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# Deliverable D14.1 Future Services PoCs: Implementation and Dissemination

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**Abstract**
GN4-1 JRA2 has developed several Software Defined Networking (SDN)-enabled use cases to address future network service capabilities and operational models for GÉANT and the NRENs. This deliverable constitutes the final report of the JRA2 activity, with a focus on implementation of the five, SDN-based proofs of concept developed by the activity, their demonstrations, dissemination activities, feedback and outlook.

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# Executive Summary

Advanced applications/use-cases from the R&E community, as well as requirements for infrastructure cost-efficiency and more efficient operations call upon GÉANT and the GN4-1 project NRENs to overcome traditional service provisioning and operational models. Software Defined Networking (SDN) has made it possible to control the network through software and handle traffic dynamically and in fine granularity. During the course of GN4-1, the Joint Research Activity 2 (JRA2) team has developed several Software Defined Networking (SDN)-enabled use cases to address relevant expectations.

The JRA2 work has focussed on:

- SDN-based use-case requirements and functionality specification for future network service capabilities (Task 1).
- SDN controller evaluation and software development (SDN applications, controller enhancements and data plane drivers' implementation in Task 2).
- A number of proof-of-concept (PoC) deployments and associated dissemination activities (Task 3).

The PoCs are intended to serve as a basis of added-value, future network services and capabilities for the GÉANT backbone and the NRENs.

The use cases have been grouped in three main categories, based on their domain of applicability:

- R&E Network Service Provider:
  - SDN-based BoD (Bandwidth on Demand) with advanced path computation capabilities.
  - SDN IP / SDX (Software Defined Internet Exchange) at Layers 3 & 2.
  - Transport SDN.
- R&E Infrastructure and Network Service Provider:
  - Infrastructure and Network as a Service (INaaS).
- Last mile/campus:
  - Network in the Campus (NitC).

This deliverable constitutes the final report of JRA2 with a focus on the SDN-based PoCs and their demonstrations. For each of the proposed use cases, the report includes the scope, objectives and proposed scenarios, as well as the achievements and findings of the corresponding PoC deployment. Additionally, the document reports on the benefits of each PoC introduced for operators (GÉANT/NRENs) and the users, as well as the lessons learnt and feedback received while working with

SDN-enabled hardware (Corsa white-boxes, Infinera DTX-N, legacy equipment) and global, community-supported SDN software controllers (ONOS and OpenDaylight) [ONOS], [OpenDaylight].

Overall, the work on SDN-enabled, future network service capabilities during GN4-1 JRA2 has resulted in:

- Significant knowledge development for the GÉANT team software and network engineers as well as operations teams.
- Significant insight on community-supported SDN controller frameworks.
- First-hand assessment of SDN support in legacy and white box hardware.
- Vendor collaboration and collaborative developments to deliver SDN capabilities.
- Contribution to the core code of ONOS controller with functionality relevant for backbone service providers and campus providers.
- Visibility of GÉANT SDN activities and evolution path.

The next steps for the use cases are also identified in Section 4 of this document. Leveraging upon the expertise, codebase and hardware assessment achieved by the GÉANT team, is the use cases' development and deployment in pre-production environments for further validation and testing, with the ultimate goal being their deployment as service capabilities in GÉANT/NREN operational environments.

# 1 Introduction

Advanced applications/use-cases from the R&E community, as well as requirements for infrastructure cost-efficiency and more efficient operations call upon GÉANT and the GN4-1 project NRENs to overcome traditional service provisioning and operational models. Expectations include:

- Multi-tenancy, multi-point network fabrics, e.g. for interconnecting clouds.
- Programmable traffic processing/monitoring for troubleshooting, network monitoring, application performance tuning or security purposes.
- User-empowered configuration and provisioning (in co-existence with core management and operations).
- Traffic engineering controls to serve data transfers (shortest path, optimal path, application-to-network, interaction-based optimisations).

The JRA2 team has developed several Software Defined Networking (SDN)-enabled use cases to address some of the aforementioned expectations. The use cases have been grouped into three main categories, based on their domain of applicability:

- R&E Network Service Provider.
  - SDN-based BoD (Bandwidth on Demand) with advanced path computation capabilities (Section 2.2)
  - SDN IP / SDX (Software Defined Internet Exchange) at Layers 3 & 2 (Section 2.3).
  - Transport SDN (Section 2.4).
- R&E Infrastructure and Network Service Provider.
  - Infrastructure and Network as a Service (INaaS) (Section 2.5).
- Last mile/campus.
  - Network in the Campus (NitC) (Section 2.6).

For a comprehensive overview of these use cases, the reader can turn to [JRA2UC].

The work done by JRA2 on SDN-based use-case requirements and requirements/functionality specification for future network services ([JRA2UC], [JRA2BOD], [JRA2NITC], [JRA2INAAS], [JRA2TRANS], [JRA2IPSDX] (Task 1), as well as SDN-controller evaluation and software development (SDN applications, controller enhancements and data plane driver implementation in Task 2) has materialised into a number of proof-of-concept (PoC) deployments and associated dissemination activities.

Collaboration with vendors has been key to delivering many of the JRA2 PoCs. JRA2 engaged with hardware manufactures Corsa and Infinera, as well as ONOS [CORSA], [INFINERA], [ONOS] and

OpenDaylight (ODL)-controller framework developers and communities. This led to the establishment of a pipeline of pre-commercial available technologies for assessment in lab environments (see Appendix B):

- JRA2 has been working with Corsa to develop the low-level OpenFlow (OF) pipeline, which enables Corsa hardware to support the SDN use cases defined by JRA2 [JRA2UC]. The team has not only provided the requirements and input for software but also the hardware features. The next release of Corsa hardware includes several of those features.
- Similarly, JRA2 has been working with the GÉANT network's current optical platform provider, Infinera, to develop an application on top of the ONOS controller, which directly interacts with the Infinera OTN card to create, delete and modify circuits on the transport layer (Layer 1). This paves the way for multi-layer SDN PCE in future.
- JRA2 is collaborating closely with ON.Lab (the organisation coordinating the development of ONOS controller) to ensure that the Layer 3 requirements of the SDN IP/SDX are supported by ONOS, with direct contributions to the core ONOS code.

This deliverable reports on the implementation of the proposed future services PoCs – one for each of the five use cases mentioned above, as well as the relevant testing activity conducted by JRA2 Task 3 and the dissemination events in which the PoCs have been or are planned to be presented. It is envisaged that the PoCs will lead to production service capabilities within the next two years.

The future service PoCs are presented in detail in Section 2. For each of the proposed use cases, the report includes the scope, objectives and proposed scenarios, as well as the achievements and findings of the deployment of the corresponding PoC. The document also reports the benefits that each PoC introduced for operators (GÉANT/NRENs) and inter-connected R&E institutions, as well as end users, the lessons learnt and feedback received while working with SDN-enabled hardware (Corsa white-boxes, INFINERA DTX-N, legacy equipment) and global community-supported SDN software controllers (ONOS and OpenDaylight). Complementary to this information are the outputs of Milestone M14.1:*UC Requirements to Features Matrix* (available from ([JRA2BOD], [JRA2NITC], [JRA2INAAS], [JRA2TRANS], [JRA2IPSDX]), where the detailed analysis of use case requirements – per-use -case – is provided, and Milestone M14.2: *Future Network Services Specification* (available from [JRA2UC]), where the use cases are presented.
Section 4 provides the details of the PoC dissemination and scientific publication activities carried out by the activity. The document concludes with overall results and proposed next steps.

Additional information on the testing methodology and the testbed infrastructures used to validate the PoCs can be found at the end of the document in Appendices. Appendix A, describes the testing methodology, test plan and all the required steps taken to ensure that the software and hardware components of each PoC have met the relevant requirements and PoC design. Appendix B provides insight to the testbed facilities used. Appendices C and D provide more details on selected PoC implementations, testing and results.

