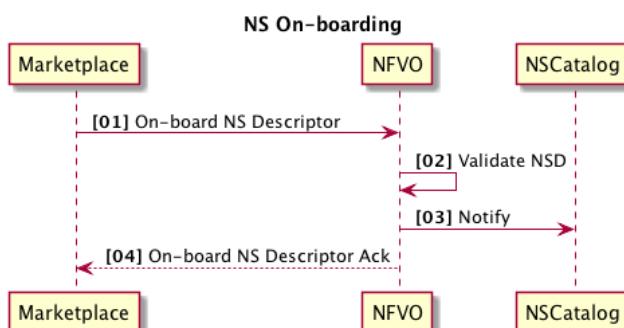


Figure 36: NS On-boarding Procedure



Steps:

1. The Marketplace submits the NSD to the NFVO for on-boarding the NS.
2. NFVO processes the NSD to check if the mandatory elements are provided.
3. NFVO notifies the catalogue for insertion of the NSD.
4. NFVO acknowledges the NS on-boarding.

5.2.2 Instantiation

NS instantiation refers to the instantiation of a new NS, i.e. Figure 37 from the Orchestrator's view, and Figure 38 from the IVM's view.

As stated above, the next sequence diagram depicts a situation where VNFs composing the NS run on different DCs and are interconnected through Non-virtual/legacy Network Links.

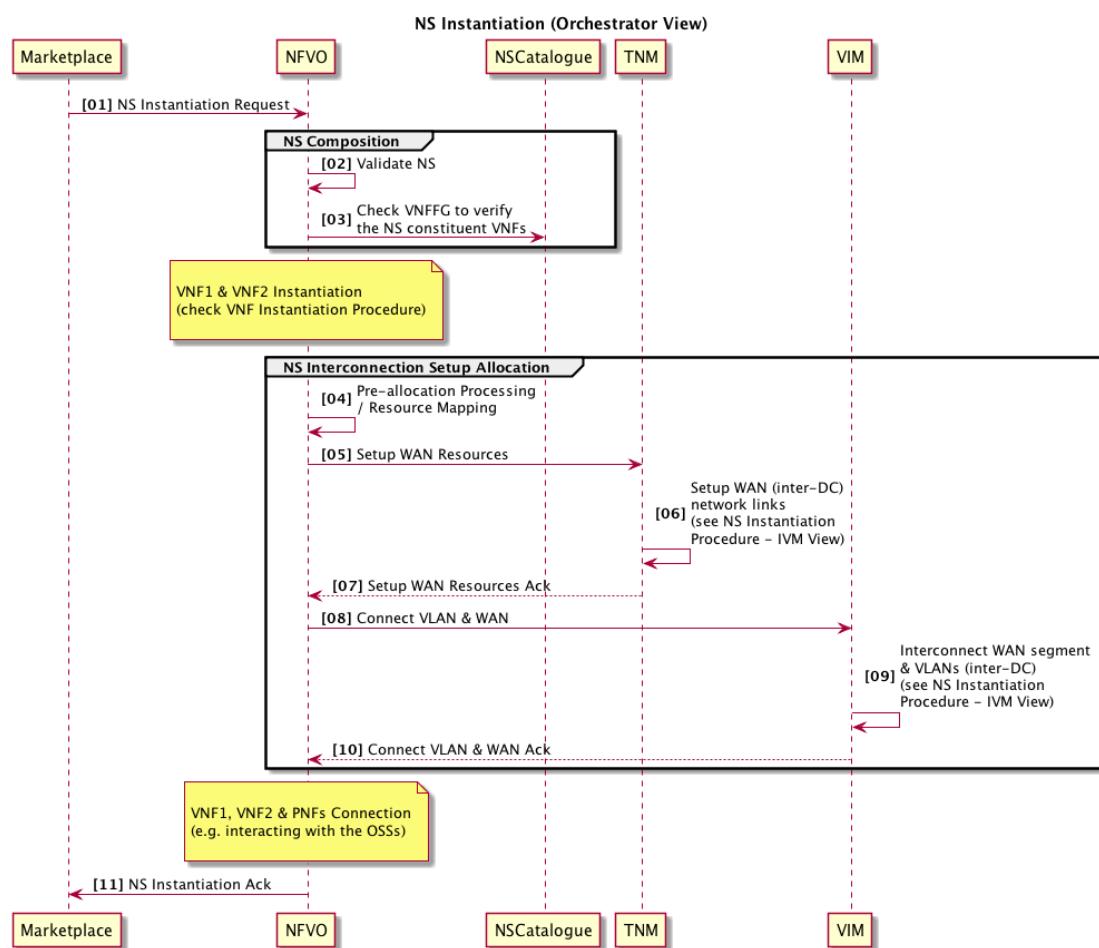


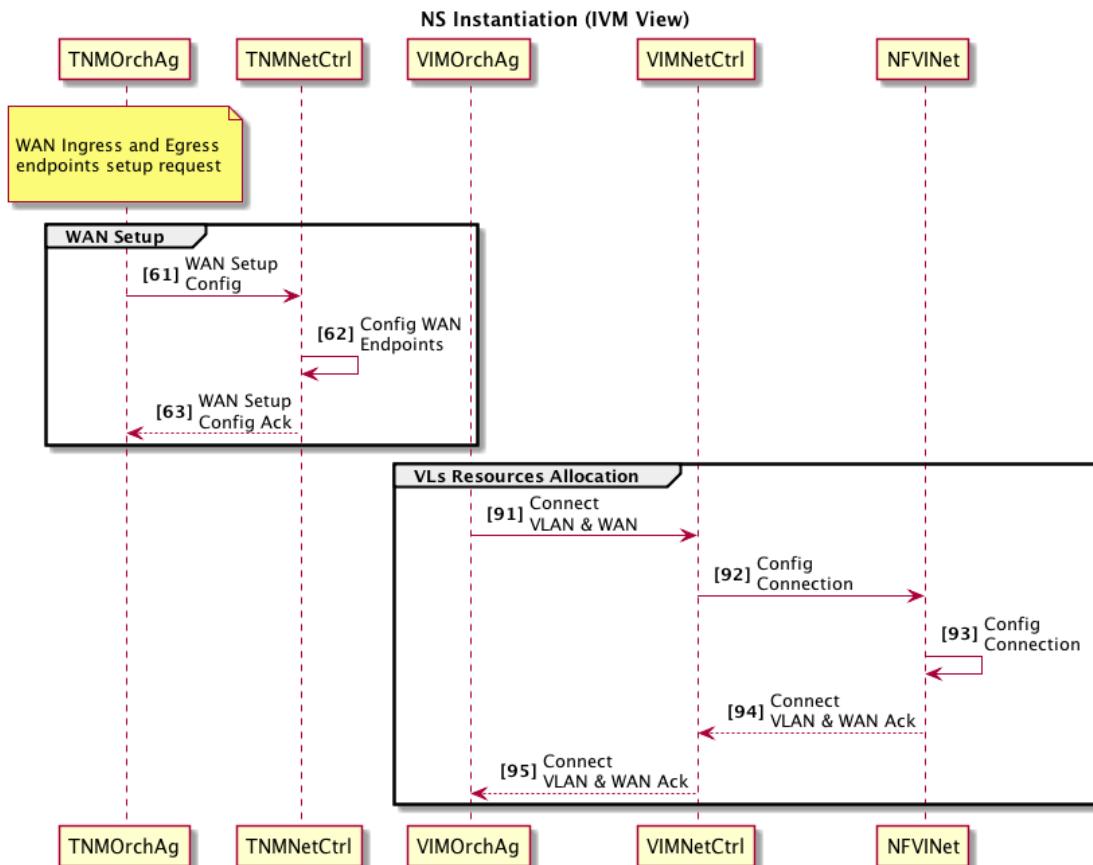
Figure 37: NS Instantiation Procedure (Orchestrator's View)



Steps (Orchestrator View):

1. The NFVO receives a request to instantiate a new NS.
2. The NFVO validates the request, both validity of request (including validating that the sender is authorised to issue this request) and confirming the parameters passed are technically correct.

3. The Orchestrator checks the NS composition (e.g. VNFFG) in the NS catalogue:
 - Thereafter, a feasibility check procedure may optionally be carried out for each VNF that is part of the NS, in this case VNF1 and VNF2. For further details about the "VNF Feasibility Check", please see the "VNF Instantiation Procedure";
 - The NFVO triggers the instantiation of the VNFs (VNF1 and VNF2). For further details about the "VNF Instantiation", please check the "VNF Instantiation Procedure".
4. The NFVO executes any required pre-allocation processing work, e.g. VNF location selection, Resource pool selection, Dependency checking. For further details see VNF Instantiation Procedure – Orchestrator's View.
5. The NFVO requests the TNM to setup the WAN resources required for interconnecting the VNFs across the DCs (resource phase establishment).
6. The TNM configures the WAN resources between DC1 and DC2.
7. The TNM sends an acknowledgment to the NFVO reporting that the WAN has been configured as requested.
8. The NFVO sends a request to the VIM to interconnect the WAN ingress and egress routers to the DC VLANs (connectivity phase establishment).
9. The VIM interconnects the configured WAN resources with VNF1 and VNF2 in DC1 and DC2, respectively.
10. The VIM acknowledges completion of the WAN / VLANs configuration:
 - If necessary, NFVO requests Network Manager to connect VNF external interfaces to PNFs interfaces:
 1. The Network Manager can be an OSS, an NMS or an EM;
 2. Connection to PNFs is assumed to be done by the NFVO.
11. The NFVO acknowledges completion of the NS instantiation.

**Figure 38: NS Instantiation Procedure (IVM' View)****Steps (IVM View):**

- 6.1. The TNM Orchestrator Agent sends the request to the TNM Network Control to configure the WAN end points.
- 6.2. The TNM Network Control configures the endpoints.
- 6.3. The TNM Network Control sends an acknowledgement indicating success or failure of the configuration setup to the TNM Orchestrator Agent.
- 9.1. When the acknowledgement of a successful WAN configuration is received the NFVO sends a request to the VIM Orchestrator Agent to connect a VLAN to WAN endpoints. The VIM Orchestrator Agent sends the request to connect a VLAN to WAN endpoints to the VIM Network Controller.
- 9.2. The VIM Network Controller sends the request to connect a VLAN to WAN endpoints to the NFVI Network.
- 9.3. The NFVI Network connects the VLAN to the WAN endpoints.
- 9.4. The NFVI endpoint sends an acknowledgement of a successful or failed connection configuration to the VIM Network Controller.
- 9.5. The VIM Network Controller sends an acknowledgement of a successful or failed connection to the VIM Orchestration Agent.

5.2.3 Supervision

NS supervision (Figure 39) refers to the monitoring of the NS performance metrics, including:

- VNF infrastructure and service specific information;
- Network links interconnecting the VNF (across multiple DCs).

Again, as stated above, the next sequence diagram depicts a situation where VNFs composing the NS run on different DCs and are interconnected through Non-virtual/legacy Network Links.

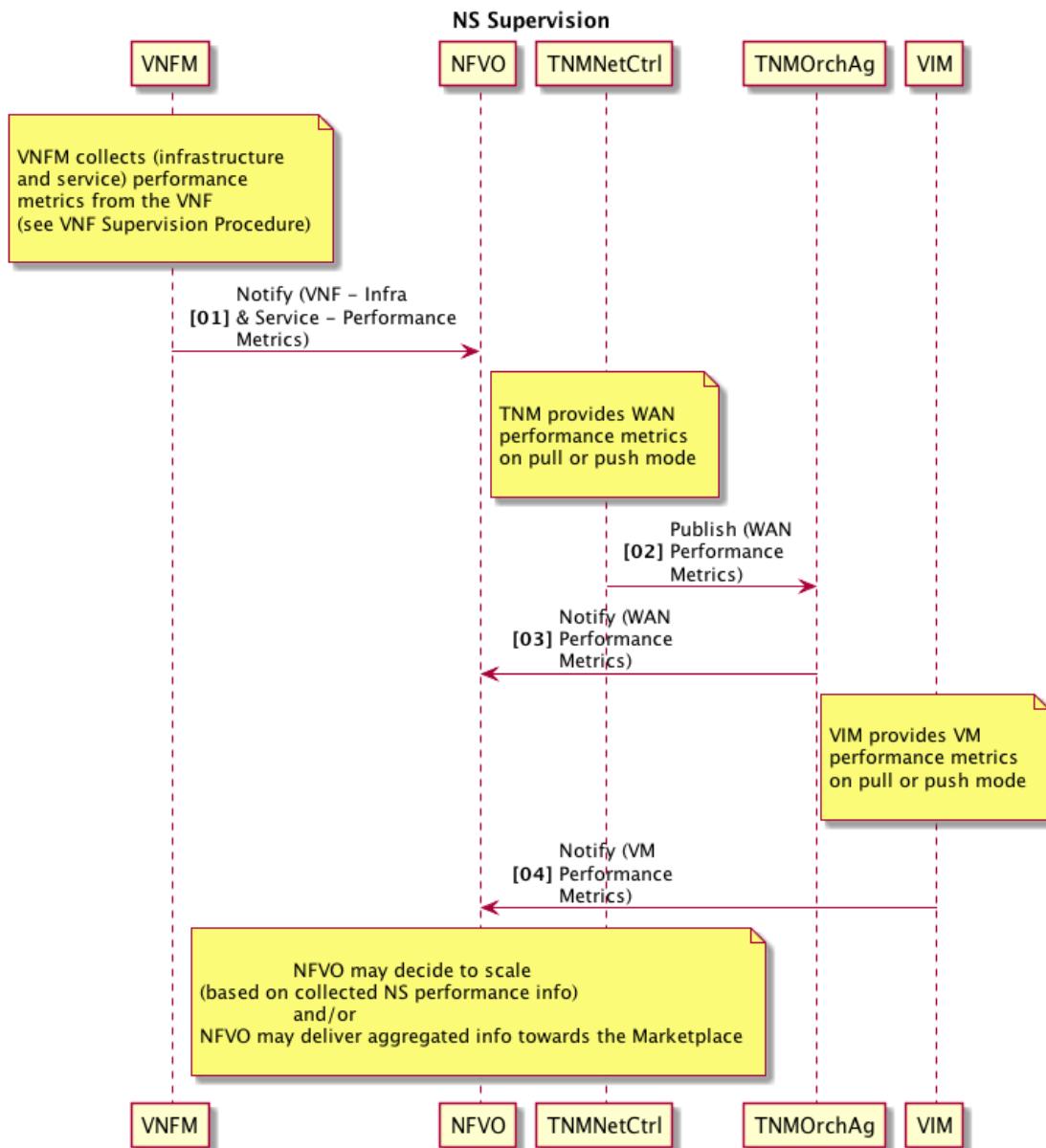


Figure 39: NS Supervision Procedure



Steps:

1. The VNFM sends performance metrics related to a VNF to the NFVO. This includes **both** metrics from the **infrastructure** supporting the VNF (VMs, Virtual Links) – obtained directly from the VIM - **as well as application/service**-specific metrics from the VNF - obtained directly from the VNF or from the EM). For further details about the VNF performance metrics retrieval, please check the "VNF Supervision Procedure", where the option to forward aggregated information to NFVO has been taken by the VNFM.
2. The TNMNetCtrl fetches and delivers the WAN segment metrics to the TNMOrchAg.
3. The TNMOrchAg provides the **WAN segment performance metrics** to the NFVO.
4. The VIM delivers **VM-related metrics** to the NFVO:
 - Based on the metrics received (VNFM, VIM and TNM) and on the defined scaling policies included in the NSD, the NFVO may decide to trigger a scaling procedure. Furthermore, if configured, the NFVO will also deliver aggregated NS-related performance metrics to the Marketplace.

5.2.4 Scale-out

NS scale-out refers to the process of increasing the capacity of the service in order to accomplish a SLA that is changing to a new NS deployment flavour, or to maintain an existing SLA.

The scale-out policies are triggered based on the following information:

- NS issues (retrieved from VNFM);
- VNF issues (retrieved from VNFM);
- WAN segment, i.e. connecting VNFs issues, retrieved from TNM.

Figure 40 illustrates NS scaling case, where a second instance of VNF B is created and the existing VNF A instance is reconfigured so that it becomes able to communicate with the two VNF B instances.

