Toward a Holistic Federated Future Internet Experimentation Environment: The Experience of NOVI Research and Experimentation

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INTRODUCTION

Over the last decade virtualization has been a promising technology for overcoming the ossification of the Internet, by enabling experimentation on new paradigms and architectures for the Future Internet (FI). Essentially, it allows for a large set of interesting experiments to run simultaneously over FI experimental facilities, pushing new ideas further into real implementations and deployment. The NOVI (Networking innovations Over Virtualized Infrastructures)1 vision stems from the realization that combining virtualized computing and network infrastructures into a federated framework will drive further the adoption of FI experimental facilities for large-scale and diverse FI experimentation. According to the NOVI concept, federated FI experimental infrastructures should cater to dynamic provisioning, control, and monitoring of user-defined baskets (slices) of virtual resources drawn from loosely coupled, dissimilar, administrative domains.

The NOVI framework provides a modular data, control, and management plane architecture, validated within an integrated experimental prototype, mounted on interconnected FI experimental facilities. This involves the implementation of early prototypes of methods, algorithms, and information models that enable users to seamlessly use virtualized resources within the federation of heterogeneous research testbeds. This federated environment needs to be managed and configured within a stitched substrate, in order to allow for efficient and dynamic instantiation of resources across administrative domains, as demonstrated for Cloud computing resources by the Reservoir2 FP7 project. In this article we report NOVI’s contributions on open issues related to federated virtual infrastructures at the data, control, and management planes. These challenges are summarized in the following.

Information Model: In order to facilitate deployment of slices over federated FI experimental facilities, the use of an information model (IM) is required, that will provide a common vocabulary of concepts and capabilities that exist...
within such a federation. An IM as such should support [1]:

- Virtualization concepts to cater to virtualized resources (e.g., virtual machines, logical routers).
- Vendor independence as virtualized infrastructures employ hardware and software from different manufacturers.
- Monitoring and measurement concepts, so that monitored metrics (e.g., CPU utilization, one-way delay, available bandwidth) and corresponding units are uniformly specified across the federation.
- Support of management policies for the federated environment.

The definition of the NOVI ontology-based IM has been guided by these requirements in order to enable policy-based provisioning, monitoring, and lifecycle management of virtualized resources from the federated environment.

- Monitoring of the federated experimental facilities is a primary requirement, both for the experimenters that need to monitor the state of their slices/virtual resources as well as for control and management plane services that require monitoring information for decision-making. However, dealing with multi-domain nature of the environment it is not a trivial task to provide federated monitoring functionalities. The heterogeneity of the federated networks (including network/computing elements and monitoring tools) poses a major challenge. The NOVI Monitoring Framework enables interoperability of monitoring tools operating within member platforms of the federation of heterogeneous testbeds catering to monitoring at the physical as well as the virtual level.

- Resource discovery and mapping/allocation are fundamental steps in the process of creating virtual networks (VNs). The problem of mapping VNs to specific nodes and links in a multi-domain substrate network is commonly referred to as the virtual network embedding (VNE) problem or the topology embedding problem. The general embedding problem is computationally intractable. Resource discovery has attracted less research attention than resource allocation [2], despite its large impact on the actual allocation process. The NOVI federation is empowered with a semantic-based, distributed resource discovery and mapping framework; semantic web techniques were exploited to facilitate interoperability in the federation of heterogeneous testbeds, while a hierarchical framework has been prototyped for distributed allocation of physical to virtual resources across the federated substrate.

- Network stitching of virtual resources belonging in different domains should provide at minimum Layer 2/Layer 3 connectivity. The problem becomes more challenging with the existence of heterogeneous network resources that need to be managed and configured within the federated environment. Appropriate stitching must be utilized allowing for transparent data-plane connectivity across dissimilar platforms involved in multi-domain slices. Toward that end, the NOVI stitching scheme, based on Ethernet over GRE, introduces a programmable switch called NSwitch based on the Open vSwitch3 implementation. Note that a similar approach was recently demonstrated by Hayashi et al.4

- Policy-based management needs to be revisited, in order to address additional requirements posed by the federated environment, such as inter-domain policies that define inter-platform duties. NOVI facilitates policy-based management of federated FI experimental infrastructures, employing a flexible engineering approach to establish relations between the testbed providers. The NOVI policy service enforces domain-independent management policies for both intra-domain and inter-domain management purposes, where each member-platform of a NOVI federation is considered as a separate domain.