This deliverable constitutes the final report of the JRA2 activity, with a focus on the SDN-based services PoCs and their demonstrations. The PoCs are intended to serve as a reference of added-value services and capabilities, which leverage SDN technologies to provide the GÉANT backbone and REN community with special-purpose networking functionality and offer a fertile environment for the development and delivery of the next generation REN services and operations.

# 2 Future Services Proofs of Concept

## 2.1 Introduction to the Use Cases

In this section, an overview of the proposed SDN use cases, as well as their value in the context of GÈANT/NREN environments is presented, based on the outcomes of JRA2's PoC.

Following the definition of the SDN use cases[1] and associated functionality requirements by JRA2 Task 1, the required software components were delivered by Task 2 and testing was conducted by Task 3. One PoC per use case was also implemented and demonstrated/disseminated by Task 3, in order to demonstrate the feasibility and potential of each use case. The ongoing coordination and feedback (an iterative process of specify–implement–test) across tasks has been crucial to enable the implementation of the SDN functionalities that match use case requirements and have enabled the delivery of the use-case PoCs. Figure 2.1 depicts the coordination among the tasks of the activity.

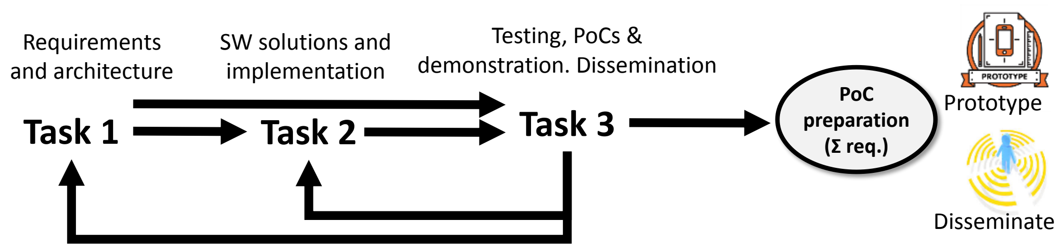

Requirements and architecture
SW solutions and implementation
Testing, PoCs & demonstration. Dissemination
Task 1
Task 2
Task 3
PoC preparation (Σ req.)
PROTOTYPE
Prototype
Disseminate

Figure 2.1: Activity lifecycle scheme

The following use-case PoCs have been implemented:

- SDN-based BoD (Bandwidth on Demand) with advanced path computation capabilities (Section 2.2).
- SDN IP / SDX at Layers 3 and 2 (Section 2.3).
- Transport SDN (Section 2.4).
- Infrastructure and Network as a Service (INaaS) (Section 2.5).
- Network in the Campus (NitC) (Section 2.6).

## 2.2 SDN-Based Bandwidth on Demand with Advanced Path Computation Capabilities Proof of Concept

### 2.2.1 Problem Statement and Objective

Bandwidth on Demand (BoD) services are already a reality in several RENs globally, including GÉANT partners, where AutoBAHN allows end-user to request multi-domain services with a guaranteed bandwidth during a period of time [AutoBAHN]. Similarly, ESnet offers On-demand Secure Circuits and

[1] Use case requirements: [JRA2BOD], [JRA2NITC], [JRA2INAAS], [JRA2TRANS], [JRA2IPSDX]),

Advance Reservation System (OSCARS) to its users, which adopts a Path Computation Element (PCE)-based architecture in order to compute the paths [OSCARS].

For instance, AutoBAHN provides the BoD service across multiple domains through the Network Service Interface – Connection Service (NSI-CS) v2 protocol [NSI]. Nevertheless, it currently does not support SDN domains. However, the NSI CS multi-domain protocol is technology agnostic. During GN3plus the possibility of using NSI CS to establish multi-domain BoD services involving OpenFlow 1.0 domains was demonstrated. The solution put forward by this use case is based on the DynPaC (Dynamic Path Computation) framework as the Network Resource Manager (NRM) of the SDN domains. [TNC_POC].

In such a scenario it is interesting to study the applicability of the DynPaC framework to provide BoD services in GÉANT. The possible benefits of this approach range from the reduction of operational costs to the enhancement of network resources' utilisation. SDN offers novel and powerful traffic engineering strategies, which are core in the case of advanced reservation systems such as the ones used for the provisioning of BoD services.

More specifically, there are two interesting aspects:

- Integration of the DynPaC framework as the domain manager of OpenFlow domains inside AutoBAHN. In this way AutoBAHN will be able to operate in OpenFlow domains, in addition to the IP, SDN and GE (Gigabit Ethernet) domains already supported.
- Enhancement of the current BoD service using SDN technologies. Deploying the DynPaC framework on top of an SDN controller (e.g. the OpenDaylight controller, the ONOS controller), provides the means to integrate new transport technologies through southbound plugins. ODL is able to operate on top of MPLS and GMPLS domains thanks to the PCEP (Path Computation Element Protocol) proposed in the PCE-based architecture. Therefore, adopting an SDN approach based on the ONOS controller will not only make it possible to include OpenFlow-capable domains to those offering BoD services, but also other SDN domains using NETCONF or PCEP.

Furthermore, the DynPaC framework provides a user friendly GUI which allows to request services just by selecting the end-points, the duration and the characterization parameters of the service. In addition, the DynPaC framework is able to handle the network state along the entire duration of the requested service allowing future service reservations.

### 2.2.2 Considerations and Limitations from Testing of Requirements

In the analysis of the SDN-based BoD use case, functional, non-functional and operational requirements were assigned priorities, and the network elements needed to fulfil the requirements were identified. Each requirement was evaluated against ONOS, OpenDaylight and DynPac features in order to select the most appropriate implementation platform. A detailed list of the requirement and their analysis is provided in [JRA2BOD].

Starting from the identified requirements, the JRA2 team has driven the required tests following the test strategy, as presented in Appendix A, to validate the requirements and the implemented software components and propose a PoC to demonstrate the added value of the SDN-based capabilities and the BoD use case. Summary information on testing is also provided in Appendix D.

Worthwhile aspects of the testing and proposition of the SDN-based BoD use case are presented in the following sections.

#### 2.2.2.1 *The Migration from ODL to ONOS*

During the DynPaC Open Call project, the DynPaC framework was implemented for the Open Daylight Hydrogen release. However, due to the massive architectural changes included in the newer Open Daylight Helium and Lithium releases, a migration of the DynPaC framework imposed a major adaptation of the code to new APIs and the new architecture.

After careful evaluation, it was concluded that the changes needed to update the DynPaC framework to a more recent version of the Open Daylight controller were similar to the changes needed to migrate the DynPaC framework to the ONOS controller. As a consequence, given that the ONOS controller was the preferred controller of most GN4-1 JRA2 use cases, and that it has been designed to be used by carrier grade service providers, it was decided to migrate the DynPaC framework from the already deprecated Open Daylight Hydrogen release to ONOS.

#### 2.2.2.2 *Introducing QoS with White Boxes*

One of the most critical requirements in this use case is the ability to enforce the required QoS constraints upon the network infrastructure. In order to be able to provide rate-limiting functionalities, it was decided to use the Corsa white boxes, which are pure OpenFlow 1.3 datapaths.

One of the main features of the Corsa white boxes is that multiple pipelines can be installed to satisfy each use case requirements. However, in order to be able to handle specific pipelines, the controller needs to be aware of how the different flow tables are interconnected, and which type of flow entries are allowed to be installed in each of them. This requires the use of specific drivers at the controller side, which for the SDN-based BoD use case, was provided by Corsa. In addition, Corsa representatives have been available to solve any problems related to the utilisation of the driver and they have provided quick response times to solve any identified bug.