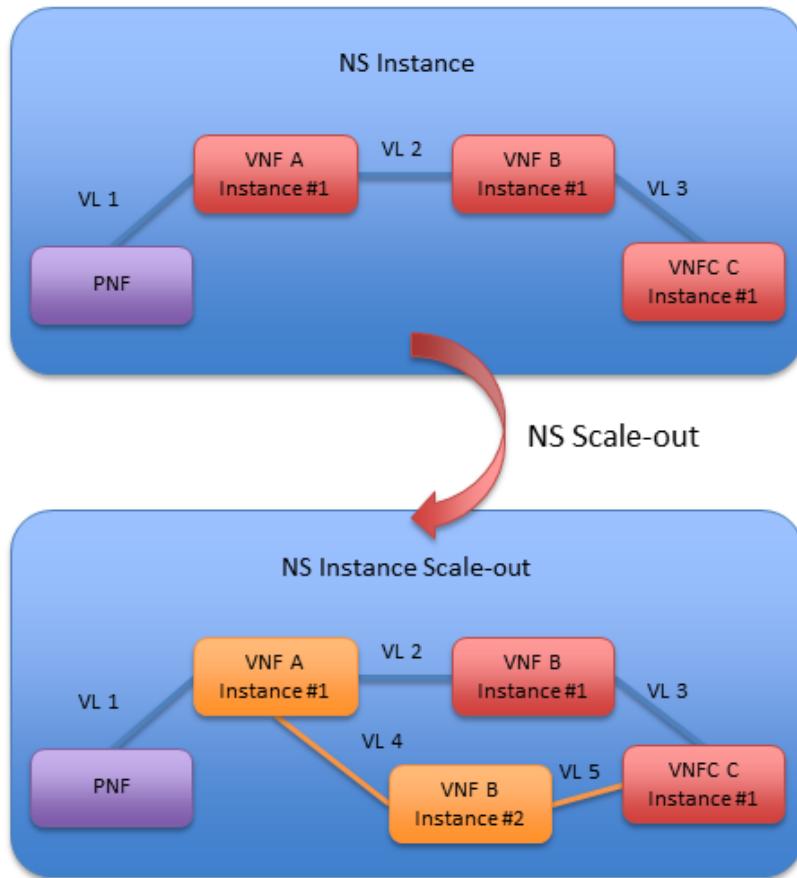
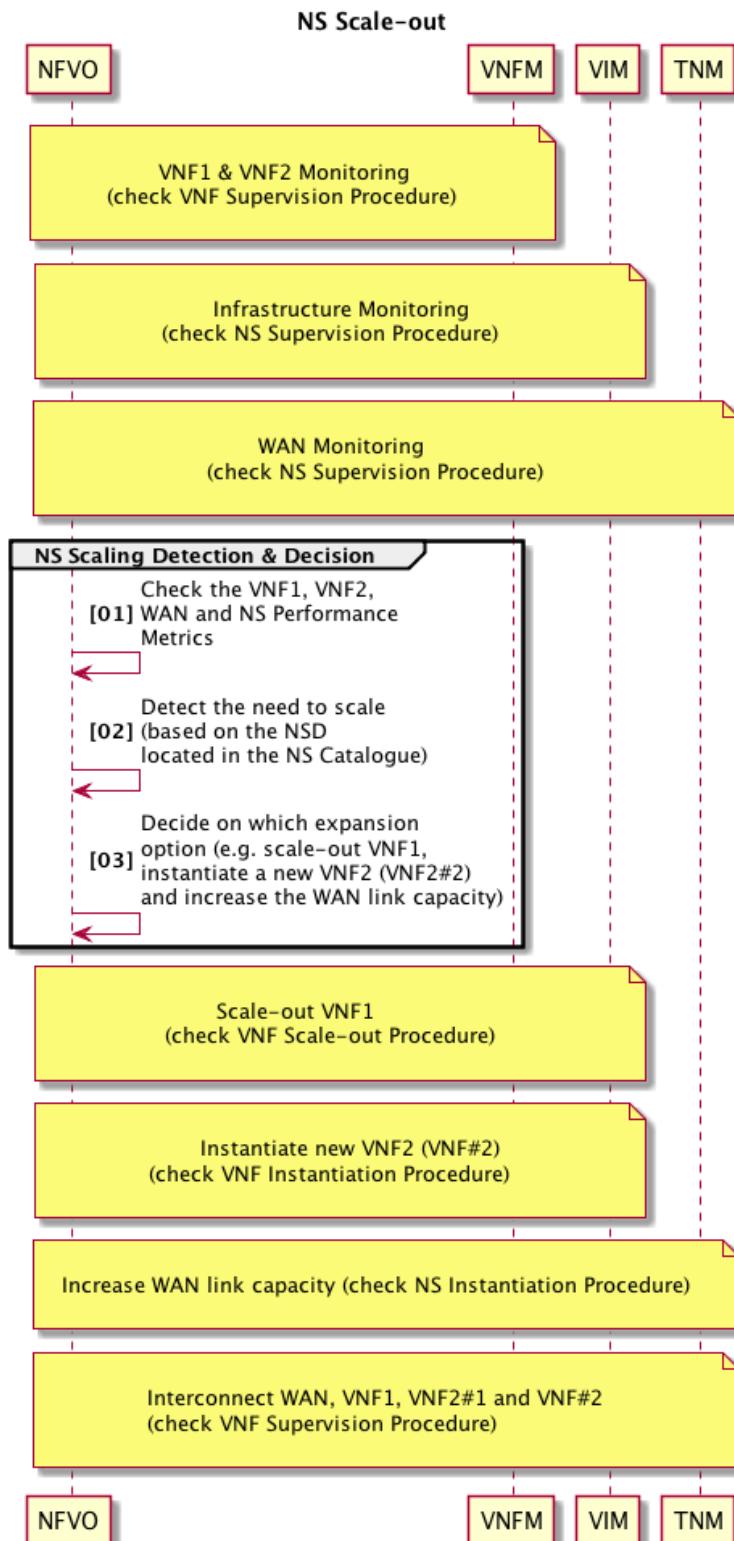
**Figure 40: Scaling-out a NS**

Figure 41 refers to a situation where, according to the metrics received, the required performance of the SLA cannot be achieved. As such the NFVO decides to scale-out to a new deployment flavour, taking also into account the auto-scaling policies included in the NSD. This implies:

- Scale-out a specific VNF to a new deployment flavour (included in this workflow);
- Creation of a new VNF instance (included in this workflow);
- Changing the VNF location to another DC (not included in this workflow);
- Increasing the WAN segment network link capacity (included in this workflow).

**Figure 41: NS Scale-out**

Steps:

1. The NFVO collects and checks monitoring information from the VNF, VIM and the WAN.

2. Based on the retrieved performance metrics and on the auto-scaling policies defined on the NSD, the NFVO detects the need to scale-out the NS.
3. The NFVO decides to change to another NS deployment flavour, which comprises the VNF1 scale-out, a new instantiation of VNF2#2 and an increase on the WAN link capacity:
 - The other procedures (VNF scale-out, VNF instantiation and WAN interconnection) have already been described in the previous workflows.

5.2.5 Termination

NS termination (Figure 42) refers to the process of releasing the NS instance, including the constituent VNFs (VNF1, VNF2#1 - instance 1 of VNF2 and VNF2#2 – instance 2 of VNF2), as well as the WAN segment.

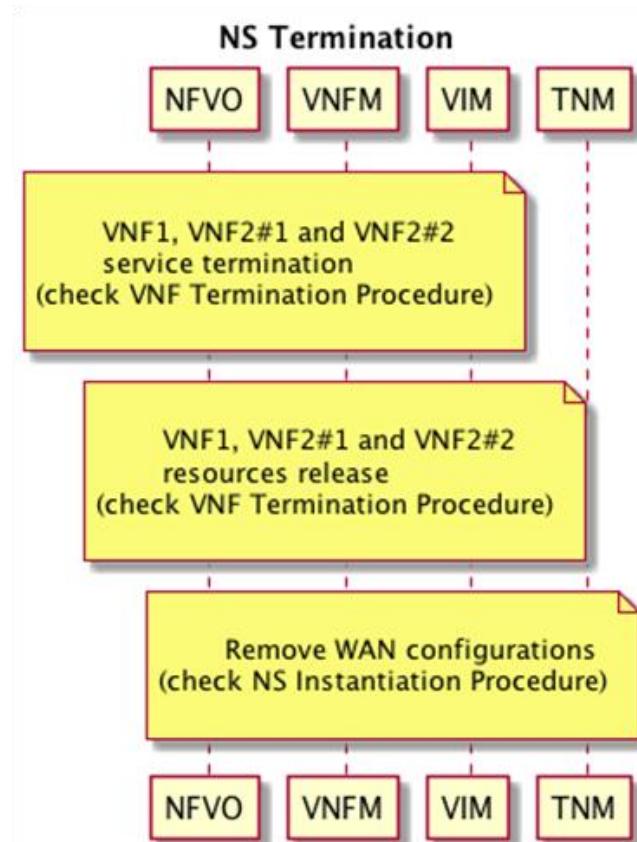


Figure 42: NS Termination Procedure

5.3 NS, VNF and Infrastructure Monitoring

Proper NS/VNF as well as infrastructure monitoring is crucial for the implementation of many of the use cases foreseen for the T-NOVA system, see D2.1 (63). Especially UC2 (Provision NFV services), UC3 (Reconfigure/Rescale NFV services) and UC5 (Bill NFV services) use the monitoring metrics, which are collected during UC4

(Monitoring). Specifically, the latter presents an overview of the T-NOVA monitoring procedures, focusing on both:

1. *VNF and Service Monitoring* - related to the status and resources of the provisioned services, as well as,
2. *Infrastructure Monitoring* - related to the status and resources of the physical infrastructure.

Monitoring metrics are mostly collected at the various domains of the Infrastructure layer and communicated to the upper layers. Figure 43 depicts a high-level view of the flow of the monitoring information across the T-NOVA system.

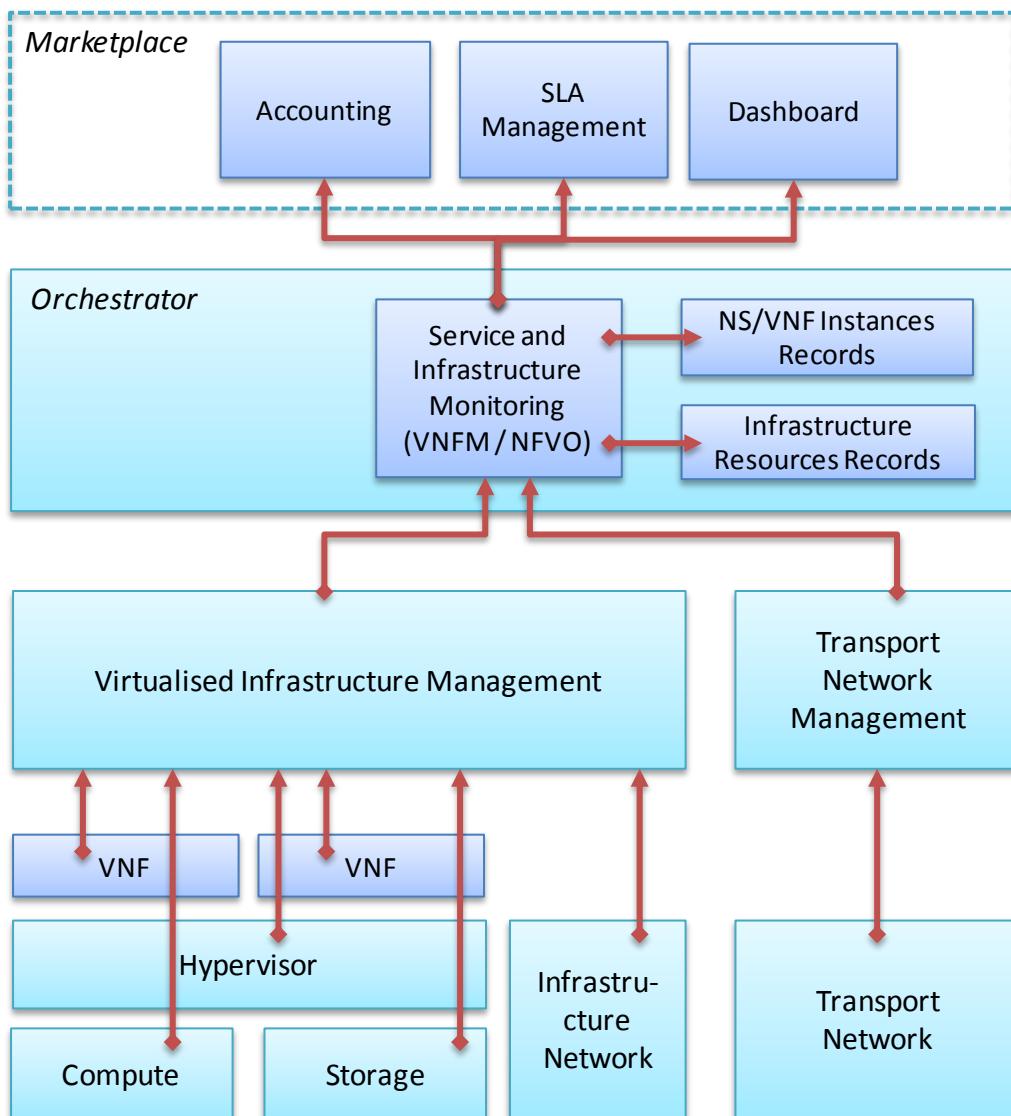


Figure 43: Communication of monitoring information across the T-NOVA system

The first step is the collection of both Infrastructure and NS/VNF monitoring metrics from different domains within the T-NOVA Infrastructure layer. These metrics are typically offered by a dedicated monitoring agent at each physical or virtual infrastructure element. In addition, some compute node and VNF/VM metrics can be

collected directly via the hypervisor, which also provides host and guest machine resource information.

Table 8 presents an indicative list of monitoring metrics to be collected at each infrastructure domain. It must be noted that this list is tentative and is expected to be modified/updated throughout the project course, as the specific metrics which will be actually needed for each step of the T-NOVA service lifecycle, will be precisely defined.

Table 8: Monitoring metrics per infrastructure domain

Domain	VNF App/Service Metrics	Infrastructure Metrics
VNF (VM, guest machine)	CPU utilisation CPU time used No. of vCPUs RAM allocated Disk read/write bitrate Network interface in/out bitrate No. of processes	-
Compute (per compute node, host machine of the DC domain)	-	CPU utilisation RAM allocated Disk read/write bitrate Network interface in/out bitrate
Storage (object or volume storage of the DC domain)	Read/write bitrate Volume usage (volume storage) No. of objects (object storage) Total objects size (object storage)	Total Read/write bitrate Total Volume usage (volume storage) Total no. of objects (object storage) Total objects size (object storage)
Infrastructure Network (per network element of the DC domain)	Per-flow packets cumulative and per second Per-flow bytes packets cumulative and per second Flow duration	Per-port packets cumulative and per second Per-port bytes packets cumulative and per second Per-port receive drops Per-port transmit drops Per-port link state and speed CPU utilisation
Transport Network (per network element)	Per-flow packets cumulative and per second Per-flow bytes packets cumulative and per second Flow duration	Per-port packets cumulative and per second Per-port bytes packets cumulative and per second Per-port receive drops Per-port transmit drops Per-port link state and speed CPU utilisation

Infrastructure metrics, as well as events/alerts are aggregated by the VIM and the TNM and communicated to the Orchestrator FEs, NFVO and VNFM, which are in charge of associating each group of metrics to specific VNFs and Network Service. Those parameters are then compared against the NS and VNF templates composed by a. o. the NSD and the VNFD, which denote the expected NS and VNF behaviour. If any mismatch is detected, appropriate actions are selected and executed, e.g. scaling.

This procedure needs to be carried out at the Orchestrator level, since only the latter has the entire view of the end-to-end service as well as the resources allocated to it. In this context, and in addition to the double check (NS and VNF) mentioned above, the monitoring processed at the Orchestrator, as part of the NFVO and VNFM, performs the following operations:

- Aggregate infrastructure-related metrics and update the Infrastructure Resources records,
- Associates metrics (e.g. VM and flow metrics) to specific services, produce an integrated picture of the deployed service and updates the NS/VNF instances records,
- Checks monitored parameters against the NS and VNF templates, composed by the NSD and the VNFD, which denote the expected NS and VNF behaviour. If any mismatch is detected, appropriate actions are selected and executed, e.g. scaling,
- Communicate service metrics to the Marketplace via the Orchestrator northbound interface.

At the Marketplace level, service metrics are exploited for accounting (especially in pay-as-you-go billing models) as well as SLA Management, in order to compare the status of the service against the contracted one. They are also presented via the Dashboard to the Customer, so that he/she can have a consolidated overall view of the status of the service and the resources consumed.

6 GAP ANALYSIS

Considering both existing industry oriented initiatives and currently available technologies that are being used commercially (or are in a development stage) a focused gap analysis was carried out to determine what steps need to be taken in order to move NFV/SDN from its current state to a position that can fully realise the needs of key areas that need to be addressed during the project activities. In the following, key results of this gap analysis are described, for all the various domains relating to the T-NOVA Orchestrator and T-NOVA IVM architectures. Where possible the gaps have been aligned with T-NOVA tasks where these could be either elucidated or progressed towards addressing the gap could be made.