NOVI builds on top of the Slice-Based Federation Architecture (SFA5). The SFA federation approach grew primarily out of the PlanetLab experience, and has been widely adopted in the NSF GENI program, as the basis for its GENI API [3]. SFA was also adopted in major European testbed federation initiatives, supported by the EU FIRE Unit.6 SFA defines the notion of a slice, which is a container abstraction for all the resources in a given experiment [4]. Researchers are associated with slices and use SFA tools to discover and include resources in their slice. NOVI complements SFA by providing the necessary abstraction of resources (e.g., by introducing an ontology based IM) that enables advanced context aware services (e.g., monitoring of federated slices, distributed semantic-based resource discovery, and intelligent resource mapping service, management policies for both intra-domain and inter-domain management purposes, etc.), and a uniform data plane stitching mechanism. These value-added services, validated within the NOVI prototype implementation, are described in the following sections.

THE NOVI FEDERATION CONCEPT AND PROTOTYPE IMPLEMENTATION

The NOVI data and control and management architecture consists of three different layers, as depicted in Fig. 1. NOVI builds on top of the Slice-Based Federation Architecture and Prototype Implementation (FIRE)

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3 Open vSwitch, http://www.openvswitch.org
6 Future Internet Research and Experimentation (FIRE), http://ict-fire.eu/
7 GÉANT — http://www.geant.net/
established on demand, between virtual resources from different platforms that belong to the same slice. This is accomplished by means of Ethernet over GRE tunneling between PlanetLab nodes (via the NSwitch driver) and the NSwitch instance that is part of the FEDERICA testbed, allowing for native Ethernet transport within the FEDERICA domain.

At the middle layer components are used to provide basic control and management federation capabilities across platforms. In the figure, we depict implementation choices provided by the SFA, for example, cross-domain authentication via synchronized registries and user-specified slice operations; creation, instantiation, deletion; and so on.

The top layer, referred to as the NOVI service layer (SL), implements NOVI control and management services that offer advanced capabilities to the federation users, consistent with challenges summarized above. These are:

- The resource information service (RIS) responsible for context-aware resource discovery across the federation.
- The intelligent resource mapping service (IRM), mapping user requests for virtual resources to the federated physical substrate topologies.
- The policy service used to provide the functionality of a policy-based management system.
- The NOVI monitoring service, implementing the NOVI monitoring framework, that allows NOVI SL services as well as experimenters to retrieve monitoring information on physical and/or virtual resources across the federation.
- The NSwitch service communicating with NSwitch drivers deployed on platform resources, pushing configuration options based on the slice request.

The above intelligent services communicate with the underlying infrastructures via a request handler (RH) service that provides the NOVI SL with an abstraction of platform characteristics. In addition, the RH provides a generic implementation of an SFA request handler service, which is used to invoke the appropriate operations to the corresponding SFA APIs. Via the NOVI API, on top of the NOVI SL, experimenters can authenticate themselves, submit slice requests, view resources available at the federation, and monitor virtual resources. A small screenshot of the NOVI GUI is also shown in the figure, which allows users to formulate requests and submit them through the NOVI API. The NOVI SL integrated prototype implementation was based on the Open Service Gateway initiative (OSGi) framework via an enterprise service bus (ESB). Services are implemented as OSGi bundles, loadable collections of classes and configuration files, thus providing modularity to the NOVI SL.

Each platform in the federation deploys a separate NSwitch, SFA, and NOVI SL. In what follows, we discuss functional and design specifications of architectural components within the above layers.