#### 2.2.2.3 *The Implications of the Multi-Domain Aspect of the Use Case Solution*

In order to handle the multi-domain connections, the DynPaC framework has been extended with an NSI-CS compliant REST API and with an additional operational mode, called asynchronous operational mode, that allows an external entity, in this case the NSA, to control the lifecycle of each service reservation, which until now was performed entirely by the DynPaC framework.

### 2.2.3 Proof of Concept Scenario

The PoC scenario consists of two SDN domains, the first one located in the GÉANT Lab and the second one located in AMRES premises. These two domains are connected through the GÉANT BoD network, a non-SDN domain that uses the AutoBAHN provisioning tool to provide multi-domain BoD services. AutoBAHN also provides the Graphical User Interface (GUI) and Topology Service (TS) elements, for user interaction and topology advertisements, respectively.

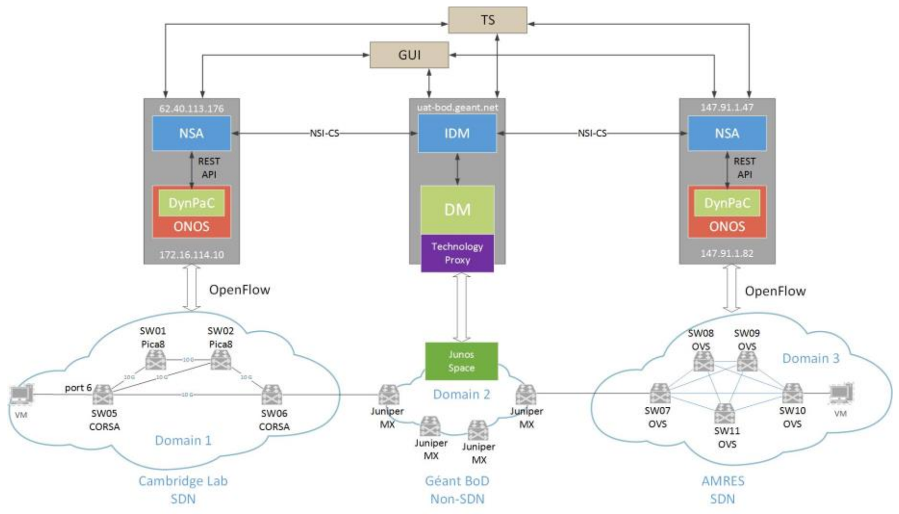


Figure 2.2: Logical view of the SDN-based BoD use case PoC

The detailed physical topology in GÉANT Lab is presented in Appendix B, Section B.1.2.

This PoC (Figure 2.2) shows bandwidth guaranteed service provisioning across three domains: The GÉANT Lab, GÉANT BoD and AMRES. It consists of the provisioning of two bandwidth-guaranteed services from AMRES to the GÉANT Lab setup, a *Gold* service with a guaranteed backup path and a *Regular* service without a guaranteed backup path. The Corsa switches are located at the edges of the GÉANT Lab domain to enforce rate limiting through their metering capabilities. The PoC can show how upon link failure, the *Gold* service is switched to its alternative path whereas the *Regular* service is not.

With this scenario the following aspects are demonstrated:

- Multi-domain BoD service provisioning, involving heterogeneous transport technologies (OpenFlow domain + MPLS domain).
- Rate-limiting enforcement at OpenFlow domains.
- Failure recovery mechanisms inside the OpenFlow BoD domain.

### 2.2.4 Proof of Concept Set-Up

For the PoC demonstration, a scenario to demonstrate the potential of the use case was defined: The delivery of bandwidth guaranteed, rate-limited, VLAN-based E-Line service across SDN enabled switches. E-Line provides a point-to-point Ethernet virtual circuit. The relevant workflow is presented in the following sections.

#### 2.2.4.1 *Step 1: Initialise ONOS+NSA VMs*

Start ONOS

- Check that ONOS is retrieving all the devices and links of the domain.
- Activate DynPaC application, wait until DynPaC has finished making the path pre-computations and the DynPaC topology information is shown.

Start NSA

- NSA should retrieve the STP information from DynPaC using the getEdgePortsVlan() function.
- The VLAN range is configured in DynPaC (500-509).
- Method getEdgePortsVlans() advertises VLANs set on interfaces configured on the edge ports.

#### 2.2.4.2 *Step 2: Check that there is no connectivity between source-VM and dst-VM*

Before requesting any service, demonstrate that no paths are allocated connecting the VMs.

- It is possible to access the ONOS GUI in any of the domains to demonstrate that no flows are installed in the devices.
- It is possible to show that the host client is not receiving any traffic (ping, Iperf, speedometer).

#### 2.2.4.3 *Step 3: Request the bandwidth-guaranteed Gold service*

The service will be identified by:

- VLAN
- Bandwidth (enough to guarantee High bandwidth delivery)
- Start time
- End time
- Golden (true)

Expected workflow

- Request the service using the AutoBAHN GUI.
- The service request will be received by the GÉANT Lab NSA. It will use allocateService(params...) to request the service and check if there are enough resources in the GÉANT Lab.
    - DynPaC receives the service allocation request. It marks the service with DynpacServiceState.REQUEST.
    - DynPaC will return a SUCCESS or ERROR message.
    - In case of SUCCESS, DynPaC will reserve the service and it will mark it as DynpacServiceState.RESERVE, in case of error it will just withdraw the request and it will not store anything in the databases.
- If the GÉANT Lab receives a SUCCESS, it will pass the request to GÉANT BoD NSA.
- If there are enough resources in the GÉANT BoD domain, the request will be passed to the AMRES NSA (repeat point 2 in this domain).
- Only if the request is successful in the three domains will it be accepted.
- When start time comes, the NSA will send a reserveCommit(serviceIdentifier) and DynPaC will send the OpenFlow messages to the switches to confirm the path and it will mark DynpacServiceState.ACTIVE.
- Once this happens in each domain, it should be possible to see the video in the VLC client.
- Once this happens in each domain, it should be possible to see the data injected from the Iperf client located in GÉANT Lab reaching the Iperf server located in AMRES, limited to the bandwidth specified in the service request.

#### 2.2.4.4 *Step 4. Request the bandwidth guaranteed Regular service*

The process should be the same as in Step3, but specifying Golden (false).

- Once this happens in each domain, we should be able to see the data injected from the Iperf client located in GÉANT Lab reaching the Iperf server located in AMRES, limited to the bandwidth specified in the service request.
- We should also see that the Iperf traffic generated for the *Regular* service does not affect the data transfer of the *Gold* service.

#### 2.2.4.5 *Step 5. Torn down the link connecting the Corsa switches*

- In order to see the resiliency mechanism in action, we should tear down the link (we will need to connect via SSH to one of the Corsas and shutdown the port with traffic).
- We should see how the Gold service is switched to a secondary path in the GÉANT Lab. The traffic from the Gold service will still reach the destination, but the data from the Regular service does not.

### 2.2.5 Findings and Conclusions

In brief, it can be concluded that the DynPaC framework is an excellent candidate to foster the migration to SDN-based BoD service provisioning. The PoC shows that it is possible to use the DynPaC framework as the NRM of OpenFlow domains, thanks to its compatibility with the NSI-CS protocol. As such, the SDN-based approach ensures that future BoD deployments can utilise a standards-based southbound interface (i.e. OpenFlow) to the data plane instead of custom-made technology specific proxies.

This solution does not only make possible the integration of OpenFlow domains in the wider multi-domain BoD solution, but it also enables a future migration to an SDN-based BoD service provisioning able to keep the strategic connections towards other NRENs.

Furthermore, thanks to the advanced traffic engineering mechanisms included in the DynPaC framework, such as the possibility to relocate flows into alternative paths to free enough resources to accept new service demands that otherwise would not be accepted, the service request acceptance ratio is improved. This means that the network resource utilisation is improved. Additionally, DynPaC also provides some failure recovery mechanisms not present in current BoD services.