6.1 Compute

The Compute domain of the T-NOVA architecture provides basic building blocks for VNFs execution. Gap analysis for this domain identified two key areas that need to be addressed during the project activities:

Table 9: Gap analysis in the compute domain

Gap	Description	T-Nova Task Alignment
Virtualisation infrastructure for telecommunication workloads	<p>Features requested by workloads need to be investigated in greater detail and special purpose processors (or co-processors) have to be integrated in compute domain infrastructures.</p> <p>Those enhanced features have also to be exposed to the upper layer of the architecture, in order to make them available from an orchestration perspective</p>	Task 3.2 Task 4.1
Interoperability between different hardware architectures	<p>Compute architecture heterogeneity needs to be improved in current compute domain infrastructure to provide a greater diversity of options for certain NFV workload types.</p> <p>Support for heterogeneity should not only apply in terms of multi-vendor technologies, but also in terms of different hardware architectures required by different VNFs.</p>	Task 4.1

6.2 Hypervisor

The Hypervisor domain is responsible for abstracting VNFs from the underlying physical resources. The main gap issues that have to be addressed by T-NOVA system for this domain are:

Table 10: Gap analysis in the Hypervisor domain

Gap	Description	T-Nova Task Alignment
Integration of vSwitches with hypervisors and vNICs	<p>The hypervisors are responsible for the integration between vSwitches and vNICs.</p> <p>However this integration currently needs further performance improvements. In order for the T-NOVA platform to provide the required level of performance, it is necessary to address these performance features.</p>	Task 4.1
Portability of Virtual Resources across different platforms	<p>In order to support the live migration of VNFs, all the vSwitch solutions need to be described using the same syntax, providing to the T-NOVA system a common interface to allow portability on different platforms and support live migration by the hypervisor.</p>	Task 3.2
Processor Pinning	<p>Some VNF vendors use a dedicated CPU placement policy, which strictly ‘pins’ the vCPUs to a set of host physical CPUs.</p> <p>This is normally done to maximise performance such L3 cache hit rates.</p> <p>However this can make migration ‘by the hypervisor challenging in order to guarantee that same pinning allocation of vCPUs to physical cores on the destination system.</p>	Task 4.1

6.3 SDN Controllers

The SDN Controller domain is responsible for the control of the SDN-enabled network elements regarding the deployment and the management of the vNets. The main issues related to the virtualisation of the SDN Control Plane (CP) are:

Table 11: Gap analysis regarding SDN Controllers

Gap	Description	T-Nova Task Alignment
Distribution of CP	Standardisation activities are required to	Task 3.3

workloads	mitigate various scalability and availability issues due to SDN Control plane centralization, where a distribution approach would have also to be considered.	Task 4.2
Bottleneck Avoidance	Standardisation activities are required to address large-scale, high load deployment scenarios to avoid bottlenecks where a distribution approach would necessitate consideration	Task 3.3
		Task 4.2
Interoperability of different controllers	Currently a uniform interface for all the SDN controllers does not exist, which increases both the complexity of development process. Work is required in the abstraction of north bound interfaces to support application developers.	Task 4.3

6.4 Cloud Controllers

The Cloud Controller represents the central management system for cloud deployments. Ranging from basic to more advanced, the T-NOVA project will investigate gaps in the current solutions within this domain, which fall short with respect to the following aspects:

Table 12: Gap analysis regarding Cloud Controllers

Gap	Description	T-NOVA Task Alignment
Interoperability between different Cloud Computing Platforms	From a T-NOVA Orchestrator perspective, a unified southbound interface is needed, in order to make the API of different IaaS providers accessible and to enable communications with different Cloud Computing Platforms. Even if most cloud platforms have widely adopted open standards, there are still inconsistencies with respect to the different versions and APIs, inconsistencies that need to be concealed under a single interface.	Task 3.1
Resource Allocation and Configuration	From a T-NOVA VNF perspective, cloud controllers need to support the allocation and configuration of network resources and allow enhanced resource management.	Task 3.2 Task 3.3
	Existing cloud management solutions need to be extended to provide an interface that would allow, for instance, enhanced configuration of network	Task 3.4

	parameters.	
Providing infrastructure utilisation data	<p>Monitoring and collecting information with respect to the current load and availability of resources is a crucial capability for T-NOVA system, as it will be a cloud management framework that needs to perform in real-time and support very high volume traffic.</p> <p>Although cloud platforms already offer monitoring capabilities, the challenge with respect to T-NOVA is to collect the information that is relevant for VNFs and how to represent it such that the Orchestration layer can best utilise it.</p>	Task 3.2 Task 3.4 Task 4.1
Platform Awareness	<p>Cloud environments need to become more aware of the features and capabilities of their constituent resources and to expose these enhanced platform features to the Orchestration layer to improve the placement decisions of workloads such as VNFs.</p> <p>A common data model to describe resources is needed, which could be used to identify specific features like DPDK enablement or SR-IOV capable devices.</p>	Task 3.2 Task 4.1

6.5 Network Virtualisation

Network virtualisation introduces several gaps and open issues that need to be addressed by the T-NOVA project:

Table 13: Gap analysis regarding Network Virtualisation

Gap	Description	T-NOVA Task Alignment
Network resource isolation	<p>VNs are by definition based on shared resources and this brings up the isolation problem, especially when the number of VNs sharing the same infrastructure is very high.</p> <p>On the other hand, the strictness of isolation varies according to the specific use case. In a Network as-a-Service scenario isolation it will obviously be a fundamental requirement.</p> <p>Isolation is required between the VNs</p>	Task 4.2

	running separate Telco services. Within the T-NOVA platform, a VN might require complete isolation while another one might share its resources when it is idle, depending on the business model and the type of the specific service.	
Multiple DC interconnection	<p>Limitations of supporting distributed cloud service provisioning and the requirement for VNs to span multiple computing farms; seamless networking handover technologies are still immature or inefficient; potentially complicating service delivery processes or business models.</p> <p>T-NOVA platform needs to manage this complexity, since one of its main features is to support service deployment over different DCs.</p>	Task 4.2 Task 4.5
Reliability of a virtual network (VN)	<p>Reliability is ultimately determined by the dependability of the underlying infrastructure. Virtualisation introduces an additional level of complexity and represents a potential extra source of failure.</p> <p>VNs must be reliable, at least as reliable as a physical network counterpart. Today most of the available products with network virtualisation capabilities are mainly targeted at the high-end segment of the market.</p> <p>On the other hand, very promising, flexible and adaptable technologies such as OpenFlow are perceived as research tools and have not yet reached a point of maturity to enable large-scale deployment.</p>	Task 4.2 Task 4.5
Interoperability between different heterogeneous domains	<p>Standardisation activities are required, especially with interconnection of non-contiguous network domains.</p> <p>Interoperability is a crucial requirement to enable widespread deployment of network virtualisation. Standardisation will be required to enable interoperability between VNs, as well as interoperability between virtualised and non-virtualised networks.</p>	Task 4.5

Scalability and dynamic resource allocation	Dealing with the increasing number of services as well as subscribers for each service would be challenging. The importance of scalability as a network virtualisation requirement is particularly relevant when the number of VNs is expected to grow. New solutions are required to help the T-NOVA system to scale with respect to the network size (for instance reducing the size of OpenFlow tables).	Task 4.1
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6.6 NFV Orchestrator

The NFV orchestrator is responsible for the NSs & VNFs lifecycle management. Several open issues are still to be addressed:

Table 14: Gap analysis regarding Orchestration

Gap	Description	T-NOVA Task Alignment
VNFs Placement	Standardisation bodies should address the definition and implementation of algorithms for optimal infrastructure allocation according to the virtualised service characteristics and SLA agreements.	Task 3.3
Interoperability between heterogeneous virtualized domains	Standardisation activities are required in order to deliver end-to-end services that have virtualised components distributed across multiple domains, owned and operated by different virtual service and/or infrastructure providers.	Task 3.1
Virtual and Physical Network Functions Orchestration	Enhancements are required in standardisation bodies, such as ETSI MANO, to address data centre WAN links interconnectivity configuration and orchestration issues.	Task 3.2 Task 3.4

7 CONCLUSIONS

Virtualisation is a foundational technology for the T-NOVA system in particular for the infrastructure virtualisation and management layer. Originating in the compute domain, use of this approach now finds application in a variety of domains including storage and networking. The approach is based on abstracting physical resources into a form that hides its physical characteristics from either users or applications. It brings a variety of benefits including better utilisation of resources, greater flexibility, improved scalability, etc. Virtualisation encompasses a number of technology approaches, at both a hardware and software level. In subsection 2.2 we reviewed the key virtualisation methods including hypervisors, storage virtualisation, microprocessor and I/O support for virtualisation, hardware and software network virtualisation and accelerators. These technologies are utilised in a variety of both commercial and open sources platforms a number of which will be utilised in the development of the T-NOVA system. Key among these technologies are Cloud OSs, such as OpenStack, for the provisioning and management of virtualised compute resources that host the VNF services. We have also reviewed SDN Controllers, such as OpenDayLight, which provision and manage the VLANs providing connectivity between the nodes hosting VNF services and also connecting the VLANs to WANs for inter-DC connectivity, if required by the VNF service architecture.

In the course of reviewing the various virtualisation technologies and considering them in both the context of the telecoms service providers and the potential needs of the T-NOVA system a variety of gaps in the capabilities of the currently available technologies were identified; see Table 9 to Table 14. While the use of virtualisation technologies in the IT domain is well established, adoption of this approach in carrier grade environments to support NFV and SDN proliferation brings a unique set of challenges that do not exist in enterprise IT environment. A variety of further developments will be required to address specific issues in the currently available compute, hypervisor, SDN Controller, Cloud OSs, network virtualisation and orchestration related technologies. Where appropriate, we have mapped T-NOVA tasks whose activities will be related to these technologies challenges or limitations. It is expected that we will further refine these gaps to specific issues identified in implementation of the T-NOVA system, and highlight progress that has been made in further elucidating the characteristics of these problems, as well as the work that T-NOVA has carried out in order to contribute towards a solution.

From an architectural point of view, the T-NOVA Orchestrator is composed by two main building blocks: the NFVO and the VNFM.

The NFVO has two main responsibilities, which are accomplished by its two FEs designated by NSO and VRO in the T-NOVA terminology. The NSO orchestrates the subset of NFVO functions that are responsible for the lifecycle management of Network Services, while the VRO performs the orchestration/management of the virtualized infrastructure resources distributed across multiple DCs. In particular, it performs the mapping of the incoming NS requests to the virtualized infrastructure resources, as well as the coordination of the resources allocation and placement for

each VM that composes the VNF (and the NS). The VRO does this by interacting with a local virtualized entity, designated by VIM, as well as with the entity that interacts with the WAN elements for connectivity management purposes, a single specialized VIM designated by TNM.

Since the NSs are composed by VNFs and PNFs, the NFVO is able to decompose each NS into the constituent VNFs and PNFs. Nevertheless, although the NFVO has the knowledge of the VNFs that compose the NS, it delegates their lifecycle management to a dedicated FE designated by VNFM.

In Section 3, the architecture for T-NOVA Orchestrator has been derived, taking into account the working Stage 1/Stage 2 methodology, which departed from the elaboration of a list of Orchestrator requirements identified after a research study involving several sources, e.g. use cases defined in D2.1 (66), ETSI ISG NFV requirements (67), ITU-T requirement for NV (10), as well as excerpts of relevant parts of the ETSI ISG MANO WG architecture and associated FEs (8). After that Stage 1 step, (see subsection 3.2), a Stage 2 methodology has taken place with the derivation of the Stage 2 reference architecture and its Functional Entities, see subsection 3.3. However, the work carried out till the moment has only produced abstracted outputs. Stage 3 work will follow in WP3/4 where specific implementation solutions are expected.

The T-NOVA IVM is responsible for providing the hosting and execution environment for VNF services in the form of virtualised resources that are abstracted from the physical resources in compute and infrastructure network domains. A system engineering approach was adopted to define the key functional blocks in the IVM and their interfaces. In addition the key objectives for the IVM were defined. Use of this information and previous T-NOVA deliverables contributed to a requirement capture process that focused on identifying the desired behaviours for the IVM. Requirements were identified for each of the functional entities within the IVM namely the VIM, TNM, NFV Infrastructure (compute, hypervisor, and infrastructure network). These requirements were then used in the design of the IVM.

From an architectural perspective the T-NOVA IVM includes the key functional blocks NFVI, VIM and TNM, which are defined and discussed in Section 4. These functional blocks are comprised of various domains that have specific technology capabilities required for the delivery and management of virtualised resources. For example the NFVI is comprised of the Compute, Hypervisor and Network domains. A number of specific interfaces provide both the internal and external connectivity that integrates the various technology components into a functional IVM. From a T-NOVA system perspective the key external interfaces of the IVM are those to the T-NOVA Orchestrator, which are implemented in the VIM. These interfaces enable the T-NOVA Orchestrator to send requests to the VIM to create and connect VMs in order to support the deployment of VNF service and to manage the virtual resources allocated to the VNFs in order to accomplish to SLAs. Additionally, these interfaces allow the IVM to send infrastructure metrics related to the utilisation and performance to the T-NOVA Orchestrator in order that this entity can perform placement decisions and management of existing deployed services. Another important interface is the one

provided by the TNM to the Orchestrator in order for it to manage the network resources related to external networks i.e. WAN transport between DCs.

In Section 4 the overall integrated architecture of the IVM was presented together with the architecture of the various domains that comprise the IVM with their respective internal and external interfaces.

Collectively, these reference architectures and FEs instantiate the requirements that were identified for the T-NOVA Orchestrator and for the T-NOVA IVM together with its goals and objectives. The reference architectures were interrogated and validated at functional level through the development of NS and VNF workflow diagrams as illustrated in Section 5, which described the key actions and interactions taken within the T-NOVA system during standard operational activities related to the deployment and management of NS and VNF services.

ANNEX A - ORCHESTRATOR REQUIREMENTS

The present annex contains a set of tables, which include the requirements identified in Subsection 3, i.e. Orchestrator internal requirements and Interface requirements.

Each requirement has associated a set of attributes related to its identification (Req. ID and Req. Name), to its text support (Alignment) and to its description (Requirement Description and complementary Comments).

A.1 Internal requirements

A.1.1 NFVO Requirements

A.1.1.1 NS Lifecycle requirements

Table 15: Orchestrator Requirements – NFVO- NS Lifecycle

Req. ID	Alignment	Req. Name	Requirement Description	Comments
NFVO.1	ETSI MANO §C.2.1	On-boarding NS	The NFVO SHALL be able to accept new or updated NSs to be on-boarded, upon request.	The NS lifecycle is initiated by a VNF on-boarding process request, e.g. by Customer or by SP, and includes providing the NS Descriptor (NSD) to the NFVO and storing in the NS Catalogue. The NSD, which must be validated, includes the NS deployment flavours, as well as references to the VNF Forwarding Graph (VNFFG) and to the Virtual Link Descriptor (VLD).
NFVO.2	ETSI MANO §C.3	NS Instantiation request	The NFVO SHALL be able to instantiate an already on-boarded NS, upon request.	In order to start a T-NOVA service, an instantiation process must be deployed, where the external request may be performed by a Customer, a SP, or even by an OSS (through the Marketplace). During the instantiation process, the NFVO validates the request, e.g. by authorizing the requester, by validating technical contents and policy conformance.
NFVO.3	T-NOVA	Extraction of NS information	The NFVO SHALL be able to decompose the incoming NS instantiation request into the set of required information to proceed with the instantiation procedure.	After receiving the NS instantiation request, the NFVO decomposes the received information about the NS (deployment flavours, VNFFG, VLDs, etc.).
NFVO.4	T-NOVA	Configure NS	The NFVO SHALL be able to configure or update the configuration of an instantiated NS, upon request.	T-NOVA NSs must be configured upon external request e.g. Customer or SP. As a NS is the result of the composition of atomic VNF instances, the configuration of a NS implies the configuration of the entire set of VNFs.
NFVO.5	UC1	NS Termination	The NFVO SHALL be able to decompose a NS when the SLA terminates, when a NS is terminated by internal triggers,, or when a NS is terminated upon request, e.g. by Customer, by SP.	The duration of the NS will be specified in the SLA. Alternatively the SLA or the NS can be terminated on-demand, e.g. by the Customer or by the SP. When the NS is no longer needed the system should decompose the NS and cancel the SLA. The NS remains on-boarded in order that other customers can use

				it.
NFVO.6	ETSI MANO §C.4.1	Scale-out NS	The NFVO SHALL be able to scale out the NS, either upon request or automatically.	Automatic scaling out depends on an algorithm and alternative architecture or deployment flavours provided by the SP when composing the NS. Scaling out a NS might imply increasing the VMs supporting its VNF(s).
NFVO.7	ETSI MANO §C.4.2	Scale-in NS	The NFVO SHALL be able to scale in the NS, either upon request or automatically.	Automatic scaling implies the use of an algorithm and alternative architecture or deployment flavours provided by the SP when composing the NS. Scaling in a NS might imply decreasing the VMs supporting its VNF(s).