**NOVI ARCHITECTURAL COMPONENTS**

**INFORMATION MODEL FOR FEDERATING VIRTUALIZED INFRASTRUCTURES**

The NOVI IM and the corresponding data models have a two-fold objective: to support the modeling abstractions to cater to a federation of the FEDERICA and PlanetLab platforms in the NOVI’s testbed; and to include the necessary...
The NOVI IM uses a semantic web approach and it is complemented by data models that use the Web Ontology Language (OWL). This choice has been driven by the desire to support reasoning and context awareness, which in turn allow NOVI to create efficient and complex services with resources available within the federation. Existing IMs do not fulfill all the expected requirements and cannot support the description of shared resources and services within a federation of heterogeneous platforms. We decided nonetheless to use the ontologies and experiences from some of the other efforts to better align the NOVI model in this ecosystem. Existing models that provide direct inputs into the development of the NOVI IM are shown in Fig. 2. Among them, the Network Markup Language (NML)\(^9\) and Network Description Language (NDL)\(^10\) provided strong influence in specifying the NOVI resource ontology.

The NOVI IM consists of three distinct yet related ontologies, thus facilitating the adoption of its modules by communities interested in specific aspects. Specifically, the NOVI IM defines a resource ontology, a monitoring ontology, and a policy ontology.

The resource ontology specifies the concepts and methods to describe the resources offered by FI platforms and how they are connected together in a federated environment. This ontology provides the basis for topology and request descriptions and the terminology for describing physical nodes, virtual nodes, virtual topologies, and so on. The monitoring ontology extends the resource ontology with descriptions of the concepts and methods of monitoring operations, for example, details about monitoring tools, their relationship to resources, and types of measurements that can be gathered. Finally, the policy ontology extends the resource ontology with descriptions of the concepts and methods enabling the management and execution of policies defined within member platforms of a NOVI federation. An extended description of the IM is provided in [1].

### Semantic-Based Resource Discovery and Mapping Service

Resource discovery enables locating and retrieving information across the federated virtualized substrate network in a decentralized way via a scalable query process. The NOVI resource information service (RIS) acts as a single point of contact within the SL for other services to acquire information about the status of virtual and substrate resources. To that end, it interacts with the request handler to communicate with the underlying platform, to reserve resources and to obtain the resource advertisements. It uses the monitoring service to query on the availability and the status of the resources and the policy service to obtain information related to the access rights or the users.

The RIS exploits the features of the NOVI IM to improve the precision of resource discovery and to apply reasoning when selecting resources and services. The RIS copes with heterogeneity by leveraging the vocabularies provided by NOVI’s IM. RIS uses a database engine based on semantic web technologies where the data is stored as RDF triples. An extended description of the RIS is provided in [2].

The intelligent resource mapping (IRM) service is responsible for mapping user requests for virtual topologies to the federated physical substrate. The IRM service gathers information from the RIS regarding substrate resources availability, utilization, and access control. The need for efficient sharing of virtualized infrastructures within NOVI has led to the introduction of novel techniques related to the inter-domain VNE problem, as reported in [2, 7, 8]. In order to solve the problem, the IRM service breaks it down to the following phases.

#### The VN Partitioning Phase

During this phase, user requests for VNs are split by a local instance of the IRM service into partial requests, which are apportioned to the platforms-members of the federation in a cost-efficient way. Request splitting is based on appropriately defined resource provisioning costs, as reported in [8]. To deal with the inherent complexity and scalability of the VN partitioning problem, a request partitioning algorithm with the use of iterated local search meta-heuristic has been introduced in [8].

#### The Intra-Domain VNE Mapping Phase

For a given VN partition, this phase provides an assignment of user VN requests to specific substrate nodes and links within a single administrative domain. In other words, VN embedding sub-problems are formulated and executed on

\(^9\) Network Mark-up Language Working Group (NML-WG), http://www.omg.org/ogf/group=xmlwg

\(^10\) Network Description Language (NDL), http://www.ontology.org/ndl
Each IRM service of the platform-members selected at the VN partitioning phase, resulting into sub-optimal allocation of virtual resources within the federated substrate. Resource mapping within the context of NOVI depends on the characteristics of the testbed and the requested resources and constraints imposed by the user. Therefore, in order to map VN requests on the FEDERICA substrate, we followed the methodology introduced in [7] denoted as networked cloud mapping, while for PlanetLab a modified version of the semantic based approach for VN mapping presented in [2] has been adopted.