All in all, this PoC demonstrates that a future migration to an SDN-based BoD solution is already a reality, and that the solution it is going to be able to expand current BoD service to a more automated, flexible and powerful one. This solution will benefit GÉANT as a service provider, by allowing the enhancement of network resources utilisation. It will also benefit current network operators, automating many of the tasks that are currently done manually. Most importantly, it will benefit end-users by increasing the service request acceptance ratio and by providing more robust services with failure recovery guarantees.

## 2.3 SDN IP/SDX at Layers 3 and 2 Proof of Concept

### 2.3.1 Problem Statement, Challenges and Objective

Some of the most important services that GÉANT provides to the NRENs and to the research and education (R&E) communities are connectivity services, such as GÉANT IP and GÉANT Open.

The GÉANT IP service has been designed to provide general purpose, IP transit services between European NRENs and other R&E partners and providers. Its core function is to provide a private service for IP traffic, separated from general-use Internet access. GÉANT Plus is a Layer 2 service that provides users with Ethernet Virtual Private Lines (EVPL) between endpoints on the access interfaces where the NRENs are located. GÉANT Open is a collaborative service to enable NRENs and researchers to interconnect with commercial teams and third-party organisations [GEANTOPEN]. GÉANT Open allows NRENs to arrange interconnections between external services and partners without the need for dedicated circuits. For example, NRENs can interconnect with cloud service providers or research labs to offer access for their users. The service uses shared switches onto which all users can connect their own circuits and then interconnect with any other participants in order to provide inter-organisation connectivity.

For service delivery purposes, GÉANT uses vendor-specific management software, a vendor-specific operating system (OS) on the routing platform and separate management software for the optical transport network. This has an impact on the general cost of operations and management of the GÉANT network. Moreover, it constitutes a barrier to innovation.

The SDN-IP/SDX use case addresses the "*SDN-isation*" of the above operational services. In literature, the introduction of SDN technologies in an Internet eXchange Point (IXP) is referred as SDX (Software Defined internet eXchange Point) [PEPELNJAK]. In the context of the work presented here, the notion of SDX is extended beyond exchange points (IXPs or Open eXchange Points (OXPs) to the GÉANT PoPs, with the introduction of L3-SDX and L2-SDX capabilities. L3-SDX and L2-SDX represent the fundamental building blocks of the augmented SDX. The former provides IP connectivity and routing between participating Autonomous Systems (ASs) through the BGP protocol. The latter allows users to create Layer 2 Virtual Circuits (VCs) between endpoints, which can be physical ports or VLAN interfaces. In practical terms, L3-SDX complements GÉANT IP, while L2-SDX represents the SDN version of GÉANT Plus and GÉANT Open.

In the current mode of service provisioning, there is a low level of automation. Service provisioning includes manual operations and the use of different management tools, resulting in provisioning lead times in the order of days. For example, in the context of GÉANT Open, the establishment of a service between two end points (ports or VLANs) entails contacting the OXP operator for the connection to be manually provisioned. This 'simple' operation may take several days to complete [SDXCONTROLLER]. The process is more complicated in cases of interconnected OXPs, where the service should be provisioned between access points in different exchange points. Service provisioning in such situations is a lengthy and cumbersome process. Considering the service lifecycle model and the practices described above, opportunities for improvements in GÉANT connectivity service delivery have been identified, based on SDN adoption. SDN presents an opportunity for the improvement of capability, flexibility and scalability of GÉANT network services as well as the automation of operational processes.

The GN4-1 JRA2 team (Task 1) has defined a set of minimal requirements that the SDN solution should satisfy in order to be implemented in GÉANT, which includes functional and operational characteristics of service, and is provided in detail in [JRA2IPSDX]. Based on these requirements, identification and analysis of available technological solutions and testing of the most suitable took place. Considering the options for an open source SDN-solution, there are several SDN-based controllers, applications and platforms that the team has identified as potentially relevant:

- SDX controller from Princeton NOISE (Network Operations and Internet Security) Lab [SDXCONTROLLER].
- SDX VANDERVECKEN LSR/router [SDXVANDERVECKEN].
- Project Cardigan [CARDIGAN].
- SDN-IP use case [SDN-IP].
- Atrium project [ATRIUM].
- ONOS project [ONOS].
- ODL platform [ODL].
- RYU SDN framework [RYU-SDN].

After a review of the state of the art of the identified solutions and comparing these to GÉANT requirements, the ONOS controller with its integrated SDN-IP application was chosen as a basis for the realisation of the SDN-IP/SDX use case. Building applications/services on the ONOS controller has been identified as an option that satisfies most of the requested functionalities. Based on preliminary test results, a list of missing features was identified, and a development plan for the design of a proof-of-concept (PoC) environment was developed.

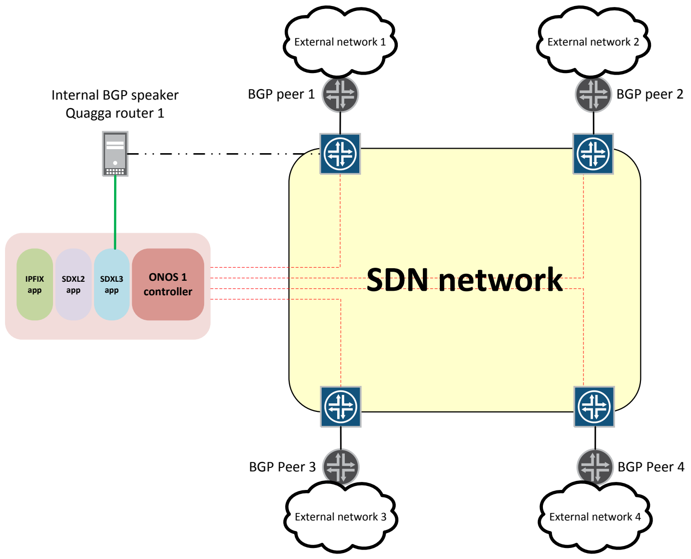


Figure 2.3: High-level architecture of the GÉANT SDX

Thus, the PoC is based on an ONOS SDN controller, ONOS SDN-IP application and the ONOS applications developed by the GN4-1 JRA2 team – SDXL3 and SDXL2.

As shown in Figure 2.3, the SDN-IP application allows an SDN network to connect to external networks (e.g. external Autonomous Systems (ASs), NRENs or Peer ASs, etc.) using the standard BGP. The SDXL3 application is an extension to the existing SDN-IP application already integrated in the ONOS controller. It provides features that enable an SDN network to be operated both as an IXP infrastructure and as a provider of an IP transit service to the external SDX users. Likewise, the SDXL2 application is a new ONOS application that allows the automated provisioning of Layer 2 tunnels between SDX connected users on physical Ethernet or VLAN-enabled interfaces.

The SDN technology is expected to bring many advantages to the GÉANT future network services delivery, including:

- **Vendor-agnostic environment**: the network should not be tied to specific vendor hardware, operating system or management software. Changing the hardware would not have an impact on how the network is managed and operated or what services could be delivered to the users. It is expected that the use of SDN technology will bring the convergence of network control from a range of different, vendor specific tools to a centralised multi-layer SDN controller.
- **Rapid application development**: capabilities to develop and enable new network applications with desired and appropriate features. SDN could enable possibilities for more advanced applications and features in the SDX that cannot be accomplished in the legacy IXP infrastructure or networks (e.g. application-specific peering, self-provisioning services, etc.).
- **Improved packet-processing rules**: provide direct control over packet-processing rules that match on multiple header fields and perform a variety of actions (e.g. possibility to allow each SDX member to apply a custom route selection process to select one or more best routes to each destination, which is contrary to a conventional BGP route-selection process, which selects a single best route to each destination, etc.).
- **Cost effectiveness**: providing the flexibility to introduce more cost-effective operations and management of the network.
- **Significant reduction in service provisioning time:** SDN applications and users can program the control and forwarding plane to achieve service provisioning without the manual intervention of operations teams.
- **Higher level of automation in provisioning of network services**: The existing (more expensive) IP routers may be replaced with WAN optimised white box switches.