A.1.1.2VNF Lifecycle requirements

Table 16: Orchestrator Requirements – NFVO- VNF Lifecycle

Req. ID	Alignment	Req. Name	Requirement Description	Comments
NFVO.8	§B.2.1	On-boarding VNF Package Request	The NFVO SHALL receive new VNF packages from the NF Store and store them in the VNF Catalogue.	VNF package includes the VNF Description (VNFD) and the VNF software image(s).
NFVO.9	ETSI MANO §B.3.1.2	VNF Instantiation Request by the NFVO	The NFVO SHALL be able to instantiate a VNF, upon request.	When a request to instantiate a VNF is received, the NFVO validates the request. Optionally, the NFVO runs a feasibility check to reserve resources before performing the actual allocation to the VIM. The NFVO acknowledges the completion of the VNF instantiation after configuring the VNF through the VNFM.
NFVO.10	UC2 UC3	VNF Configuration Request by the NFVO	The NFVO SHALL be able to request the VNFM to configure an instantiated VNF.	T-NOVA VNFs must be configured upon external request, e.g. Customer or SP, or automatically upon the completion of an instantiation process. It includes the notification of the successful configuration.
NFVO.11	ETSI MANO §B.3.1.1	Check VNF instantiation feasibility by the NFVO	The NFVO SHALL be able to accept and process a check feasibility request regarding a VNF instantiation.	NFV Orchestrator receives a request to check feasibility of VNF instantiation/scaling. This request may come from an OSS, from commissioning of a new VNF or VNF scaling, or as part of an order for a Network Service instantiation/scaling.

				The Check Feasibility runs a feasibility check of the VNF instantiation or scaling request and reserves resources before doing the actual instantiation/scaling.
NFVO.12	ETSI MANO §C.3	Check of VNFs of a NS by the NFVO	The NFVO SHALL be able to request the VNFM for checking the VNFs associated with a NS, according to the NS descriptor.	For each VNF instance indicated in the NS descriptor, the NFVO checks with the VNFM if an instance matching the requirements exists already. The procedure includes re-instantiation of mal-functioning VNFs. The procedure does not include any resource reservation.
NFVO.13	UC3.2	VNFM Request – VNF Scale Out	The NFVO SHALL recognise and act upon a VNFM request to scale-out an existing VNF by creating new VMs and deploying VNFs onto the new VMs.	The T-NOVA system must provide the ability for additional VMs requests in order to meet business needs.
NFVO.14	UC3.2	VNFM Request – VNF Scale In	The NFVO SHALL recognise and act upon a VNFM request to scale-in an existing VNF by releasing VMs used by instances of the VNF.	T-NOVA system must provide the ability for a reduction of VMs or to completely remove a VNF as required by their changing business needs.
NFVO.15	UC3.1	VNFM Request – VNF Scale Up	The NFVO SHALL recognize and act upon a VNFM request to scale-up an existing VNF by increasing specified amounts of VM resources from VMs used by instances of the VNF.	The T-NOVA system must provide the ability for increasing in a VNF in order to meet business needs.
NFVO.16	UC3.1	VNFM Request – VNF Scale Down	The NFVO SHALL recognize and act upon a VNFM request to scale-down an existing VNF by decreasing specified amount of allocated resources from VMs, such as memory and storage., used by instances of the VNF.	The T-NOVA system must provide the ability for decreasing resources in a VNF in order to meet business needs.

A.1.1.3 Resource Handling Requirements

Table 17: Orchestrator Requirements – NFVO- Resource Handling

Req. ID	Alignment	Req. Name	Requirement Description	Comments
NFVO.17	ETSI MANO §C.3	Mapping of resources	The NFVO SHALL be able to optimally map the VNFs that are part of a NS to the existing infrastructure, according to an agreed NS SLA.	Based upon the current infrastructure status, the requested VNF and SLA, the NFVO must be able to find the resources it should allocate in terms of VMs and connections.
NFVO.18		IT resources instantiation	The NFVO SHALL be able to request the VIM for the instantiation of the VMs that compose each VNF of the NS.	During the NS instantiation/scaling procedures, after deciding on the best location for the VMs, the NFVO requests the VIM to allocate the required virtualised IT resources (a.k.a. VMs).
NFVO.19	ETSI MANO §5.4.1,	Management of VM images	The NFVO SHALL be able to manage VM images related to the VMs supporting a given VNF.	The NFVO is the FE in charge of handling VM and VM resources in the T-NOVA system. As such, it must be able to manage VM images, e.g. by providing

	§5.4.3			VIM with VM images for VNF on-boarding or updating, or by removing images for VNF removal.
NFVO.20	UC3.1	Resources Inventory Tracking	The NFVO SHALL update its inventory of allocated/available resources when resources are allocated/released.	The T-NOVA System must maintain the Infrastructure Catalogue and accurately track resource consumption and the details of the services consuming those resources.

A.1.1.4 Monitoring Process requirements

Table 18: Orchestrator Requirements – NFVO- Monitoring Process

Req. ID	Alignment	Req. Name	Requirement Description	Comments
NFVO.21	UC2, UC3, UC4	NS-specific resource monitoring by the NFVO	The NFVO SHALL be able to monitor NS-related resources on a real time basis.	NS-specific monitoring is related with the monitoring of the virtual network links that interconnect the VNFs (retrieved from the VIM), as well as monitoring of VNF-specific details that can be used to assure that the NS is fulfilling the established SLA with the customer.
NFVO.22	UC4	Monitoring metrics consolidation by the NFVO	The NFVO SHALL be able to aggregate and consolidate all monitoring metrics associated with a service.	A consolidated operational picture of the service via the dashboard is considered a mandatory customer requirement. The gathered metrics should be presented to the Customer, to the SP, or to the FP, with an integrated status of the provisioned service.

A.1.1.5 Connectivity Handling requirements

Table 19: Orchestrator Requirements – NFVO- Connectivity Handling

Req. ID	Alignment	Req. Name	Requirement Description	Comments
NFVO.23	UC1, UC2, UC3	NS Composition	The NFVO SHALL be able to compose a NS from atomic VNF instances and define the Forwarding Graph based on the logical topology to interconnect the several components.	The creation of a NS from the combination of atomic/simple VNF is important in order to simplify the process provision of NS to the customers and avoid complex path calculations.
NFVO.24		IT Network connectivity instantiation	The NFVO SHALL be able to request the VIM for instantiation and inter-connection of required VMs in the IT compute domain .	During the NS instantiation/scaling procedures, after installing the VMs for the VNF/NS, the NFVO requests the VIM to allocate the required virtual IT network resources (a.k.a. IT virtual network links).

NFVO.25	ETSI MANO §C.3	Virtual Network connectivity instantiation	The NFVO SHALL be able to request the VIM for the instantiation and inter-connection of every needed VM in the IT network domain .	During the NS instantiation/scaling procedures, after installing the VMs for the VNF/NS, the NFVO requests the VIM to allocate the required virtual network resources (a.k.a. virtual network links).
NFVO.26		Legacy Network connectivity instantiation	The NFVO SHALL be able to request the TNM for instantiation and inter-connection of nodes in the infrastructure network .	During the NS instantiation/scaling procedures, after installing the VMs for the VNF/NS, the NFVO requests the TNM to allocate the required legacy network resources.
NFVO.27	ETSI MANO §C.3.6	IT network connectivity deletion	The NFVO SHALL be able to request the VIM the deletion of IT network connectivity for a given NS instance and the removal of the infrastructure allocated for a given VNF.	The T-NOVA system should able to ask the deletion of IT network connectivity. This requirement includes notification of the VNFM of the removed VNF. VNFs having instances participating in NS instances cannot be removed until the NS instance stops and is requested to be removed. Also used in re-instantiating VNF infrastructure (e.g., for performance or mal-function reasons).
NFVO.28	ETSI MANO §C.3.6	Virtual Network connectivity deletion	The NFVO SHALL be able to request the VIM to delete of virtual network connectivity for a given NS instance and to remove the infrastructure allocated for a given VNF.	The T-NOVA system should able to ask for the deletion of virtual network connectivity. This requirement includes notification of the VNFM of the removed VNF. VNFs having instances participating in NS instances cannot be removed until the NS instance stops and is requested to be removed. Also used in re-instantiating VNF infrastructure (e.g., for performance or mal-function reasons).
NFVO.29	ETSI MANO §C.3.6	Legacy network connectivity deletion	The NFVO SHALL be able to request the TNM to delete legacy network connectivity for a given NS instance and to remove of the infrastructure allocated for a given VNF.	The T-NOVA system should able to ask TNM for the deletion of legacy network connectivity.

A.1.1.6 Policy Management requirements

Table 20: Orchestrator Requirements – NFVO- Policy Management

Req. ID	Alignment	Req. Name	Requirement Description	Comments
NFVO.30	UC4 ETSI MANO §4.5.2, §5.4.1	Policy enforcement	The NFVO SHALL provide the means for setting/changing policies associated with an existing VNF.	The T-NOVA system must provide the ability for customers and SPs to change how their VNFs behave to meet evolving business needs, e.g. by applying new packet handling rules.

A.1.1.7 Marketplace-specific interactions requirements

Table 21: Orchestrator Requirements – NFVO- Marketplace specific

Req. ID	Alignment	Req. Name	Requirement Description	Comments
NFVO.31	T-NOVA	Publish NS instantiation	The NFVO SHALL be able to notify that the requested (new, updated) NS instantiation is ready to be used.	T-NOVA system must notify relevant external entities upon successful instantiation of every VNF and connections between them. If the external entity is the Marketplace, it may use this notification for Accounting/Billing purposes.
NFVO.32	T-NOVA	Publish NS metrics	The NFVO SHALL be able to publish the NS metrics, if allowed by SLA.	The T-NOVA system must provide to external entities NS metrics in order to enable service control.
NFVO.33	UC1.1	NFV mapping of SLA data	The NFVO SHALL map the SLA related data to NFV attributes.	Results of selection offerings materialized in SLAs need to be translated into NFV attributes in order to be processed by the T-NOVA system, according to the contents of the VNF descriptor where the amount of needed resources is indicated.
NFVO.34	T-NOVA	SLA enforcement request	The NFVO SHALL be able to take the required actions (e.g. scale out, new instantiation) upon request to enforce a SLA.	It is assumed that the SLA provides all the information about metrics and thresholds to be compared with, together with the NS descriptor providing alternative architectures or deployment flavours, e.g. scaling in when metrics show under-used resources should be automatic.
NFVO.35	UC4, UC5	NS usage accounting and billing	The NFVO SHALL store all the information about resources usage per service, and SHALL provide it to external entities to bill on a pay-per-use mode.	Pay-as-you-go may be considered attractive for some Customers, as an option, as opposed to flat-rate. The NFVO should notify relevant FEs in order that the T-NOVA system becomes able to deploy this type of billing/charging.

A.1.2 VNFM Requirements

A.1.2.1 VNF Lifecycle requirements

Table 22: Orchestrator Requirements – VNFM- VNF Lifecycle

Req. ID	Alignment	Req. Name	Requirement Description	Comments
VNFM.1	ETSI MANO §B.3.1.2	VNF Instantiation Request by the VNFM	The VNFM SHALL be able to accept a request from the NFVO to instantiate a VNF.	After receiving a VNF instantiation request from the NFVO, the VNFM will start coordinating the VNF instantiation procedure. Nevertheless, the virtualized resources allocation is under the scope of the NFVO and therefore the VNFM will have to request the later to allocate the required resources for the VNF.
VNFM.2	UC2 UC3	VNF Configuration Request by the VNFM	The VNFM SHALL be able to accept a NFVO request to configure an instantiated VNF.	T-NOVA VNFs must be configured upon external request or following an external instantiation request. It includes the notification of the successful configuration.
VNFM.3	ETSI MANO §B.3.1.1	Check VNF instantiation feasibility by the VNFM	The VNFM SHALL be able to accept requests coming from the NFVO and process a check feasibility procedure regarding a VNF instantiation.	The VNFM receives a request to check feasibility of a VNF instantiation/scaling and processes the VNF descriptor after validating the request.
VNFM.4	ETSI MANO §C.3	Check of VNFs part of a NS by the VNFM	The VNFM SHALL be able to accept a request from the NFVO to check the VNFs associated with a NS, according to the NS descriptor.	For each VNF instance indicated in the NS descriptor, the VNFM checks if a VNF instance matching the requirements already exists. Includes re-instantiation request of mal-functioning VNFs..
VNFM.5	UC2	VNF lifecycle automation by the VNFM	The VNFM SHALL be able to automate the instantiation of VNFs and associated VM resources by triggering scaling procedures.	Automation of VNF lifecycle is an essential characteristic of the T-NOVA system. Triggering of scaling procedures is based on the monitoring process maintained over VNFs, as well as on policy management and other internal algorithm criteria.
VNFM.6	UC3.2	Auto VNF Scale Out	The VNFM SHALL provide the means to automatically scale-Out a VNF.	T-NOVA system needs to automatically scale-out a VNF to meet SLAs in an efficient and timely manner.
VNFM.7	UC3.2, UC4	Auto VNF Scale In	The VNFM SHALL provide the means to automatically scale-In an existing VNF.	T-NOVA system needs to automatically scale-in a VNF to meet SLAs in an efficient and timely manner.
VNFM.8	UC3.1	Auto VNF Scale Up	The VNFM SHALL provide the means to automatically scale-Up an existing VNF.	This procedure ensures that resources are consumed in an efficient manner and SLA specified targets on resource consumption are met.

VNFM.9	UC3.1	Auto VNF Scale Down	The VNFM SHALL provide the means to automatically scale-down a VNF.	This procedure ensures that resources are consumed in an efficient manner and SLA specified targets on resource consumption are met.
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A.1.2.2 Monitoring Process requirements

Table 23: Orchestrator requirements – VNFM- Monitoring Process

Req. ID	Alignment	Req. Name	Requirement Description	Comments
VNFM.10	UC2, UC3, UC4	VNF-specific resource monitoring by the VNFM	The VNFM SHALL be able to monitor VNF-related resources on a real time basis.	VNF-specific monitoring is related with the monitoring of information retrieved from the VIM, related to the virtualized infrastructure resources allocated to the VNF (i.e. compute/storage/memory of the VMs and virtual network links that interconnect the VMs), as well as monitoring of VNF-specific metrics that can be used to assure that the VNF is behaving as it should.
VNFM.11	UC4	Monitoring metrics consolidation by the VNFM	The VNFM SHALL be able to aggregate and consolidate all monitoring VNF metrics associated with a service.	A consolidated operational picture of the service via the dashboard is considered a mandatory customer requirement. The collected metrics should be presented by the VNFM to the NVFO, and from this FE to the dashboard with an integrated status of the provisioned service.

A.2 Interface requirements

A.2.1 Interface with VIM

The requirements identified for the Interface with the VIM module are as follows:

Table 24: Requirements between the Orchestrator and VIM

Req. id	Alignment	Domain(s)	Requirement Name	Requirement Description	Justification of Requirement
Or-Vi.01		Orchestrator, VIM	Reserve / release resources	The Orchestrator SHALL use this interface to request the VIM to reserve or release the entire required infrastructure needed for a given VNF	Care must be taken in order not to have resources allocated for long periods of time, thus impacting on the optimisation of resource usage.
Or-Vi.02	T_NOVA_03, T_NOVA_21, T_NOVA_22, T_NOVA_26, T_NOVA_31, T_NOVA_33, T_NOVA_34, T_NOVA_36, T_NOVA_37, T_NOVA_38, T_NOVA_39, T_NOVA_40, T_NOVA_42, T_NOVA_43, T_NOVA_44, T_NOVA_45, T_NOVA_58 ⁴	Orchestrator, VIM	Allocate / release / update resources	The Orchestrator SHALL use this interface to request the VIM to allocate, update or release the required infrastructure needed for a given VNF	It is assumed that configuration information is a resource update. Resource update might imply stop and re-start, with a migration in between.