**NOVI Monitoring Framework**

A key component of NOVI’s control and management plane is the monitoring service (MS), responsible for both substrate and slice monitoring. In the former, monitoring is performed on the physical substrate resources (physical hosts, links, paths, etc.), while in the latter monitoring is performed on slices composed of virtualized resources allocated to a user. The NOVI experiments use diverse monitoring tools deployed within the federated infrastructures, leading to two challenges:

- Handling the monitoring tools in a common way.
- Harmonizing the measurement data produced by the underlying tools.

To this end, we developed a generic monitoring ontology (MO), enabling us to describe, parameterize, and use various active and passive monitoring tools installed within the different federated platforms.

Depending on the usage scenario, the MS can support two main tasks. The first task is triggered by RIS prior to resource allocation in order to collect monitoring and measurement information from the substrate, which can be used by IRM to ensure that the constraints defined in the resource requests are satisfied. The second task is used after the resource reservation process, to perform slice monitoring for diagnostic purposes, that is, checking the current status of a given set of virtual resources across the NOVI federation. MS supports advanced monitoring tools that enable users to measure key performance metrics of the network (e.g. one-way delay, round-trip time, packet loss, available bandwidth). Testbed-specific configuration ontologies [1] are used to describe the testbed-specific implementation of metrics to be monitored, enabling MS to automatically instantiate monitoring tasks in a federated environment.

In order to help users with slice monitoring, we developed a graphical front-end. For example, the experimenter can define a resource-specific measurement during an experiment in their virtual topology as depicted in Fig. 3, by clicking on the selected resource.

Measurements of selected metrics can be managed individually, based on user-specified monitoring tasks that can be started, stopped, or removed from the task list of the GUI. Measurements can be viewed via the GUI, uploaded to a database within the resource information service, or even trigger event-condition-action policies in the policy service (see section below). Figure 4 illustrates that the user can retrieve real-time monitoring information (e.g. memory utilization) through the monitoring GUI.

**NOVI Policy-Based Management System**

The Policy Service (PS) is used in NOVI as a management service controlled by policies, following the Policy-based Network Management (PBNM) [9] approach and building upon the Ponder2 policy framework. Using the abstractions of the NOVI IM, we define and enforce domain-independent management policies for both intra-domain and inter-domain management purposes, considering as a domain a member platform of a NOVI federation, that is, one domain could be the PlanetLab platform while another domain could be the FEDERICA platform.

Intra-domain policies are specified in the Ponder2 policy language. There is support for:

- **Access control policies** that specify which rights users have on specific resources.
- **Event-condition-action policies** enforcing management actions upon events indicating failures or performance degradation, where events are received by the MS.
- **Role-based access control (RBAC) policies** where the notion of role provides a semantically grouping of policies with a common subject, generally pertaining to a position within a platform-member of a NOVI federation, for example, user, administrator, or principal investigator in the PlanetLab experimental platform.

Inter-domain policies, defined in the form of Ponder2 mission policies, denote the duties of the remote domain in terms of obligations it must enforce, i.e. the management obligations that a platform must fulfill against another platform in a NOVI federation. These obligation policies are written in terms of the corresponding interfaces for each domain, denoting events, notifications, local actions, and remote actions.

**Events**: These refer to a specific cross-domain operation and can trigger its policies. They are the events that can be received by the corresponding interface in order to perform the actions based on inter-domain policies.

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Notifications: These are events that the inter-domain policy can raise within either the local domain in which it has been loaded, or a remote domain. They can trigger actions based on other policies that exist in each platform.

Local actions: These may be invoked by the inter-domain policies in the domain in which it has been loaded. They may be management actions on local physical or virtual resources. They are expressed as methods in the managed objects that represent each resource.

Remote Actions: These may be invoked by an inter-domain policy either when it is running locally or in a remote domain. They control and manage resources in a remote platform based on the agreement between domains.

NETWORK STITCHING
Assigning and using virtual resources in a federated environment requires configuration, management, and control of multi-domain VNs across an interconnecting substrate. Although federation architectures, such as SFA, are capable of providing a homogenized way of interaction between substituent domains, they do not explicitly deal with data-plane stitching that is the prerequisite for multi-domain operations. The problem becomes more challenging when dealing with widely heterogeneous network resources (e.g. virtual machines with different hypervisors, user-defined instances within dissimilar networking equipment). This loosely coupled environment needs to be managed and configured within a stitched substrate, across diverse networking technology domains.