### 2.3.2 Consideration and Imitations from Testing of Requirements

In this section, the limitations and the problems encountered during the testing of the requirements are described. Table 2.1: reports the list of the requirements that cannot be fully tested due to limitations or problems in the data plane and control plane, or due to the lack of available methodology and required tools for lab testing.

| Requirement | Limitations and problems encountered |
|---|---|
| L2 virtual circuit using same VLAN ID and MPLS encapsulation between two ports and different VLAN IDs and | ONOS-configured MPLS intents issues.[2] |

[2] At the time of writing, the JRA2 team is directly contributing to the ONOS codebase to address this issue.

| Requirement | Limitations and problems encountered |
|---|---|
| MPLS encapsulation between two ports. | |
| Support for topology changes. | Partial success. Success for links' addition. Due to lack of available hardware it is not tested in the case of switches' addition. |
| Number of IPv4 routes at BGP speaker control plane. | Requirement was not tested. Scalability directly depends on chosen solution for the internal BGP speaker implementation. |
| Number of IPv6 routes at BGP speaker control plane. | Requirement was not tested (planned for pilots in production environment). Scalability depends on chosen solution for the internal BGP speaker implementation. |
| Number of IPv4 routes supported – 5K, 20K, 550K. | Fail performance/scalability problem of Pica8 switches. Corsa switch testing pending.[3] |
| Support for different switch table pipelines. | Tested for Pica8 and HP switches. Not tested for Dell switches. Corsa switch testing pending.[5] |
| Number of flow rules supported by SDN switches. | Tested for Pica8 switches. Not tested for Dell switches. Corsa switch testing pending.[5] |
| Speed of flow installation. | Not tested in the GÉANT Lab. Testing results available ON.lab documentation [ONOSWP]. |
| Hierarchy of users and admin accounts. | Not tested. Further software development is needed. |
| GUI to configure the SDN-IP/SDXL3 features. | Not tested. Further software development is needed. |
| GUI to configure SDX-L2 features (VCs). | Development in progress at the moment of writing. Will be tested in the future. |
| Export of the switch interface counters from the controller. | Development in progress at the moment of writing. Will be tested in the future. |

[3] At the moment of writing, the next release of CORSA boxes, based on GÉANT requirements, is expected from the vendor for testing to be repeated.

| Requirement | Limitations and problems encountered |
|---|---|
| Export of the VC traffic statistics. | Development in progress at the moment of writing. Will be tested in the future. |

Table 2.1: Limitations and problems encountered

Some of the proposed and required features have been tested in an emulated, virtualised, software environment, in order to acknowledge the functional characteristics of an ONOS controller. Subsequently, a physical environment with hardware components in GÉANT Lab (see Appendix B) was configured, and testing continued in the Lab.

Testing in the GÉANT Lab environment was carried out based on the available SDN hardware switches that inter-work with ONOS controller and the SDN-IP/SDX use case scenario (Pica8 P3922 and Corsa 6410 switches). In particular, the capabilities of Corsa switches have been continuously developed in collaboration with the vendor in an evolutionary process, which is still underway at the moment of writing. Due to the capacity of available switches in the GÉANT Lab, relative to the number of supported flow rules, testing could not emulate the current GÉANT network environment (with more than 500,000 route prefixes in the routing table). Changes in the configuration of testing environment components resulted in unpredictable outcomes and issues with environment convergence. Also, testing has revealed some aspects of SDN technology immaturity (e.g. configuration changes resulting in unpredictable outcomes), which emphasise the need for interoperability testing between different software and hardware components.

In addition, the dynamics of testing were impacted by the dynamics of the development of new ONOS applications that are used by the SDN-IP/SDX use case, the development of the hardware data path components (Corsa 6410 switches) and their availability in the GÉANT Lab, availability of on-site support, etc.

### 2.3.3 Proof of Concept Scenario

Figure 2.3 shows the high-level architecture of the GÉANT Software Defined internet eXchange Point (SDX). The SDX assumes the exchange of IP prefix information between external BGP peers through the centralised route server component and traffic exchange following received routes. This is realised through the SDX L3 function, which is implemented in the architecture by the SDXL3 application. Moreover, it is possible to guarantee the private point-to-point exchange of traffic between SDX users. The SDX users can use the Layer 2 circuits for whatever reason, including private BGP peering. The SDXL2 application implements this functionality. Finally, the IPFIX application implements the OAM requirements. It guarantees access to all the statistics and exports this information to the northbound interface through the IPFIX protocol.

Using the L2 and L3 functions, the proposed SDX solution combines the features of IXP and OXP. The interfaces of the SDX users are partitioned using VLANs. Accessing the L3 SDX function is possible by using one or more VLANs, while other VLANs are used for direct connection to other SDX users, their interfaces and VLANs.

The SDX use-case deployment envisages scenarios where SDX external users (BGP peers) are connected over their BGP-enabled routers to the SDN OpenFlow-enabled network. These BGP peers establish EBGP sessions with dedicated, internal BGP speakers (Quagga routers, L3 function) or with external peers (L2 function) inside the SDN OpenFlow network. In the case of SDX L3, the external BGP peers advertise their IP prefixes to internal BGP speakers, which calculate the single best BGP route and advertise it to other SDX users (BGP peers). The internal BGP speakers establish IBGP sessions with instances of the SDXL3/SDN-IP application on ONOS controllers, advertising IP prefixes received from external BGP peers. Based on prefixes received from the internal BGP speakers, the primary SDN-IP/SDXL3 instance creates appropriate policy-based directives, 'intents', which the ONOS controller translates to flow rules and installs SDN OpenFlow switches. The SDN-IP/SDXL3 application provides the integration mechanism between the BGP protocol and ONOS controller flow rules. At the protocol level, the SDN-IP/SDXL3 application behaves as a regular IBGP peer that only receives prefixes from others (internal BGP speakers). From the external BGP peers' perspective, the SDN OpenFlow network appears as a single autonomous system that behaves as any traditional AS, providing IP transport to externally connected users (ASs)(Figure 2.4).