⁴ Refers to T-NOVA requirements described in deliverable D2.1 (63)

Or-Vi.03		Orchestrator, VIM	Add / update / delete SW image	The Orchestrator SHALL use this interface to add, update or delete a SW image (usually for a VNF Component)	Performance will probably demand having these images ready to be deployed on the Orchestrator's side
Or-Vi.04	UC4, T_NOVA_46	Orchestrator, VIM	Retrieve infrastructure usage data	The Orchestrator SHALL use this interface to collect infrastructure utilisation data (network, compute and storage) from the VIM	Some of this data is used to determine the performance of the infrastructure (including failure notifications) and to inform decisions on where to provision newly requested services or to where to migrate an already provisioned NS that is predicted to break its SLA. This interface will very likely have to support very high volume traffic.
Or-Vi.05	UC4, T_NOVA_20	Orchestrator, VIM	Retrieve infrastructure resources metadata	The Orchestrator SHALL use this interface to request infrastructure's metadata from the VIM	Due to high performance needs, this metadata will most probably have to be cached on the Orchestrator's side
Or-Vi.06	T_NOVA_24, T_NOVA_25, T_NOVA_35, T_NOVA_27	Orchestrator, VIM	Manage VM's state	The Orchestrator SHALL use this interface to request the VIM to manage the VMs allocated to a given VNF.	We can assume a finite and small number of possible VM states, e.g., 'Being configured', 'Not running', 'Running', 'Being re-scaled', 'Being stopped'. It is assumed that when in a 'Running' state the VM is ready to be (re-) configured.
Or-Vi.07	T_NOVA_02	Orchestrator, VIM	Secure interfaces	The interfaces between the Orchestrator and the VIM SHALL be secure, in order to avoid eavesdropping (and other security threats)	We should keep in mind that encrypting all the communication between these two entities will probably make a performing solution too costly

A.2.2 Interface with VNF

The requirements identified for the Interface with the VNF module are as follows:

Table 25: Requirements between the Orchestrator and VNF

Req. id	Alignment	Domain(s)	Requirement Name	Requirement Description	Justification of Requirement
Vnfm-Vnf.01	T_NOVA_02	VNFM, VNF	Secure interfaces	All the interfaces between the VNFM and the VNF SHALL be secure, in order to avoid eavesdropping (and other security threats)	Required to avoid eavesdropping the connection between the VNFM and each VNF. We should keep in mind that encrypting all the communication between these two entities will probably make a high performance solution too costly
Vnfm-Vnf.02		VNFM, VNF	Instantiate/terminate VNF	The VNFM SHALL use this interface to instantiate a new VNF or terminate one that has already been instantiated	Required to create/remove VNFs during the VNF lifecycle
Vnfm-Vnf.03	T_NOVA_46, T_NOVA_48	VNFM, VNF	Retrieve VNF instance run-time information	The VNFM SHALL use this interface to retrieve the VNF instance run-time information (including performance metrics)	VNF instance run-time information is crucial both for automating VNF scaling and for showing Network Services' metrics in the Marketplace's Dashboard
Vnfm-Vnf.04	T_NOVA_23 T_NOVA_33	VNFM, VNF	Configure a VNF	The VNFM SHALL use this interface to (re-)configure a VNF instance	In the general case, the Customer should be able to (re-)configure a VNF (instance). Includes scaling.
Vnfm-Vnf.05	T_NOVA_24, T_NOVA_35, T_NOVA_58	VNFM, VNF	Manage VNF state	The VNFM SHALL use this interface to collect/request from the NFS the state/change of a given VNF (e.g. start, stop, etc.)	This interface includes collecting the state of the VNF (as well as changing it). The VNF instance should include a state like 'Ready to be used' when it is registered in the repository.
Vnfm-Vnf.06	T_NOVA_36, T_NOVA_37, T_NOVA_38, T_NOVA_39, T_NOVA_42, T_NOVA_43, T_NOVA_44, T_NOVA_45	VNFM, VNF	Scale VNF	The VNFM SHALL use this interface to request the appropriate scaling (in/out/up/down) metadata to the VNF	VNF scaling depends on the (mostly architectural) options the FP provided when registering the VNF. The VNF scaling metadata is then used by the NFVO to request the VIM to allocate the required infrastructure

A.2.3 Interface with Marketplace

The requirements identified for the Interface with the Marketplace are as follows:

Table 26: Requirements between the Orchestrator and the Marketplace

Req. id	Alignment	Domain	Requirement Name	Requirement Description	Justification of Requirement
NFVO-MKT.01	UC1, T_NOVA_10, T_NOVA_15	Orchestrator, Marketplace	Provide available VNFs	The Marketplace SHALL use this interface with the Orchestrator to provide the Service Provider with a list of the VNFs, so that it can select and parameterise them, or use them in the composition of a new network service.	It is assumed that this VNF metadata includes a URL/repository name from which to fetch the actual VNF software and install it on the previously allocated infrastructure (see NFVO.10 below). Note that, although this information will most certainly have to be cached on the Orchestrator's side for performance reasons, the available VNFs will be dynamic, so updates to this cached information will be rather frequent.
NFVO-MKT.02	UC2, T_NOVA_04, T_NOVA_08, T_NOVA_20	Orchestrator, Marketplace	Provision a new network service	The Marketplace SHALL use this interface to inform the Orchestrator to provision the network service, after the Customer has selected and parameterised the network service. The Orchestrator SHALL read the SLA and the date/time to start the new network service. Each NS can be composed of one or more VNFs.	The date/time of start/end the service are part of the SLA.
NFVO-MKT.03	UC3, T_NOVA_31, T_NOVA_32, T_NOVA_33, T_NOVA_36, T_NOVA_42, T_NOVA_44	Orchestrator, Marketplace	Change configuration of a deployed network service	The Marketplace SHALL use this interface to change the configuration of an already provisioned network service on the Orchestrator .	It is assumed that information about scaling (up/down/in/out) is included in the SLA (or at least reasonable values can be inferred).
NFVO-MKT.04	UC5, T_NOVA_28, T_NOVA_29, T_NOVA_34,	Orchestrator, Marketplace	Provide network service state transitions	The Marketplace SHALL use this interface to determine the state transitions of a given network service, e.g. to facilitate starting and stopping billing for the service.	It is assumed that each NS has a pre-defined state-diagram, like 'Ready to run', 'Running', 'Stopped', etc., that is also known to the Marketplace.

	T_NOVA_41, T_NOVA_48, T_NOVA_56, T_NOVA_57				
NFVO-MKT.05	UC4, T_NOVA_28, T_NOVA_29, T_NOVA_30, T_NOVA_46, T_NOVA_52	Orchestrator, Marketplace	Provide network service monitoring data	The Marketplace SHALL use this interface to show the Customer how the subscribed network service is behaving, how it compares to the agreed SLA and bill the service usage.	This interface will very likely have to support very high volume traffic.
NFVO-MKT.11	UC6, T_NOVA_03, T_NOVA_58	Orchestrator, Marketplace	Terminate a provisioned NS	The Marketplace SHALL use this interface to request the Orchestrator to terminate provisioned NSs	It is assumed that the impact on the dependent modules like billing, are taken care by the Marketplace (see NFVO.04). SLA Management is part of the Marketplace. Either after a customer's request or by the pre-defined ending date had been attained, the SLA Management notifies the Orchestrator of the end of the SLA.
NFVO-MKT.12	T_NOVA_02	Orchestrator, Marketplace	Secure communication	Interfaces between the Marketplace and the Orchestrator SHOULD be secured.	Encryption should be used, in order to prevent eavesdropping. Even between the Marketplace and the Orchestrator, since the Marketplace is really a set of distributed apps.

ANNEX B - VIRTUALISED INFRASTRUCTURE MANAGEMENT REQUIREMENTS

B.1 Virtual Infrastructure Management Requirements

Table 27: IVM Requirements - VIM

Req. id	T-NOVA Use Case Alignment	Domain	Requirement Name	Requirement Description	Justification of Requirement
VIM.1	UC1, UC2.1	VIM	Ability to handle heterogeneous physical resources	The T-NOVA VIM SHALL have the ability to handle and control both IT and network physical infrastructure resources.	Basic functional requirement of the VIM.
VIM.2	UC1, UC2.1	VIM	Ability to provision virtual instances of the infrastructure resources	The T-NOVA VIM SHALL be able to create virtual resource instances from physical infrastructure resources upon request	Required to support VIM integration with the T-NOVA Orchestrator.
VIM.3	UC3/3.1/3.2	VIM	API Exposure	The T-NOVA VIM SHALL provide a set of API's to support integration with its control functions with the T-NOVA Orchestration layer.	Required to support VIM integration with the T-NOVA Orchestrator
VIM.4	UC2.1	VIM	Resource abstraction	The T-NOVA IVM system SHALL provide resource abstraction at the VIM level for representation of physical resources.	Required to support VIM integration with the T-NOVA Orchestrator.
VIM.5	UC1.1 UC1.3 UC2.1 UC4	VIM	Ability to support different service levels	The VIM network controller SHOULD provide the ability to request different service levels with measurable reliability and availability metrics.	Required to supported SLA's agreement when purchasing a VNF service in the T-NOVA Marketplace
VIM.6	UC3.1, UC3.2	VIM	Live VM and link migration	The VIM network controller SHOULD support live VM migration within a data centre and between data centres including migration of virtual links without traffic disruption	This capability is required for a number of operational reasons such as service optimisation, SLA management, service resilience etc.

VIM.7	UC1	VIM	Translation of references between logical and physical resource identifiers	The VIM network controller SHOULD be able to assign IDs to virtual components (e.g., NFs, virtual links) and provide the translation of references between logical and physical resource identifiers.	Need to track the use of physical network resources.
VIM.8	UC2 UC3	VIM	Isolated virtual networks sharing the same physical infrastructure	The VIM network controller SHALL guarantee isolation among the different virtual network resources created to provision the requested services through the marketplace.	T-NOVA system will be providing services for different customers through the composition and deployment of VNFs. Those services will share the same physical network infrastructure, at the same time they belong to different customers. Thus, isolation at the physical level must be guaranteed for each customer.
VIM.9	UC3.1, UC3.2, UC3.3 UC4	VIM	Control and Monitoring	The VIM network controller SHALL be able to visualise the real-time status and the history reports related to the performance and resource utilisation of both the physical network infrastructure and multiple instances of virtual networks running over it.	T-NOVA must be able to visualise the real-time status and the history reports related to the performance and the resource utilisation of both the physical infrastructure and the multiple instances of virtual networks running over it.
VIM.10	UC3	VIM	Scalability	The VIM network controller SHOULD scale in accordance to the number of virtual resource instances and physical network domains	The T-NOVA system should be able to manage a large network infrastructure.
VIM.11	UC1	VIM	Network service and resource discovery	The VIM network controller SHOULD provide mechanisms to discover physical network resources.	The Orchestrator must be aware of the available physical network resources.
VIM.12	UC1.1 UC2.1 UC3.1 UC3.2 UC3.3 UC4	VIM	Specification of performance parameters	<p>The VIM network controller SHOULD allow the infrastructure connectivity services to specify the following performance related parameters:</p> <ul style="list-style-type: none"> • Maximum overhead (bits required for the network virtualisation technique, per packet or percentage of traffic) • Maximum delay • Maximum delay variation 	T-NOVA system should support a high level of customisation for the network service.

				<ul style="list-style-type: none"> • Throughput (CIR, CIR+EIR and packets per second) • Maximum packet loss allowable 	
VIM.13		VIM	Flow entry generation	The VIM network controller SHOULD be able to generate and install the required flow entries to the OF switches for packet forwarding and NF policy enforcement (i.e., ensuring that traffic will traverse a set of NFs in the correct order).	Required to support the Network Service definition.
VIM.14		VIM	Path computation	The VIM Network Controller MAY be able to compute paths that satisfy given bandwidth requirements (within and between DCs). Path redundancy in DCs should be exploited.	The Patch Computation functionality is required when the overall end-to-end virtual network topology is constructed over the actual infrastructure. The critical part is the calculation of cost for the transport network in order to guarantee certain QoS attributes for the transport links. However in T-NOVA the transport network and its management will be addressed at demonstration level with a set of basic functionalities. In this context PCE implementation will follow a similar simple approach.
VIM.15		VIM	Virtual address space allocation	The VIM network controller SHOULD be able to allocate virtual address space for NF graphs (virtual addresses of NFs belonging to different graphs could overlap).	Required to support isolation among different virtual network domains.
VIM.16	UC4	VIM	QoS support	The VIM network controller SHALL provide mechanisms to support QoS control over the network infrastructure.	Required to support the specific performance needed by a network service.
VIM.17		VIM	SDN Controller performance	The VIM network controller SHOULD minimise the flow setup time maximising the number of flows per second that it can setup.	Required to provide a responsive configuration of the underlying infrastructure.
VIM.18		VIM	VIM Network Controller Robustness	The VIM network controller SHALL be able to deal with control plane failures (e.g., via	Required for resiliency in the T-NOVA system.

				redundancy) in a robust manner.	
VIM.19		VIM	Hypervisor Abstraction and API	The VIM Hypervisor Controller SHALL abstract a basic subset of hypervisor commands in a unified interface and in a Plug-In fashion. This includes commands like start, stop, reboot etc.	Different Hypervisors have various advantages such as full hardware emulation or paravirtualization. In order to get the best functionality and the best performance for a VM, different Hypervisors must be supported.
VIM.20		VIM	Query API and Monitoring	The VIM Hypervisor Controller SHALL have a Query API that allows other T-NOVA components to retrieve metrics, configuration and used hypervisor technology per compute node.	The orchestrator must be able to make the best decision regarding performance, functionality and a SLA for the creation of VMs. The orchestrator requires information from the hypervisor and the compute infrastructure under its control to make placement and management decisions.
VIM.21		VIM	VM Placement Filters	The VIM Compute Controller SHALL offer a set of filters that are appropriate to VNF deployments to achieve a more granular placement strategy with a scheduler.	Some requirements set by the orchestrator do need a more specific placement of the VM. E.g. a CPU core filter can be applied to the scheduler so that the VM is only placed on a compute node, if more than 3 CPU cores are available.
VIM.22		VIM	Base-Image Repository integration	The VIM Compute Controller SHALL have an integration-module to interact directly with the non-configured VM images that need to be deployed.	The compute controller must have access to the repository with the basic VM images. Those base images will be deployed in the desired flavour by the orchestrator regarding configuration, disk space, CPU and memory.
VIM.23	UC2	VIM	Hardware Information Collection	The VIM Compute Controller SHALL be able to receive physical hardware information and provide this information via an API to the orchestrator.	In order to operate efficient high level NF like deep packet inspection, specific capabilities need to be available on the CPU or in the form of co-processor cards.. This module can retrieve such information automatically and provide it to the orchestrator for intelligent decisions.

VIM.24	UC4	VIM	Virtualised Infrastructure Metrics	The VIM SHALL collect performance and utilisation metrics from the virtualised resources in the NFVI and report this data in raw or processed formats via a northbound interface to the Orchestrator.	The Orchestrator needs data to make scaling decisions on VNF service based on SLA criteria.
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B.2 Transport Network Management Requirements

Table 28: IVM Requirements - TNM

Req. id	T-NOVA Use Case Alignment	Domain	Requirement Name	Requirement Description	Justification of Requirement
TN.1		Transport Network Management	Legacy (non-SDN) Network Management	The IVM SHOULD be extensible in order to support interaction with WAN network devices via a Network Infrastructure Manager.	It is assumed that any legacy network technology used for the realisation of transport network links interconnecting NFVI-PoPs is managed through this Network Management system. The implementation is out T-NOVA scope.
TN.2	UC1.1, UC2.1, UC3.1, UC3.2, UC3.3, UC4	Transport Network Management	Specification of performance parameters	The network SHOULD allow the provisioning of network services according to the following performance related parameters: <ul style="list-style-type: none"> • Maximum overhead (bits required for the network virtualisation technique, per packet or percentage of traffic) • Maximum delay • Maximum delay variation (jitter) • Throughput (CIR, CIR+EIR and packets per second) • Maximum packet loss allowed • QoS level • Failover/Resiliency 	Some or all of these parameters will be taken into account when configuring and provisioning transport network links.

TN.3	UC1.1, UC1.3, UC2.1, UC4	Transport Network Management	Ability to support different service levels	The TNM SHOULD provide the ability to request different service levels with measurable reliability and availability metrics, (e.g. percentage of time the network is available) from the Transport Network.	To support SLA's availability in the T-NOVA marketplace.
TN.4	UC2	Transport Network Management	Path computation	The TNM SHOULD be able to compute paths that satisfy given bandwidth requirements (i.e. between DCs). Path redundancy in DCs should be exploited.	Given a demand for a NS transport links inter-connecting NFVI-PoPs need to be configured and provisioned. The actual path in the network that needs to be installed and provisioned should be calculated in order to ensure the service parameters (see T2) and service levels (see T3). It is expected that path computation algorithms will be re-used.
TN.5	UC2	Transport Network Management	Tunnels setup	The TNM SHALL cooperate with the NFVI-PoP Network domain to configured VLAN tunnels between different NFVI-PoP's hosted at different Data Centres.	This functionality is required to set-up the necessary tunnels between different NFVI-PoPs through external legacy networks as required by VNF service architecture, SLA's and service provider business needs.

B.3 NFV Infrastructure Requirements

B.3.1 Computing

Table 29: IVM requirements - Computing

Req. id	T-NOVA Use Case Alignment	Domain	Requirement Name	Requirement Description	Justification of Requirement
C.1	UC2	Compute	Nested/Extended	Hardware page virtualisation SHALL be utilised to improve performance.	Performance benefits from hardware page virtualisation are tied to the prevalence of VM exit transitions. CPU

					should have large TLBs
C.2	UC2, UC3	Compute	Central Storage	A central storage subsystem (SAN) SHALL be available in order to enable advanced functionalities like VM migration and server clustering	Required to support use cases 3/3.1/3.2. Also required for system resilience.
C.3	UC4	Compute	No SPOF	All hardware components SHALL be deployed with proper redundancy mechanisms (e.g. redundant SAN switches and network switches) in order to avoid single points of failure	Required to support use cases 3/3.1/3.2. Also required for system resilience.
C.4	UC4.1	Compute	Performance	All hardware components SHALL satisfy specific performance parameters (e.g. IOPS and R/W operation ratio in case of storage resources) in order to provide required performance levels	Required to guarantee proper SLAs
C.5	UC2	Compute	Hypervisor compatibility	Servers and storage SHOULD be compatible with the chosen hypervisor(s)	Required to ensure basic system functionality and reliability.
C.6	UC2, UC3	Compute	Central Storage - efficiency	Central storage SHALL support functionalities like Automatic Storage Tiering (AST), thin provisioning and deduplication, in order to reduce costs, improve efficiency and performance	Required to support SLA's associated with VNF services.
C.7	UC4	Compute	Compute Domain Metrics	<p>The compute domain SHALL provide metrics and statistics relating to the capacity, capability and utilisation of hardware resources:</p> <ul style="list-style-type: none"> • CPU cores • Memory • IO (including accelerators) • Storage subsystem <p>These metric shall include both static and dynamic metrics</p>	This information is required at the Orchestration layer to make decisions about the placement of new VNF, services, to manage existing services to ensure SLA compliance and to ensure reliable of the system.