NOVI’s network stitching approach was implemented by introducing the NOVI Switch (NSwitch) component, a software programmable switch, based on the Open vSwitch (OVS). The NSwitch distributed software complements NOVI’s federation architecture by providing a unified way of interaction between heterogeneous domains at the data-plane. It enables a virtual entity in one domain (e.g. PlanetLab) to be connected at protocol Layer 2 (L2) with another virtual entity in a remote domain (e.g. FEDERICA) taking into account concurrence, isolation, elasticity, and programmability aspects. This is achieved with the use of a specific implementation of a distributed component (NSwitch driver) per testbed.

Specifically, in order to map PlanetLab slivers into an L2 broadcast domain, we adopted an approach similar to the one developed within the VINI project in the U.S. that used an Ethernet over GRE (EGRE) mechanism to provide point-to-point virtual network capabilities to user configured virtual resources over the Internet. NOVI’s NSwitch driver at the PlanetLab testbed enhanced VINI’s capabilities by introducing the OVS software in PlanetLab’s host operating system, thus enabling point-to-multipoint virtual links. Inside the FEDERICA domain, L2 data plane connectivity is provided by means of VLANs used by logical routers, switches, and VMs. The FEDERICA NSwitch driver relies on processes running in a border node with a public IP interface toward the PlanetLab side and a L2 connection toward the FEDERICA side. In essence, it performs the translation of EGRE key values of packets originating from PlanetLab slivers to VLAN IDs of FEDERICA resources (Fig. 5).

The distributed nature of the NSwitch mechanism does not introduce scalability limitations as far as the total number of concurrent network slices is concerned. The use of well known and widely supported network protocols (GRE tunnels and IEEE 802.1Q VLANs) ensures compatibility with a large number of FI infrastructures. Finally, the NSwitch does not introduce any significant performance degradation on end-to-end delays and bandwidth between virtual entities, compared to physical (substrate) entities [10].

NOVI SERVICE LAYER INTERFACES
The NOVI service layer (Fig. 1) supports two interfaces:

- A northbound interface (NOVI API) that provides the means to the user for interacting with the NOVI environment.
- A southbound interface (request handler) that is responsible for the communication of the NOVI service layer with the federated testbeds.

The NOVI API: Provides the entry point for interacting with the NOVI control and management services. It has three main tasks:
• It accepts requests from authenticated users containing resource requirements represented in the NOVI IM.
• It handles and delivers the request to the appropriate component within the NOVI service layer.
• It provides feedback to the users on how their request is handled before the experiment starts being executed in a combined NOVI slice.

The user can follow the communication between NOVI components in real-time and assess the status of their request via a Web-based GUI provided on top of the NOVI API. Thus, a user can define a virtual network topology along with the characteristics for requested resources. For every request, the GUI generates an OWL document based on the NOVI IM, which is sent to the NOVI API as an HTTP request.

The Request Handler (RH): Acts as an intermediate component between NOVI control and management services and the federated substrate. Its main purpose is to perform two types of operations:
• Delivering resource allocation requests to the underlying platforms.
• Enabling the RIS to retrieve information from testbeds that are members of a NOVI federation.

To this end, the NOVI IM specifications need to be translated into platform-specific specifications. In our testbed implementation, this entailed translating NOVI IM concepts into SFA RSpec based on the ProtoGENIv2 RSpec. Note that PlanetLab resource specifications are SFA enabled. However, in the case of FEDERICA, several extensions had to be made for SFA compliance of network-specific resources, for example, logical routers. Via this translation mechanism, the RH enables users with a unified method to create, update, and delete resources of his/her slice.

Scalability Issues
NOVI provides methods and tools to federate heterogeneous FI infrastructures. Experimental testbeds can be added to and removed dynamically from the NOVI innovation cloud. These testbeds are managed by separate, yet interworking providers that can also add/remove resources in each underlying substrate dynamically. The NOVI SL should be able to leverage the addition of extra resources and testbeds. Therefore, we investigated key scalability issues of the NOVI framework such as the scalability of the inter-domain topology embedding methodology used in the NOVI framework.