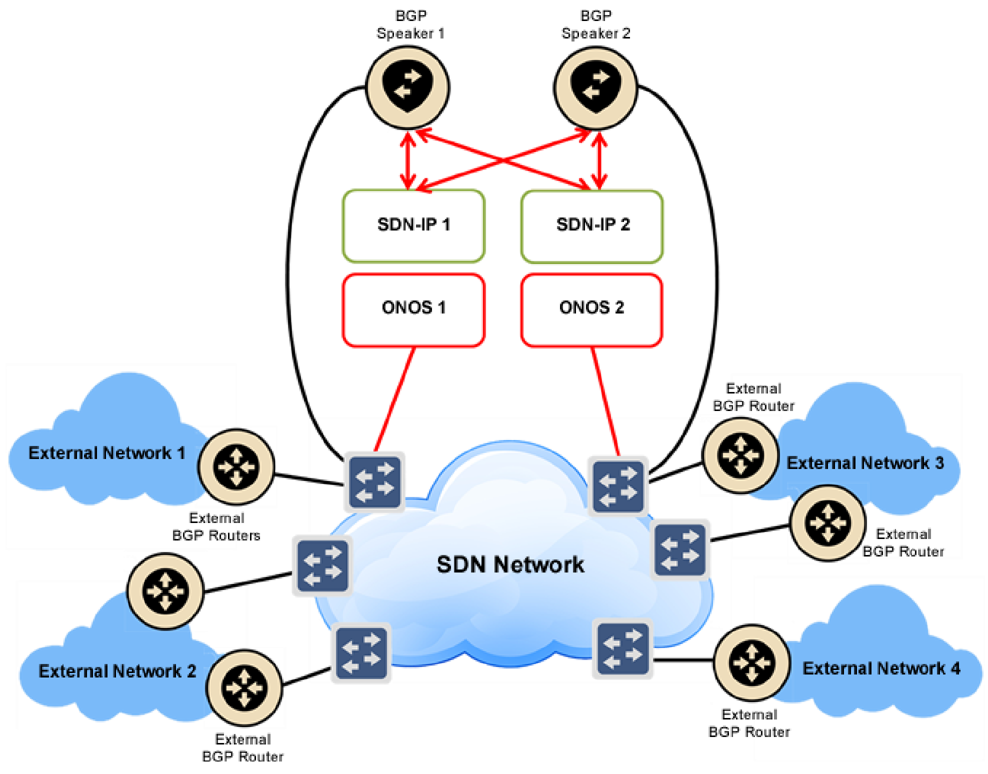


Figure 2.4: ONOS SDN-IP network model, *Source: [SDN-IP-ARCH]*

Regarding L2 services, the SDXL2 application provides the necessary mechanisms for service provisioning and monitoring. Operators can manage and monitor the application through the CLI and GUI that accepts high-level user requests and translates them into ONOS point-to-point intents. From a user perspective, the network appears as a black box that transports traffic from the source to the destination end-point, as if it was on the same Ethernet LAN. SDXL2 provides operators with powerful APIs and abstractions. It eases service management and provisioning, e.g. enforcing isolation and avoiding several types of conflicts:

i) Resources (ports or VLAN tags) associated with a connector cannot be reused.
ii) An edge connector can only be used in a single circuit.
iii) A connector in a virtual SDX instance cannot be interconnected with a connector in another virtual SDX.

Both SDXL3 and SDXL2 applications are available under a liberal open source licence and can be downloaded [GÉANT CODE].

Several PoC scenarios were designed with the aim to verify:

i) The functional and operational requirements of SDXL2 and SDXL3 applications [JRA2IPSDX].
ii) The coexistence of SDX L2 and L3 functions in the same deployment scenario.

The following sections describe all of the PoCs that have been realised by the SDN-IP/SDX team during GN4-1.

### 2.3.4 Proof of Concept Set Up

The PoC set up has been carried out in several phases, considering different scenarios according to the required testing. The initial testing environment was emulated and later the testing was moved to the Lab to obtain more realistic results.

#### 2.3.4.1 *Software-Based PoC*

The first PoC has been deployed in a laboratory at the University of Rome, 'Tor Vergata', and has been mainly used for validation and testing of the SDXL2 application. It is an emulated environment based on Virtual Machines (VMs), which have been used to emulate the data plane and the control plane. In particular, nine Debian VMs with Kernel 4.1 emulate the data plane through the software switch Open vSwitch (OVS) 2.490. Then, a cluster of three Ubuntu VMs compose the ONOS control plane. A management VM has been introduced to automate the deployment of the data plane and the control plane. Finally, four Debian VMs have been used to emulated the SDX users. Figure 2.5 shows the software-based PoC deployed at Tor Vergata.

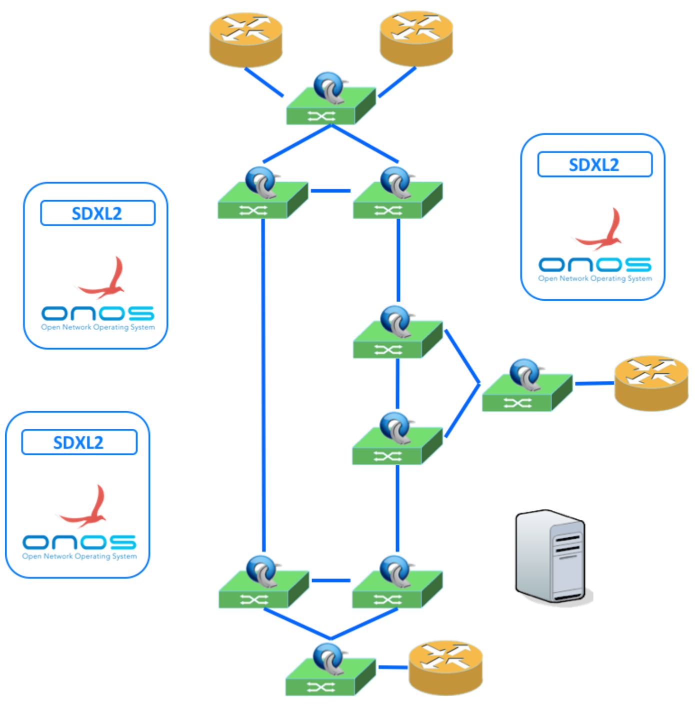

SDXL2
onos
Open Network Operating System
SDXL2
onos
Open Network Operating System
SDXL2
onos
Open Network Operating System

Figure 2.5: Software PoC deployed at University of Rome

### 2.3.4.2 *Proof of Concept Within GTS*

The second PoC has been realised within the GÉANT Testbed Service (GTS) environment. GTS delivers virtual testbeds powered by several facilities that are co-located with GÉANT PoPs, offering different resource types, such as VMs, SDN devices, virtual circuits, and interconnections with external domains through the GÉANT network [GTS]. Using GTS, the JRA2 team has built a large-scale PoC with seven HP OpenFlow switches, deployed in seven PoPs: AMS, BRA, HAM, LJU, LON, MIL and PRG. This data plane is controlled by a cluster of three ONOS instances located in AMS, MIL and BRA. Three VMs, working as BGP peers and two stub networks with perfSONAR hosts have been deployed. Figure 2.6 shows the PoC deployed on the GTS.