C.8	UC3	Compute	Power Management	The compute domain SHALL provide power management functions that enable the VIM to remotely control the power state of the domain	This capability maybe required to meet SLA requirements on energy utilisation, service costs or time of day service settings {Non-functional requirement}
C.9	UC2, UC3	Compute	Hardware Accelerators	The compute domain SHALL support discovery and reservation of hardware (HW) /functional accelerators	Certain VNF functions may require or experience performance benefits from the availability of co-processor cards such as FPGA's, MIC (e.g. XEON PHI) or GPU's (e.g. Nvidia). The Orchestrator should be aware of these capabilities to ensure correct placement decisions.
C.10	UC2, UC3	Compute	Hardware Accelerators	All HW accelerators SHOULD be able to expose their resources to the VIM Controllers.	The Orchestrator should be aware of accelerator capabilities available within an NFVI-PoP for placement of VNF's that can utilise these capabilities to improve their performance.
C.11	UC2, UC3	Compute	Hardware Accelerators	HW accelerator resources MAY be virtualisable themselves and this feature SHALL be made available to the host processor.	Typically accelerator HW is not virtualisable with the exception of GPUs. Virtualising the accelerator can provide performance improvement and guarantees and could be exposed and used by the T-NOVA system.
C.12	UC4	Compute	Hardware Accelerators	HW accelerators SHALL provide performance metrics to the VIM.	Necessary to measure performance, guarantee SLAs and determine limits for scaling up and down the service if necessary.
C.13		VIM	Traffic classification	The VIM Network Controller SHOULD be able to classify packets among VMs (where NFs are hosted). Packet classification offloading to the NIC is desirable (e.g., Intel VMDq)	This is required to ensure appropriate performance of VNF's running on VM's

B.3.2 Hypervisor

Table 30: IVM Requirements - Hypervisor

Req. id	T-NOVA Use Case Alignment	Domain	Requirement Name	Requirement Description	Justification of Requirement
H.1	UC3 UC4	Hypervisor	Compute Domain Metrics	The Hypervisor SHALL gather all relevant metrics and resource status information required by the Orchestrator from the compute domain and will provide the data to the VIM via a VIM-Hypervisor interface	The Orchestrator requires the information from the compute domain to make decisions regard the placement of new VNF services to adjusting existing services to maintain SLA's
H.2	UC3, UC4	Hypervisor	Network Domain Metrics	The hypervisor SHALL gather all relevant metrics (e.g. bandwidth requirements) from the infrastructure networking domain and provide data to the VIM via a VIM-Hypervisor interface	The Orchestrator requires the information from the next work domain to make decisions regard the placement of new VNF services to adjusting existing services to maintain SLA's
H.3	UC3	Hypervisor	VM Portability	The T-NOVA hypervisor SHALL be able to unbind the VM from the hardware in order to allow the VM to be migrated to a different physical resource.	Required to ensure that VNF are fully portable in the T-NOVA systems for support various conditions such as scaling, resilience, maintenance etc.
H.4	UC3	Hypervisor	VM Migration - Notification	The T-NOVA hypervisor SHALL support instructions to provision, migrate, rescale, delete etc. a VM received via a Hypervisor-VIM interface	Fundamental requirement for the T-NOVA system to function
H.5	UC3	Hypervisor	Predictive VM Migration Performance	The hypervisor SHALL provide metrics to allow the VIM and Orchestrator to make predictions as to the impact of migration.	This capability is required to ensure that any infrastructure management actions such as consolidation will not impact on VNF service performance
H.6	UC2	Hypervisor	Performance Impact	The hypervisor SHALL have minimal impact on VNF workload performance	Require to ensure that the performance of the hosted VNF is not impacted.

H.7	UC2 UC3	Hypervisor	Platform Features Awareness/Exposure	The hypervisor SHALL be able to discover the existence of features and functionality provided by resources such as the compute, accelerators, storage and networking and to expose these features to the Orchestrator via the VIM.	Enhanced platform awareness by the Hypervisor and making this information available to the Orchestrator will allow the Orchestrator to make more intelligent placement decisions during the deployment of VNF services.
H.8	UC3.	Hypervisor	VM Reconfigure /Rescale	The hypervisor SHALL have the ability to scale a VM up and down: to add / remove compute and memory dynamically	Prerequisite to meet the requirements described in UC3/3.1/3.2
H.9	UC2	Hypervisor	VM Low Power State	The hypervisor SHALL have the ability to put resources into a lower power state based on utilization/SLA requirements to expose a lower power state to the Orchestrator.	This capability maybe required to meet SLA requirements on energy utilisation, service costs or time of day service settings
H.10	UC2 UC6	Hypervisor	Request Results Information	The hypervisor SHALL make available to the VIM the results of requests completion	Required so the VIM and Orchestrator can maintain a consistent view of the infrastructure resources.
H.11	UC2, UC4	Hypervisor	Performance – Resource overcommit	The hypervisor SHALL be able to provide mechanisms to control resource overcommit policies	Required to improve performances and guarantee proper SLAs
H.12	UC4	Hypervisor	Alarm/Error Publishing	The hypervisor SHALL publish alarm or error events to the Orchestrator via the VIM	The Orchestrator requires this information in order for it react appropriately
H.13	UC2 UC3	Hypervisor	Security	The hypervisor SHALL be able to guarantee resource (instruction, memory, device access, network, storage) isolation in order to guarantee performance	Necessary to ensure that VNF services do interfere with each other and impact performance or reliability
H.14	UC2 UC3	Hypervisor	Network	The hypervisor SHALL be able to control network resources within the VM host and provide basic inter-VM traffic switching.	This is required to allow proper VNF graph creation for VNFs that are instantiated within the same VM Host.

B.3.3 Networking

Table 31: IVM Requirements - Networking

Req. id	Alignment	Domain	Requirement Name	Requirement Description	Justification of Requirement
N.1	UC1-UC6	Networking	Switching	Networking devices of the T-NOVA NFVI PoP SHOULD support L2 and L3 connectivity	Mandatory requirement
N.2	UC1-UC6	Networking	Virtualization	Networking devices of the T-NOVA IVM SHOULD have the ability to be virtualised to allow the VNFs deployment.	Required to support scalability within the T-NOVA system.
N.3	UC1-UC6	Networking	QoS configuration and performance configuration	Networking devices of the T-NOVA NFVI PoP MAY allow the configuration of specific quality of service parameters such as overhead, throughput, service differentiation and packet loss.	Required to ensure QoS configurability for the NSS.
N.4	UC1-UC6	Networking	Transport technologies support	Networking devices of T-NOVA NFVI PoP MAY support transport technologies (e.g. MPLS, Metro Ethernet, etc.) for the support of traffic trunks between NFVI-PoPs	Required for inter-NFVI-PoP connectivity
N.5	UC1-UC6	Networking	Tunnelling	Networking devices of the T-NOVA NFVI PoP MAY support the creation of multiple distinct broadcast domains (VLANs) through one or more tunnelling protocols (e.g. STT, NVGRE, VxLAN) to allow the creation of virtual L2 networks interconnected within L3 networks (L2 over L3).	This is a requirement for the deployment of VNF's across different NFVI-PoPs
N.6	UC1-UC6	Networking	Usage monitoring	Networking devices of the T-NOVA NFVI PoP SHOULD provide monitoring mechanisms of their usage through commonly used APIs.	Required for trouble-shooting, events/alarms detection, and live optimisation
N.7	UC1-UC6	Networking	Configuration	Networking devices of the T-NOVA NFVI PoP SHOULD allow configuration through common technologies and protocols such as NETCONF and SNMP.	Required for (remote) uniform configuration access.
N.8	UC1-UC6	Networking	SDN	Physical and Virtual Networking devices performing L2 switching of the T-NOVA NFVI-PoP SHOULD be SDN enabled.	Required to allow the use of SDN in order to dynamically configure the network at runtime.

N.9	UC1-UC6	Networking	Open Flow	All L2 networking devices of the T-NOVA NFVI-PoP SHOULD support the OpenFlow protocol.	Required to allow the use of SDN in order to dynamically configure the network at runtime.
N.10	UC1-UC6	Networking	SDN Management	All L2 networking devices of the T-NOVA NFVI PoP SHOULD be managed by an SDN controller located in the VIM.	Required to ensure the network infrastructure properly works.
N.11	UC1-UC6	Networking	Network slicing	Networking devices of the T-NOVA NFVI PoP SHOULD allow programmability of their forwarding tables through the Open Flow protocol. Each flow SHOULD be handled and configured separately to enable network slicing.	VIM should be able to create network slices composed with different networking devices, which are then configured independently.
N.12	UC1-UC6	Networking	Scalability	The infrastructure network of the T-NOVA NFVI PoP SHOULD be able to support a large number of connected servers, which in turn, SHOULD be able to support a large number of concurrent VMs.	Required to support scalability and multi-tenancy.
N.13	UC1-UC6	Networking	Address uniqueness	The virtual networks of the T-NOVA NFVI PoP MUST ensure address uniqueness within a given virtual network.	Required to uniquely identify the VM's attached to a VLAN.
N.14	UC1-UC6	Networking	Address space and traffic isolation	<p>For L2 services, the infrastructure network of the T-NOVA NFVI PoP MUST provide traffic and address space isolation between virtual networks.</p> <p>For L3 services, the infrastructure network of the T-NOVA NFVI PoP MUST provide traffic isolation between virtual networks. If address isolation is also required it can be achieved using various techniques:</p> <ul style="list-style-type: none"> • An encapsulation method to provide overlay networks (L2 or L3 service). • The use of forwarding table partitioning mechanisms (L2 service). • By applying policy control within the 	Required to ensure the correct function of multi-tenancy in the T-NOVA system.

				infrastructure network (L3 service).	
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ANNEX C - TERMINOLOGY

This annex contains general terms used throughout the deliverable in association with all main T-NOVA architectural entities.

The terms marked with an asterisk (*) have been aligned with ETSI NFV ISG terminology (77).

C.1 General Terms

Table 32: General terms

Name	Description
Virtualised Network Function (VNF)*	A virtualised (pure software-based) version of a network function.
Virtualised Network Function Component (VNFC)*	An independently manageable and virtualised component (e.g. a separate VM) of the VNF.
T-NOVA Network Service (NS)	A network connectivity service enriched with in-network VNFs, as provided by the T-NOVA architecture.
NFV Infrastructure (NFVI)*	The totality of all hardware and software components which build up the environment in which VNFs are deployed.

C.2 Orchestration Domain

Table 33: Orchestration Domain terminology

Name	Description
Orchestrator*	The highest-level infrastructure management entity which orchestrates network and IT management entities in order to compose and provision an end-to-end T-NOVA service.
Resources Orchestrator*	The Orchestrator functional entity which interacts with the infrastructure management plane in order to manage and monitor the IT and Network resources assigned to a T-NOVA service.
NS Orchestrator*	The Orchestrator functional entity in charge of the NS lifecycle management (i.e. on-boarding, instantiation, scaling, update, termination) which coordinates all other entities in order to establish and manage a T-NOVA

	service.
VNF Manager*	The Orchestrator functional entity in charge of VNF lifecycle management (i.e. installation, instantiation, allocation and relocation of resources, scaling, termination).
NS Catalogue*	The Orchestrator entity which provides a repository of all the descriptors related to available T-NOVA services
VNF Catalogue*	The Orchestrator entity which provides a repository with the descriptors of all available VNF Packages.
NS & VNF Instances Record*	The Orchestrator entity which provides a repository with information on all established T-NOVA services in terms of VNF instances (i.e. VNF records) and NS instances (i.e. NS records).
NF Store	The T-NOVA repository holding the images and the metadata of all available VNFs/VNFCs.

C.3 IVM Domain

Table 34: IVM Domain terminology

Name	Description
Virtualised Infrastructure Management (VIM)*	The management entity which manages the virtualised (intra-NFVI-PoP) infrastructure based on instructions received from the Orchestrator.
Transport Network Management (TNM)	The management entity which manages the transport network for interconnecting service endpoints and NFVI-PoPs, e.g. geographically dispersed DCs.
VNF Manager Agent*	The VIM functional entity which interfaces with the Orchestrator to expose VNF management capabilities
Orchestrator Agent*	The VIM/TNM functional entity which interfaces with the Orchestrator to expose resource management capabilities.
Hypervisor Controller*	The VIM functional entity which controls the VIM Hypervisors for VM instantiation and management.
Compute Controller*	The VIM functional entity which manages both physical resources and virtualised compute nodes.
Network Controller @ VIM*	The VIM functional entity which instantiates and manages the virtual networks within the NFVI-PoP, as well as traffic steering.
Network Controller @	The TNM functional entity which instantiates and manages the virtual networks within transport network,

TNM

as well as traffic steering.

APPENDIX I – ETSI ISG NFV FRAMEWORK

This appendix is the repository for the results of a research study carried out on the ETSI ISG NFV framework.

I.1 ETSI ISG NFV Overview

The IT and Networks industries have been combining their complementary expertise and resources in a joint collaborative effort to reach broad agreement on standardised approaches and common architectures, which address identified technical challenges, are interoperable and have economies of scale.

As a result, a network operator supported Industry Specification Group (ISG) with open membership was setup in the last quarter of 2012 under the umbrella of ETSI to work through the technical challenges of NFV.

However, it should be noted that ETSI ISG NFV is not a Standards Development Organisation (SDO) but a body that produces guideline documents. The ETSI ISG NFV delivers its findings in the form of Group Specifications and not in the form of European Norms (EN) or Technical Standards (TS). The outputs are openly published and shared with relevant standards bodies, industry Fora and Consortia, to encourage a wider collaborative effort. If misalignments are detected, the ETSI ISG NFV will collaborate with other SDOs in order to meet the requirements.

The ISG NFV also provides an environment for the industry to collaborate on Proof-of-Concept (PoC) platforms to demonstrate solutions, which address the technical challenges for NFV implementation and to encourage growth of an open ecosystem.

In the following sections, the NFV concept will be introduced, as well as the manner in which it has been handled by the ISG NFV and by the ISG NFV WGs. In addition, a status of the work will also be provided.

It is recognised that the ETSI ISG NFV Phase 1 won't cover all the aspects of the NFV domain and, as such, a Phase 2 is being prepared. As its scheduled timeline, with a start in January 2015, will have potential to influence the deployment of T-NOVA; a brief description of their activities is presented.

I.2 High-level NFV framework and reference architecture

The NFV concept envisages the implementation of NFs as software-only entities that run over the NFV Infrastructure (NFVI). Figure 44, published in October 2013 by the ETSI ISG NFV in its document on global architecture, illustrates the high-level NFV framework, where three main working domains can be identified:

- **Virtualised Network Function (VNF)**, as the software implementation of a network function which is capable of running over the NFVI,
- **NFV Infrastructure (NFVI)**, which includes the diversity of physical resources and how these can be virtualised. NFVI supports the execution of the VNFs,

- **NFV Management and Orchestration (NFV MANO)**, which covers the orchestration and lifecycle management of physical and/or software resources that support the infrastructure virtualisation and the lifecycle management of VNFs. NFV MANO focuses on all virtualisation-specific management tasks necessary in the NFV framework.