Large Scale Topologies: We have evaluated experiments requesting interconnected topologies of growing sets of resources per request with regards to VN partitioning. The evaluation results are reported in [8] and indicate that the implemented approach effectively addresses time performance/scalability issues for large incoming requests (less than three seconds for a partial mesh VN comprised of 350 nodes). Partitioning time increases linearly with the number of requested nodes at less than three percent increase in the partitioning cost compared to an exact algorithm.
**Horizontal Scalability**: The impact of the addition/removal of testbeds within the NOVI federation was also evaluated in [8] with regards to the topology embedding approach. Two sets of five and 10 distinct infrastructure providers have been tested, signifying the effectiveness of the implemented approach in a multi-domain environment (less than two percent increase in the partitioning cost compared to an exact approach).

Regarding the addition/removal of resources in each underlying platform (vertical scalability), the performance of the resource allocation process highly depends on the specific resource mapping algorithm being used by each provider, thus it is outside the realm of NOVI.

**DEMONSTRATIONS AND USAGE SCENARIONS**

The NOVI prototype was demonstrated in two flagship European Union events, namely FIA-2011 (Future Internet Assembly, Poznan, Poland, October 2011) and FIA-2012 (Future Internet Assembly, Aalborg, Denmark, May 2012). In the former, the working prototype of the NOVI framework was demonstrated, while the latter demonstrated the creation of two concurrent interconnected slices utilizing specific resources from both PlanetLab and FEDERICA platforms, as depicted in Fig. 6.

The NOVI testbed was used to study network performance aspects requiring a diversity of network characteristics (QoS constraints). For example, we conducted a video streaming experiment across FEDERICA and PlanetLab platforms. To conduct this experiment, a VLC video server was installed in a FEDERICA VM located within a FEDERICA host, while several video clients were launched in both FEDERICA VMs and PlanetLab hosts. During the execution of the experiment we obtained QoS-related statistics with the use of the VLC player software in the client side. The results showed that FEDERICA users perceived considerably better performance than PlanetLab clients, as the video was produced from a QoS-enabled environment (FEDERICA) and routed to clients in a non QoS-enabled environment (PlanetLab) over the best-effort public Internet. This behavior highlights the ability of the NOVI platform to cater to user-driven experimentation in diverse interconnected networking environments, which may arise as a requirement in federated usage scenarios.

Finally, the NOVI federation framework can be exploited by FI researchers, and it can also be used as an academic tool for graduate/undergraduate courses. As a proof of concept, academic NOVI participants (NTUA, ELTE, UvA, and UPC) created NOVI lab exercises that were delivered to more than 100 students in the fall 2012 semester, as part of their academic training. The lab exercises consisted of slice creation, update and deletion operations on the NOVI integrated testbed, with the use of the NOVI GUI. Instructions for three types of slices were instantiated by the students via unbound, bound, and partially bound requests.

**CONCLUSION**

The NOVI framework specifies a distributed data, control, and management plane federation architecture that respects individual domain mechanisms and can be applied on stitched heterogeneous FI testbeds. As a proof of concept, the NOVI framework has been developed and successfully applied to federate a private PlanetLab domain with resources interconnected over the best-effort Internet and FEDERICA, an infrastructure of virtual resources interconnected via dedicated L2 networking facilities of European NRENs and GÉANT. NOVI’s prototyped architecture demonstrated the applicability and validity of the framework on extending virtualization across dissimilar platforms, resources (i.e. computing and networking), and protocols.

Further development and adoption of the NOVI platform can empower smart, user-controlled configurations of virtual resources homed in dissimilar yet stitched communities. NOVI participants are active players in FI research and innovation, both academic and industrial. Their extensive experimentation on the NOVI testbed demonstrated the capabilities and limitations of individual and federated platforms. This pre-normative work could contribute to bridging FI experimental federations with interconnected cloud architectures and interworked public/private data-centers, adding value via its intelligent services, IMs, and composite algorithms.

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