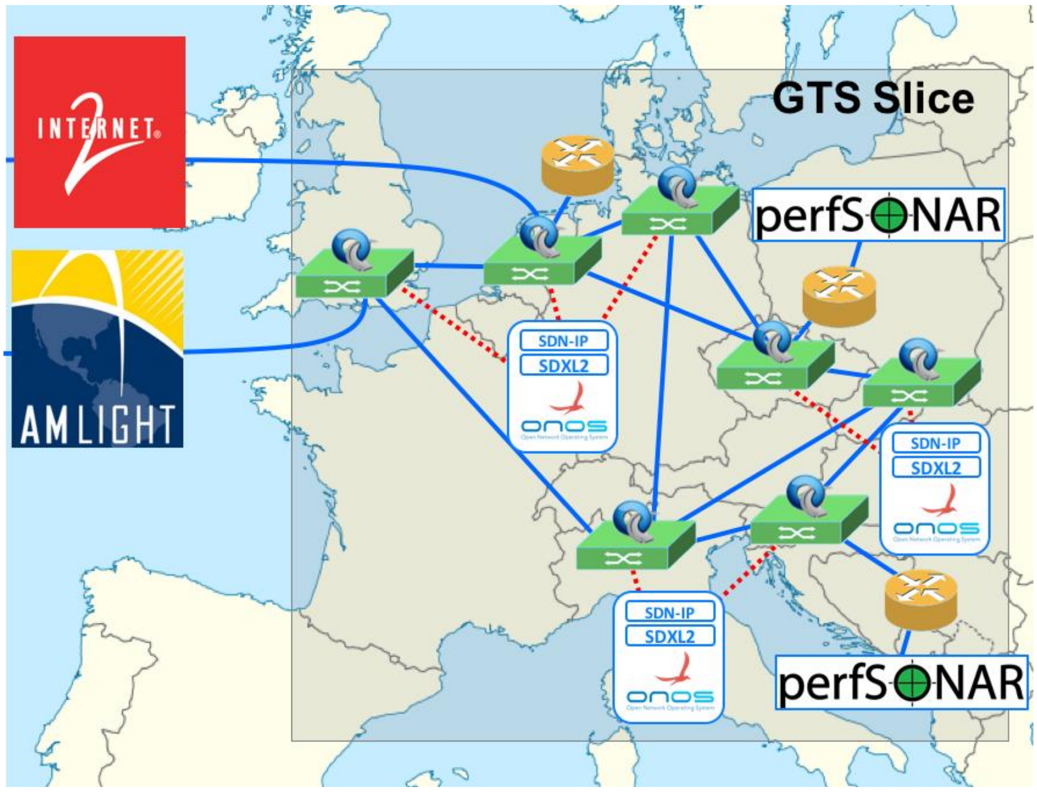


Figure 2.6: SDN-IP/SDX in the GTS

The SDX PoC on GTS has been integrated in a worldwide demo hosted at the Open Networking Summit 2016, where ON.Lab successfully deployed ONOS and SDN-IP, creating a global network facility entirely based on SDN [ONS2016]. The network spans 5 continents, interconnecting 9 RENs and more than 30 universities and research centres from Australia, Brazil, Caribbean, Chile, Europe, Korea and the United States. Over 50 core switches from different vendors are controlled by different ONOS clusters that are geographically distributed and administratively isolated.

### 2.3.4.3 *Proof of Concept at the GÉANT Lab*

The GÉANT-specific PoC was delivered in the GÉANT Lab utilising off-the shelf switching and routing hardware ‘white boxes’ and available network equipment. Based on equipment availability, it was divided into two, subsequent phases during which the use-case requirements were tested.

#### Phase 1

As shown in Figure 2.7, the first phase of testing components included an Ubuntu VM running the ONOS controller (sdx-onos1), a second Ubuntu VM for running Quagga as IBGP speaker (sdx-quagga1), two Pica8 switches (P3922) connected by a single link representing the SDN network (pica8-sw01 and pica8-sw02), and two Juniper MX routers (to enable possible configuration of multiple logical systems (LS) for simulating a connected, external network) acting as external peers (MX1 and MX2). MX1 and sdx-quagga1 were connected to specific SDN edge ports of pica8-sw01, and MX2 connected to an edge port of pica8-sw02. On each Pica8 switch, one OVS bridge (br0) was used to represent one logical OF switch, which yielded a one-to-one mapping between physical and logical switches.

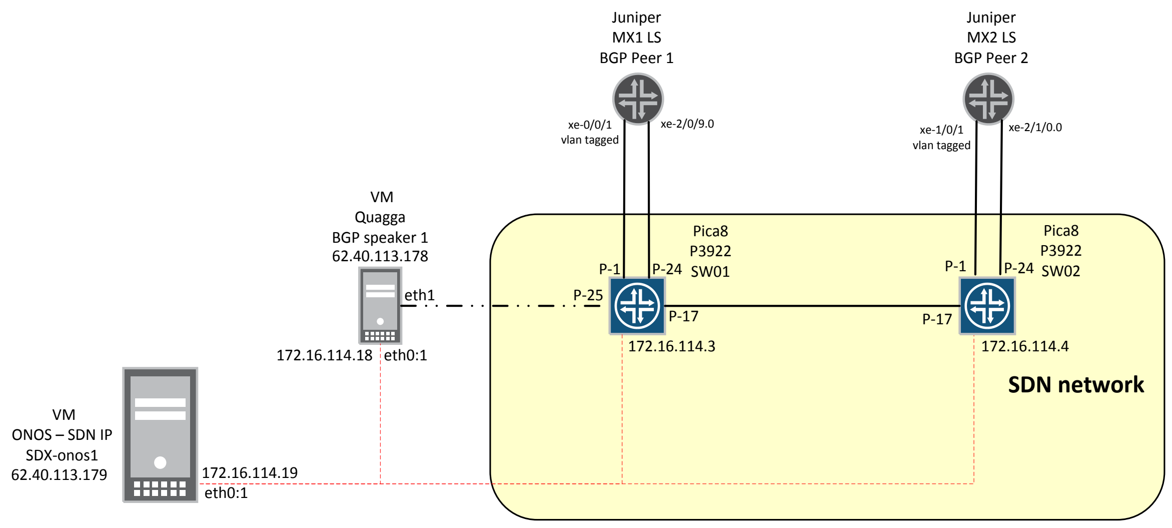


Figure 2.7: SDN-IP/SDX PoC in the GÉANT Lab – Phase 1

### Phase 2

In the second phase of testing, the scenario was extended with new components so that all required features could be tested. The two physical Pica8 switches from Phase 1 were used, each configured with an additional Open vSwitch (OVS) bridge, i.e. logical OpenFlow (OF) switch, (br3 in addition to already used br0). On each physical switch bridges br0 and br3 were interconnected via a physical link between appropriate ports. In addition, both of the new br3 bridges on both switches were interconnected via a link between new ports on the switches. The resulting SDN network topology took the form of a square/ring. Figure 2.8 shows the network topology as deployed for Phase 2.

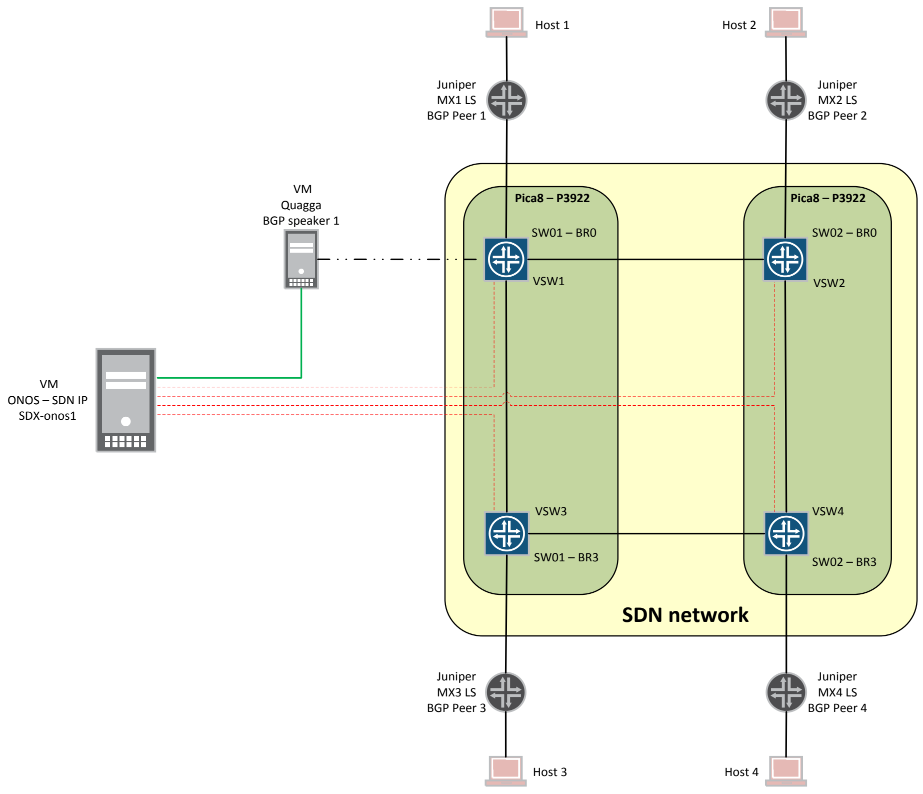


Figure 2.8: SDN-IP/SDX PoC in the GÉANT Lab – Phase 2

A logical naming system was used for bridges vsw1 to vsw4, i.e. pica8-sw01-br0=vsw1, pica8-sw02-br0=vsw2, pica8-sw01-br3=vsw3, pica8-sw02-br3=vsw4. In this topology, the existing MX routers MX1 and MX2 were connected to vsw1 and vsw2, respectively. On each of the new bridges br3, additional Juniper MX routers were connected at respective edge ports: MX3 at vsw3 and MX4 at vsw4. Furthermore, behind each of the used MX routers a respective Ubuntu VM (sdx-host1 to sdx-host4) was connected for representing external BGP networks.