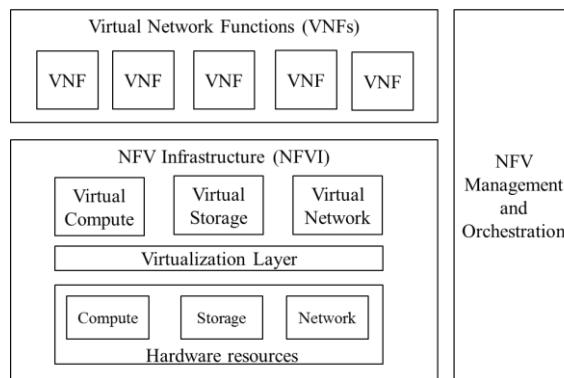


Figure 44: High-level NFV framework
(Source: GS NfV 002 v1.1.1 - NFV - Architectural Framework (66))

The NFV architectural framework handles the expected changes that will probably occur in an operator's network due to the network function virtualisation process. Figure 45 shows this global architecture, depicting the functional blocks and reference points in the NFV framework:

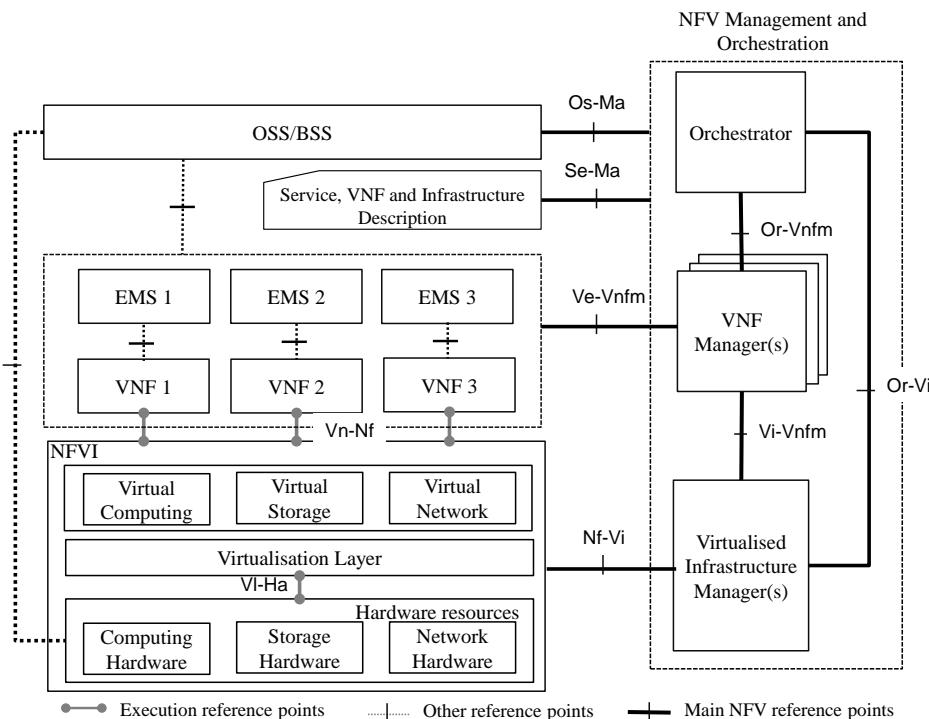


Figure 45: NFV reference architectural framework
(Source: GS NfV 002 v1.1.1 - NFV - Architectural Framework (66))

The architectural framework shown in Figure 45 focuses on the functionalities that are necessary for the virtualisation and the consequent operation of an operator's

network. It does not specify which network functions should be virtualised as that is solely a decision of the owner of the network.

I.3 Relevant Working Groups and Expert Groups

As stated above, looking at the high-level NFV framework and at the global NFV architecture, three main domains can be identified:

- NFVI,
- VNFs,
- NFV MANO.

This domain partition is the basis of the WGs⁵ currently operating in ETSI ISG NFV: INF, SWA and MANO.

I.3.1 WG INF (Infrastructure Architecture)

This WG is responsible for the NFVI. They have identified three sub-domains within the NFVI, which are as follows:

- **Hypervisor Sub-domain**, which operates at a **virtual level**, encompassing the computing and storage **slices**,
- **Compute Sub-domain**, which operates at the **lowest level**, also in the computing and storage **slices**,
- **Network Sub-domain**, which operates both at **virtual level** and at **hardware level**, of the network **slice**.

The global architecture of the NFVI domain, shown in Figure 46 details the specific infrastructure-related Functional Entities. All the three sub-domains can be decomposed into smaller functional blocks, both at the virtual and hardware levels. In addition, the VIM, part of the MANO domain, is also shown in Figure 46 as it manages this specific infrastructure level from the architecture level, or functional level perspective.

⁵ WGs work at an architecture or functional level, not at an implementation or physical level.

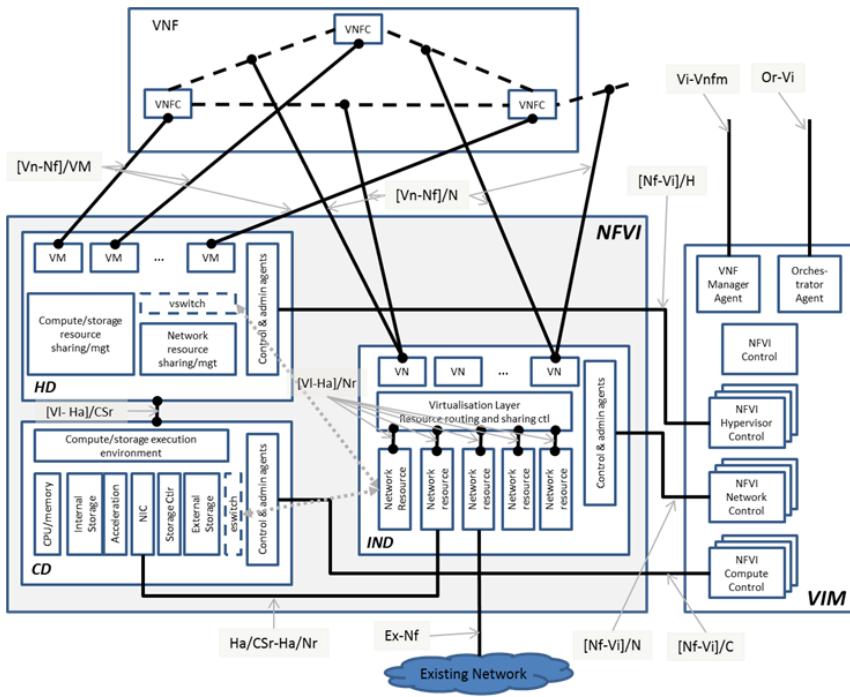


Figure 46: High Level Overview of the NFVI Domains and Interfaces
 (Source: DGS NFV INF 005 v0.3.0 (2014-05) (5))

I.3.2 WG SWA (Software Architecture)

As described in the Terms of Reference (ToR) of the NFV SWA WG in the ETSI portal (<http://portal.etsi.org/TBSiteMap/NFV/NFVWGSGsToR.aspx>) (6), the main responsibilities of this group are to:

- Define a reference software architecture for network functions to be deployed, provisioned, run and managed on a virtualised infrastructure,
- Describe the functionalities specific to VNFs, i.e. functional behaviour, deployment model, and characteristics such as security and performance,
- Identify/define the reference points/interfaces with other NFV WG building blocks, typically MANO and INF, and preserve reference points/interfaces to legacy OSS and BSS,
- Collect and define requirements for this reference SWA architecture from relevant stakeholders, i.e. provided by MANO, INF and legacy OSS/BSS,
- Validate this reference functional software architecture with concrete use cases,
- Identify gaps, where existing standards/specifications do not fulfil the requirements of the reference architecture.

With respect to the architecture, and taking into account that the WG is devoted to the domain that handles the VNFs and their manager, i.e. the VNF lifecycle, the detailed architecture is depicted in Figure 47.

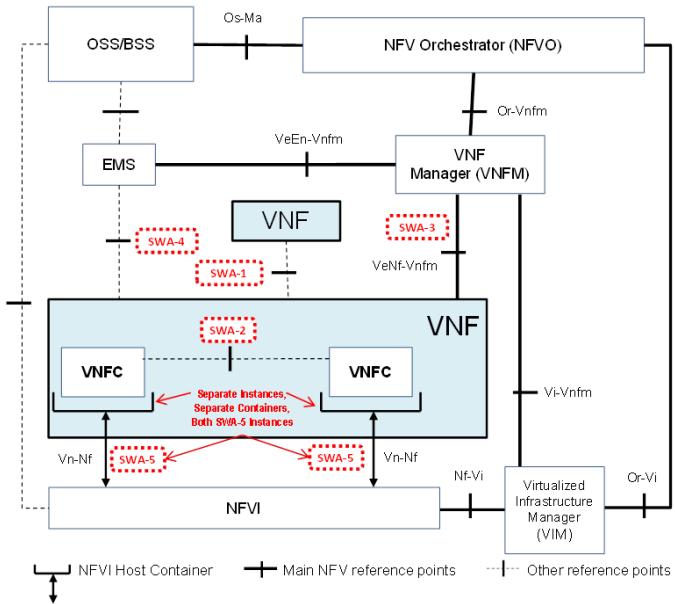


Figure 47: SWA Architectural Framework and interfaces types
 (Source: DGS NFV SWA 001 v0.2.0 (2014-05) (7))

I.3.3 WG MANO (Management and Orchestration Architecture)

The ToRs indicated in the ETSI portal for this WG are to:

- Develop ETSI deliverables on issues related to the deployment, instantiation, configuration and management framework of network services based on NFV infrastructure, focused on:
 - abstraction models and APIs,
 - provisioning and configuration,
 - operational management,
 - interworking with existing OSS/BSS,
- Provide requirements for orchestration and management,
- Identify gaps in current standards and best practices.

The current working architecture conceived by the NFV MANO WG is shown in Figure 48.

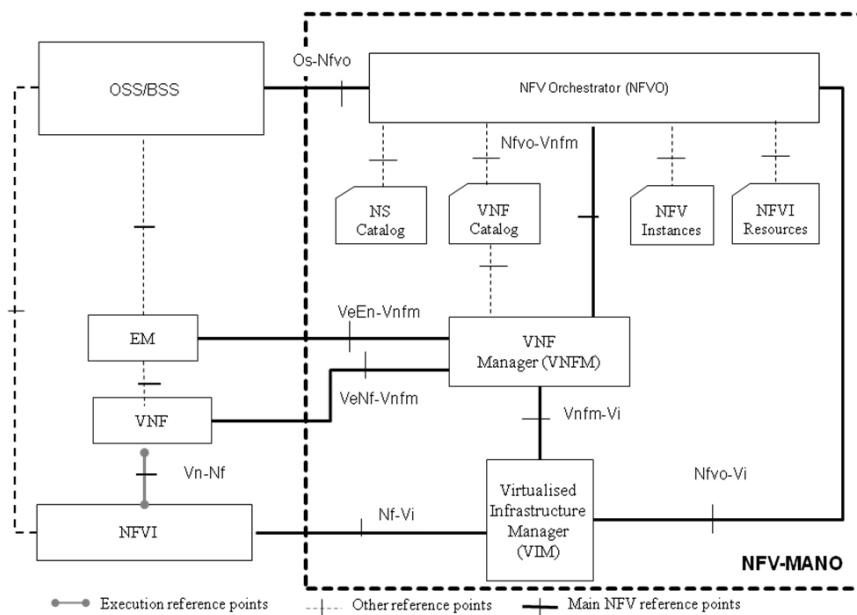


Figure 48: NFV MANO reference architectural framework
 (Source: DGS NFV MAN 001 v0.6.3 (2014-09) (8))

I.4 ETSI ISG NFV impact in WP2 of T-NOVA

The overall set of standards in the current approval process appear to be aligned with T-NOVA, due to the fact that they have been carefully considered in the development of both the overall T-NOVA architecture and the architectural components to ensure appropriate alignment to the ETSI NFV reference architecture.

In this context, the scope of the three main WGs, INF, SWA and MANO, are aligned with the various architecture related tasks in WP2:

- T2.3 orchestrator requirements and architecture clearly point to the NFVO Functional Entities currently being worked in ETSI NFV MANO WG,
- T2.4 infrastructure key requirements and architecture clearly point to the NFVI and Functional Entities currently being worked on in the ETSI NFV INF WG,
- T2.5 virtual network functions requirements and architecture clearly point to the VNF Functional Entities currently being worked on in the ETSI NFV SWA WGs.

Figure 49 illustrates the mapping between ETSI ISG NFV Functional Entities and the Work Packages / Tasks of the T-NOVA system as described above.

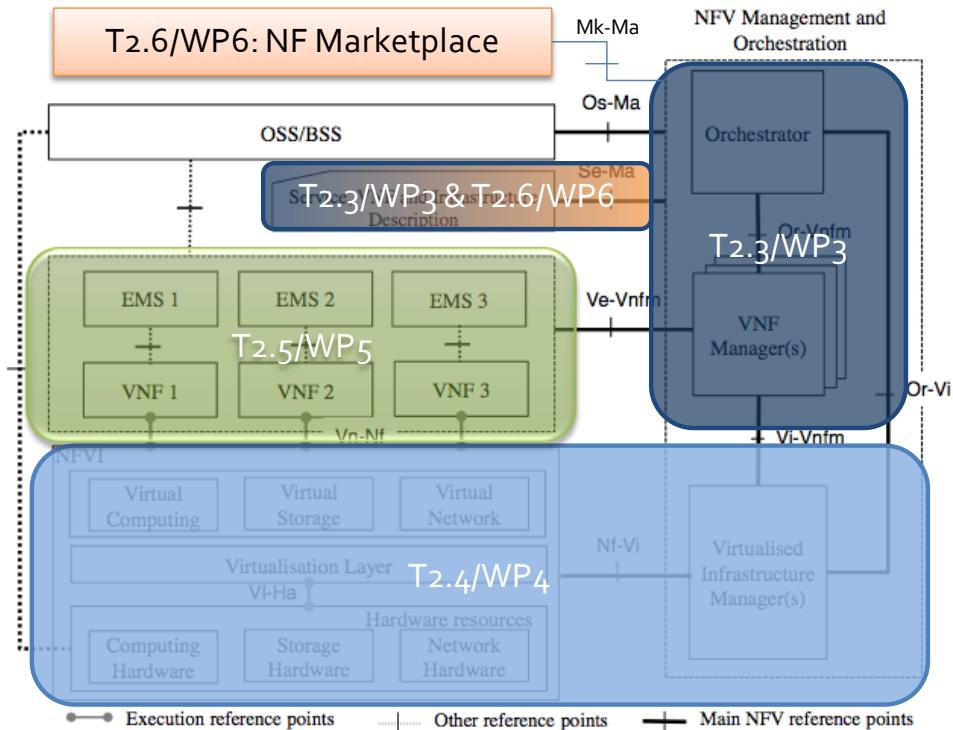


Figure 49: T-NOVA mapping into ETSI MANO
(Source: T-NOVA T2.3 Kick-Off Call 2014/04/24 (3))

I.5 Status of work

The current section outlines the status of the work that has been carried out in the ETSI ISG with respect to the new paradigm of NFV. In this context, the following will be provided:

- an overview on what has been achieved to date,
- the status of the release 1 set of documents under the responsibility of each WG, and
- the current roadmap of publications up to the end of the year.

In addition, several activities carried out under the scope of NFV Phase 2 will be indicated. The current scheduled timeline includes a January 2015 start, and therefore has the potential to influence the deployment of T-NOVA.

I.5.1 What has been achieved to date

From the beginning of 2013, the ETSI ISG NFV WGs have been constituted and have started their work in accordance with their Terms of Reference (ToRs), i.e. responsibilities and activities. Therefore, several documents have been initiated related with their currently on-going work.

Figure 50 illustrates the roadmap of activities of the ISG NFV from the start of 2013 up to the middle of 2014.

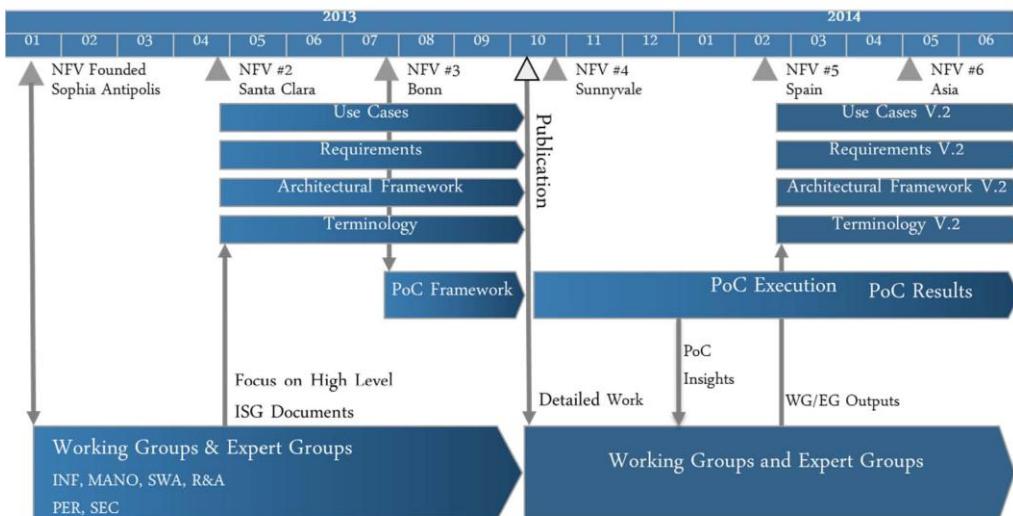


Figure 50: Timeline for ISG Work Program from beginning of 2013 to mid-2014
 (Source: ETSI ISG NFV 2nd White Paper, October 15-17, 2013 at the "SDN and OpenFlow World Congress", Frankfurt-Germany (78))

Also in October 2013, a first set of parallel high level documents have been published by ETSI to inform the on-going work and to provide guidelines to the industry in a number of different areas:

- **NFV Use Cases document** describing initial fields of application,
- **NFV Requirements document** describing the high level business and technical requirements for an NFV framework including service models,
- **NFV Architectural Framework document** describing the high-level functional architecture and design philosophy for virtualised network functions and the underlying virtualisation infrastructure. By delineating the different constituents and outlining the reference points between them, it paves the way for fully interoperable multi-party NFV solutions,
- **NFV Terminology document** is a common repository for terms used within the NFV ISG documents,
- **NFV Proof of Concept Framework document**, which appears as a consequence of the launch of a global call for multi-party NFV Proof of Concepts (PoC) to validate NFV approaches and to encourage progress towards interoperability and development of an open ecosystem.

I.5.2 WG focus

Table 35 shows the status of the documents under the responsibility of each WG. In addition the table has links to related documents located in the ETSI servers.

Table 35: Overall GS documents status (as of June 18th)
 (Source: WG SWA internal)

	Date	Target is Final Draft ASAP
GS SWA	May 28th	Final Draft: http://docbox.etsi.org/ISG/NFV/SWA/70-DRAFT/SWA001/NFV-SWA001v020.zip
GS MANO	May 23rd	Stable draft: http://docbox.etsi.org/ISG/NFV/MAN/70-DRAFT/MAN1/NFV-MAN001v050.zip
GS REL	June 12th	Stable Draft: http://docbox.etsi.org/ISG/NFV/REL/70-DRAFT/REL1/NFV-REL001v013.docx
GS SEC #1	June 6th	Stable Draft: http://docbox.etsi.org/ISG/NFV/SEC/70-DRAFT/SEC001/NFV-SEC001v013.zip
GS SEC #2	April 29th	Early Draft: http://docbox.etsi.org/ISG/NFV/SEC/70-DRAFT/SEC2/NFV-SEC002v003.docx
GS SEC #3	Nov 25th	Early Draft: http://docbox.etsi.org/ISG/NFV/SEC/70-DRAFT/SEC3/NFV-SEC003v007.docx
GS PER	April 25	Final Draft: http://docbox.etsi.org/ISG/NFV/PER/70-DRAFT/PER001/NFV-PER001v009.zip
GS INF #1	Final Draft	Final Draft: http://docbox.etsi.org/ISG/NFV/INF/70-DRAFT/INF1/NFV-INF001v038.doc
GS INF #2	Final Draft	Final Draft: http://docbox.etsi.org/ISG/NFV/INF/70-DRAFT/INF2/NFV-INF002v032.docx
GS INF #3	May 29th	Final Draft: http://docbox.etsi.org/ISG/NFV/INF/70-DRAFT/INF3/NFV-INF003v031.docx
GS INF #4	May 27th	Final Draft: http://docbox.etsi.org/ISG/NFV/INF/70-DRAFT/INF4/NFV-INF004v031.doc
GS INF #5	May 30th	Final Draft: http://docbox.etsi.org/ISG/NFV/INF/70-DRAFT/INF5/NFV-INF005v031.docx
GS INF #6	N/A	
GS INF #7	May 25th	Final Draft: http://docbox.etsi.org/ISG/NFV/INF/70-DRAFT/INF7/NFV-INF007v031.zip
GS INF #8	N/A => 2/3/4	Stable Draft: http://docbox.etsi.org/ISG/NFV/INF/70-DRAFT/INF8/NFV-INF008v012.doc
GS INF #9	N/A	
GS INF #10	June 12th	Stable Draft: http://docbox.etsi.org/ISG/NFV/INF/70-DRAFT/INF10/NFV-INF010v009.docx

I.5.3 Publication of documents for ETSI ISG NFV Release 1

The activities of the ETSI ISG NFV will continue until the end of the year, when its mandate is expected to terminate. The agreed timeline for the outputs from this group are shown in Figure 51:

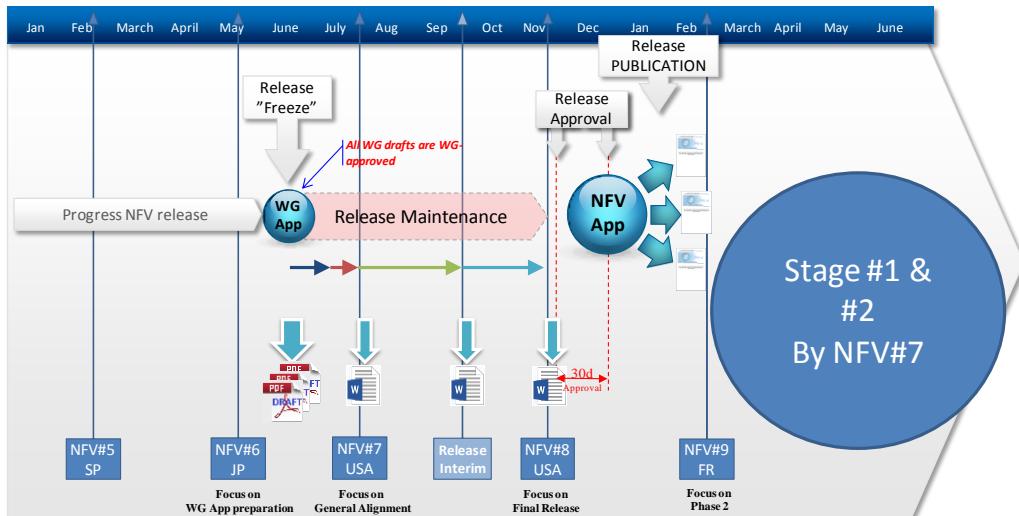


Figure 51: Timeline for ISG Work Program during 2014 and beginning of 2015
(Sources:

[NFV\(14\)000034r1_NFV_Drafts_maintenance_process_and_release_plan_proposal_invoked_by_NFV\(14\)000028_NFV5_Plenary_draft_Minutes](#) (6)

Table 36 presents the expected timeline and outputs for the ETSI ISG NFV:

Table 36: Expected timeline and outputs for the ETSI ISG NFV

Due Date	Expected Output
mid of June 2014	Progress all NFV WG documents (INF+SWA+MANO+PER+etc) and approval,

	Freeze release and begin release maintenance, envisaging consistency update ⁶
Mid November 2014	End release maintenance followed by beginning of release approval.
end of December	30 days of release approval by ETSI ISG NFV
end of January 2015	Release 1 NFV documents publication.

I.5.4 Phase 2 preparation

The mandate of the ETSI ISG NFV runs for two years until the end of 2014.

It is widely recognised that the ETSI ISG NFV Phase 1 documents won't cover the NFV domain in its entirety, i.e. there are business and technical issues that will be left for further study in Phase 2, which is scheduled to begin in January 2015, by NFV#9. This is the key reason why a set of activities has been in preparation since February-March of 2014, in order to ensure a successful end to Phase 1 followed by a smooth transition to a sustained Phase 2 with well-defined objectives and a clear schedule.

In the remaining part of this subsection, a selected number of those activities that are taking place will be briefly outlined bearing in mind that discussions are still ongoing and no definitive results have been obtained at the moment.

I.5.4.1 Global objectives

In this context, it is worth to be considered what the Chairman has pointed out as global objectives in his presentation during the last Okinawa closing plenary meeting (6):

"There is room for quite a lot of issues, technical and non-technical, to be considered, e.g.:

- *To foster interoperable implementations,*
- *To facilitate development of an open ecosystem,*
- *To provide guidance to open source and open innovation efforts,*
- *To drive towards commonly defined operating environment that can support a variety of VNFs,*
- *To provide direction for NFV outbound messaging,*
- *To develop documents that provides requirements to relevant SDOs."*

I.5.4.2 Governance model

In this Phase 2 preparation, the governance model that will lead to a new structure is under discussion. When compared to the structure adopted in Phase 1, one of the main drivers is the replacement of a vertical-based structure by another one that

⁶ The Release Maintenance concept has been introduced in order to guarantee harmonisation between overall documents. In this phase, drafts are WG approved, i.e. technical content is ready for publication, only corrections and inter WG alignments are allowed

might be considered as horizontal, with a NFV Steering Board (NSB), and still a Network Operator Council (NOC) and a Technical Steering Committee (TSC), on the top, but with slightly different responsibilities. The innovation relies on the intention to close the WGs and EGs, replacing them by ad hoc groups with a very limited scope and timeframe, i.e. the group is disbanded upon completion of the work by the agreed deadline.

However, this position is not consensual as there are other people that consider that a lot of outstanding issues remain to be addressed in the WGs and, as such, the preference is to retain the current working groups.

The outcome will probably merge the two approaches.

I.5.4.3 Documents maintenance

It is expected that the documents that the ISG NFV will publish by the end of this year will require a maintenance process due to errors and inconsistencies that will only be discovered when people start using them extensively.

In addition, as stated in a draft document recently circulated, some operators expect that the ETSI NFV's new work items will lead to two types of deliverables, equivalent in contents to ETSI Technical Specifications (TSs) and to ETSI Technical Reports (TRs). This does not preclude both types of documents to be published as ETSI Group Specifications.

However, once again, the issue is not consensual and it is still being discussed in the mailing list and in the Phase 2 wiki.

I.5.4.4 Issues related to NFV evolution

The evolution of NFV must also be considered. In the future, new requirements will emerge as NFV matures and will likely justify new releases/phases of NFV specification work. In addition, the activity carried out in this area will be close to the work performed in the new Open Platform for NFV (OPN), as detailed below.

As an example, the importance of focusing on **interoperability**, in order to guarantee an e2e architecture framework, may be one of most inevitable issues, one of those that can't be avoided. This has to be addressed by the specification of some interfaces that were left as almost void in Phase 1.

Another example of a recognised (technical) issue, but with less priority, is the **interworking with legacy OSS/BSS** and a plan for migration.

Finally, some new documents may be necessary to cover areas that in the initial phase were **thought to be out of scope**.

I.5.4.5 3rd White Paper

The elaboration of a 3rd White Paper by NOC was agreed in order to position the published release 1 documents and to describe the operators' vision for the next steps (i.e. role and governance of ISG NFV Phase 2, maintaining influence on the wider industry). It will not contain any proprietary information and the objective will

be to secure the widest possible support of network operators. The agreed timescale is October 2014, in time for Layer123 conference in Dusseldorf.

I.5.4.6 Open Platform NFV

Mission and Goals, Scope and Objectives

According to a contribution presented at the NFV#6 closing plenary, 13-16 May Okinawa, Japan, the **mission** of this envisaged new forum is to drive NFV's evolution through the creation of a new an Open Platform for NFV (OPN), which the carrier and vendor community will benefit from, i.e.:

- To create an integrated and tested **open (SW, HW)** platform to address the industry's needs,
- To create an environment for **continuous system level validation and integration**,
- **To contribute** changes to and influence **upstream open source projects** leveraged in the platform,
- **To build new** open source components within the project where needed,
- To use the **open** implementations to drive an open standard and **open ecosystem for NFV solutions**.

The **scope** of the work will be based on the ETSI MANO and NFVI architectures. As far as the **objectives** are concerned, the following have been indicated:

- To provide an environment for **realisation and implementation** of the ETSI ISG NFV architecture and requirements,
- To create an **open platform which supports NFV and is carrier grade** (meets performance, scale and reliability requirements):
 - To take advantage of the innovation in the open source community,
 - To coordinate upstream contributions to address gaps for supporting NFV, in current open source projects,
 - To integrate open source components and develop glue-code to create an E2E solution,
- **To drive for faster traction** and **lower development cost** on realising a carrier grade NFV open platform:
 - To take advantage of the resource multiplier effect due to multiple company support,
 - To improve speed development and breadth of features.

Internal Governance Model

So far, an internal governance model has already been proposed and is being discussed amongst internal representatives in charge of OPN forum constitution, as well as other NOC and TSC representatives. Basically, it will be composed by three

internal bodies, i.e. the **End-User Advisory Council**, the **Board** and the **TSC**, whose responsibilities are:

- The **End-User Advisory Council** is a broad open body to every NFV member, which is in charge of selecting gathering and selecting use cases and respective requirements. Participation in this body is meant to be free of any fees,
- The **Board** is a body composed by selected expertise members, which are in charge of validating the proposal, by analysing the project scope, the business case including financial and marketing analysis, and the technical strategic direction. To be part of the Board, a company companies have to pay a fee, which terms of payment are still being studied but will depend for sure on the company's size,
- The **Technical Steering Committee** is a body that is more related with the execution part by being responsible for overseeing its design and development,
- The **Projects** are groups constituted to execute a validated proposal.

External Relationships

In terms of external relationships, the Forum communicates with the ETSI ISG NFV, as well as any other SDOs in order to collect use cases and requirements. Additionally, the Forum also communicates with other relevant Open source projects.

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LIST OF ACRONYMS

Acronym	Description
ACPI	Advanced Configuration and Power Interface
API	Application Programming Interface
AST	Automatic Storage Tiering
BSS	Business Supporting System
CAM	Control, Administration and Monitoring
CAPEX	Capital Expenditure
CLC	Cloud Controller
CLI	Command Line Interface
CP	Control Plane
CPU	Control Processing Unit
D2.1	Deliverable D2.1
D2.21	Deliverable D2.21
D2.41	Deliverable D2.41
DC	Data Centre
DCN	Data Centre Network
DMC	DOVE Management Console
DOVE	Distributed Overlay Virtual Ethernet
DP	Data Plane
DPDK	Data Plane Development Kit
DPI	Deep Packet Inspection
E2E	End-to-End
EG	Experts Group
EM	Element Manager
EN	European Norm
EPT	Extended Page Tables
ETSI	European Telecommunications Standards Institute
EU	End User

EVB	Edge Virtual Bridge
FE	Functional Entity
FN	Future Networks
FP	Function Provider
FPGA	<u>Field Programmable Gate Array</u>
GS	Global Standard
GPU	Graphical Processing Unit
GW	Gateway
HG	Home Gateway
HW	Hardware
I/O	Input/Output
IaaS	Infrastructure as a Service
IEEE	Institute of Electrical and Electronics Engineer
IETF	Internet Engineering Task Force
INF	Infrastructure
IP	Internet Protocol
IP	Infrastructure Provider
IPAM	IP Address Management
IPsec	IP security
ISG	Industry Specification Group
ISO	International Organisation for Standardisation
IT	Information Technology
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
IVM	Infrastructure Virtualisation and Management
KPI	Key Parameter Indicator
L2	Layer 2
L3	Layer 3
LAN	Local Area Network
LINP	Logically Isolated Network Partition
MAC	Mmedia Access Control

MAN	Metro Area Network
MANO	Management and Orchestration
MEF	Metro Ethernet Forum
MIC	Multi-Integrated Cores
MPLS	Multiprotocol Label Switching
NaaS	Network as a Service
NC	Network Controller
NETCONF	Network Configuration Protocol
NF	Network Function
NFaas	Network Functions-as-a-Service
NFV	Network Functions Virtualisation
NFVI	Network Functions Virtualisation Infrastructure
NFVIaaS	Network Function Virtualisation Infrastructure as-a-Service
NFVI-PoP	NFVI-Point of Presence
NFVO	Network Function Virtualisation Orchestrator
NG-OSS	Next Generation Operations Supporting System
NIC	Network Interface Cards
NIP	Network Infrastructure Provider
NOC	Network Operators Council
NS	Network Service
NSD	Network Service Descriptor
NV	Network Virtualization
NVGRE	Network Virtualization using Generic Routing Encapsulation
OAN	Open Access Network
OCCI	Open Cloud Computing Interface
ONF	Open Networking Foundation
OPEX	Operational Expenditure
OPN	Open Platform for NFV
OS	Operating System
OSI	Open Systems Interconnection
OSS	Operations Supporting System

PF	Physical Function
PNF	Physical Network Function
PoC	Proof of Concept
PC	Personal Computer
PER	Performance & Portability Best Practices
QPI	Quick Path Interconnect
QoS	Quality of Service
RAM	Random Access Memory
RAS	Reliability Availability and Serviceability
REST API	Representation State Transfer API
RFC	Request for Comments
RPC	Remote Procedure Call
RTP	Real Time Protocol
SAN	Storage Area Network
SBC	Session Border Controller
SDN	Software-Defined Networking
SDO	Standards Development Organisation
SG13	Study Group 13
SLA	Service Level Agreement
SNMP	Simple Network Management Protocol
SOTA	State-Of-The-Art
SP	Service Provider
SR-IOV	Single Root I/O Virtualisation
SSD	Solid-state-disk
STP	Spanning Tree Protocol
STT	Stateless Transport Tunnelling
SW	Software
SWA	Software Architecture
ToR	Terms of Reference
ToR	Top of Rack
TMF	TeleManagement Forum

TNM	Transport Network Manager
TR	Technical Report
TS	Technical Standard
TSC	Technical Steering Committee
T-NOVA	Network Functions as-a-Service over Virtualised Infrastructures
UC	Use Case
UML	Unified Modelling Language
VEB	Virtual Edge Bridge
VEPA	Virtual Ethernet Port Aggregator
VIM	Virtualised Infrastructure Manager
VL	Virtual Link
VLD	Virtual Link Descriptor
VLAN	Virtual Local Area Network
VM	Virtual Machine
VMM	Virtual Machine Manager
VMX	Virtual Machine Extension
VN	Virtual Network
VNF	Virtual Network Function
VNFC	Virtual Network Function Component
VFND	Virtual Network Function Descriptor
VNFFG	Virtual Network Function Fowarding Graph
VNFFGD	Virtual Network Function Fowarding Graph Descriptor
VNFM	Virtual Network Function Manager
VRF	Virtual Routing and Forwarding
VPN	Virtual Private Network
VSAN	Virtual Storage Area Network
vNIC	Virtual Network Interface Cards
VPN	Virtual Private Network
VTN	Virtual Tenant Network
WAN	Wide Area Network
WG	Working Group

WP	Work Package
WP	Working Procedures
XML	Extended Markup Language
ZOOM	Zero-touch Orchestration, Operations & Management