### 2.3.5 Findings and Conclusions

The SDN-IP/SDX use case was formed to explore possibilities and benefits of SDN technology for the most important network services listed in current GÉANT service portfolio, such as GÉANT IP, GÉANT Plus and GÉANT Open [GÉANTIP], [GÉANTPlus], [GÉANTOpen]. The requirements of the GÉANT network have been taken into account and the prototypes of two SDN applications, SDXL3 and SDXL2, have been developed and deployed in several PoCs: Software-based PoC, GTS PoC, and GÉANT Lab PoC. The application development has been based on the open source ONOS controller platform for SDN. A functional evaluation of the PoCs has been performed, as well as an analysis of the potential benefits for GÉANT, which has been very satisfactory.

The evolution of the SDN technology is very rapid, with continued development of new applications and versions of software components. In the case of SDN IP/SDX at Layers 3 & 2, deploying the PoC onto real hardware has been a priority due to the post GN4-1 plans for production deployment. Testing demonstrated the inability of the hardware to support some of the required features.

Nevertheless, the adopted software suite (ONOS controller and integrated (SDN-IP) and developed applications (SDXL3, SDXL2 and IPFIX)) cover the majority of requested features.

Overall, the PoCs lived up to expectations, with ONOS, SDXL2 and SDXL3 applications succeeding in the functional tests. Regarding operational requirements, the scalability and reliability of SDXL2 and SDXL3 applications are tightly related to ONOS performance. It has been demonstrated in the ONOS technical white paper that the platform can meet carrier grade requirements in specific deployment conditions [ONOSWP]. In order to fulfil all requested feature sets, further development and testing are needed.

Due to limited hardware availability it has not been possible to test a GÉANT network environment that was much closer to production with an appropriate number of supported routing prefixes. Such performance tests will be conducted in the future. Also, taking into account the current level of SDN ONOS controller maturity, the required set of features imposes the need for further development of existing or new ONOS applications that are relevant for GÉANT (i.e. SNMP monitoring, user hierarchy authentication and authorisation) and further ONOS driver development and interoperability with a wider set of networking equipment vendors.

In order to bring the SDXL2 and SDXL3 applications to production, some additional concerns related to security and integration with management systems need to be addressed. Future work will also include the integration of the missing requirements (for example, the realisation of a custom route-selection process for SDXL3), the development of new services such as VPLS, and the continued testing of white box switches. The results have been distributed as open source, so that in the long term it may be possible to benefit from the open source community around ONOS.

The developed SDN-based capabilities can bring considerable operational cost savings can dramatically reduce the service provisioning time, as they automate many tasks that are currently performed manually. Similar improvements in service provisioning and management, such as the ones reported in [IBARRA] are an affordable objective, representing tangible results when compared to the current status (5 days to obtain IP connectivity or to set-up a Layer 2 circuit).

## 2.4 Transport SDN Proof of Concept

### 2.4.1 Problem Statement and Objective

Optical equipment vendors are currently working on OpenFlow interfaces to their platforms. The ONF has recently published Optical Transport Protocol extension 1.0 specification for OpenFlow [ONFSPEC]. Many optical equipment vendors are choosing to develop proprietary SDN approaches. The JRA2 team is working on testing Infinera's SDN implementation (known as the Open Transport Switch (OTS), which when combined with the PXM card, provides GÉANT with an opportunity to use SDN capabilities at the optical Layer.

At the moment of writing, the traffic load on some of GÉANT's 100GE IP trunks is between 20% to 30%, and each trunk needs a separate 100GE interface on a Juniper router and Infinera DTN. This means some of the PoPs (such as Geneva) have more than two 100GE trunks with the total traffic on those trunks being less than 100Gbps. The use of SDN to control the capacity at the optical layer presents an opportunity to manage the transmission capacity intelligently to meet the needs of elephant flows and make use of route bypass to save on router interfaces.

### 2.4.1.1 *Introduction*

The Infinera PXM card is a 200G Ethernet switch on a blade for its DTN-X platform [DTN-X]. The optical equipment in GÉANT is based on Infinera DTN-X platform. The PXM card has following functionalities:

- Packet Switching Module with the following interface options: 16x10GE/16x1GE or 1 x 100GE.
- Built-In 200G Packet Switch, Enables QoS and Packet Classification, VLAN and QinQ, MPLS-TP on network side.
- Metro Ethernet Forum (MEF) services [MEF].
- Point-to-point services: EP-LINE, EVP-LINE.
- Multipoint services: EP/EVP-LAN, EP/EVP-TREE.

The Infinera Open Transport Switch (OTS) (Figure 2.9) is a lightweight, virtual transport switch that provides an SDN interface to the DTN-X.  In the first release of the OTSv, this is a REST- based interface which is not compatible with the OF wireline interface. The OTS adds transport extensions to the OpenFlow interface, which can be used to control OTN transport circuits. The interface can also be used to offer deterministic Layer 2 services over the optical layer and BoD services delivered over the optical layer instead of offering it over Layer 2/3.

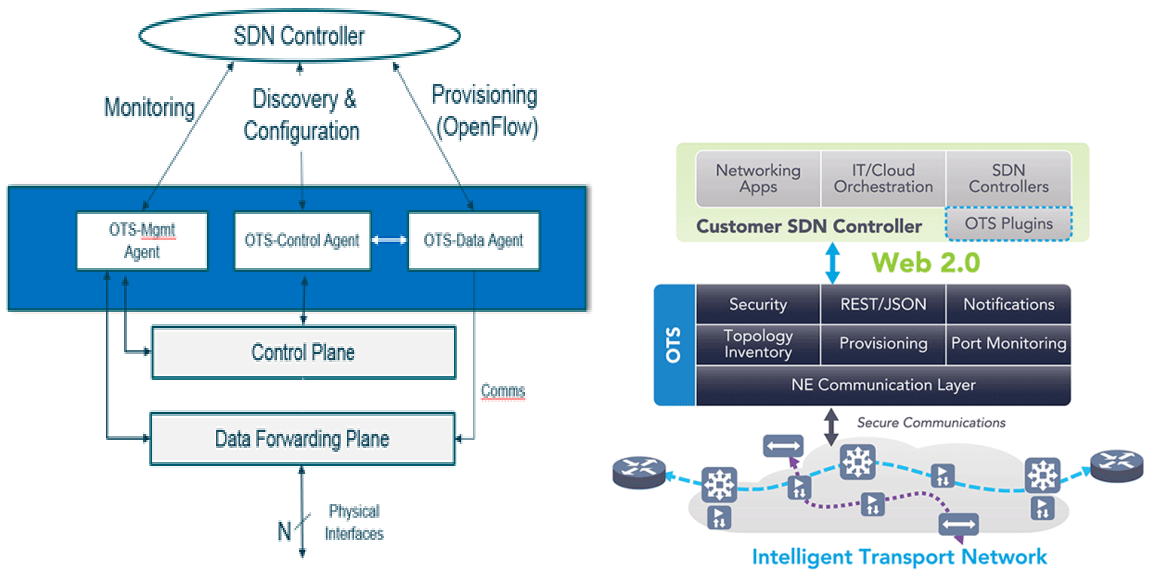


Figure 2.9: Open Transport Switch architecture

Figure 2.10 below shows how the PXM card can be connected using 100G to the local router interface and act as an aggregation device. The GÉANT Backbone trunks can use the PXM card, which could reduce the number of 100G cards needed for the routers. The diagram illustrates how several 10G trunk links can be consolidated in to a single 100GE.

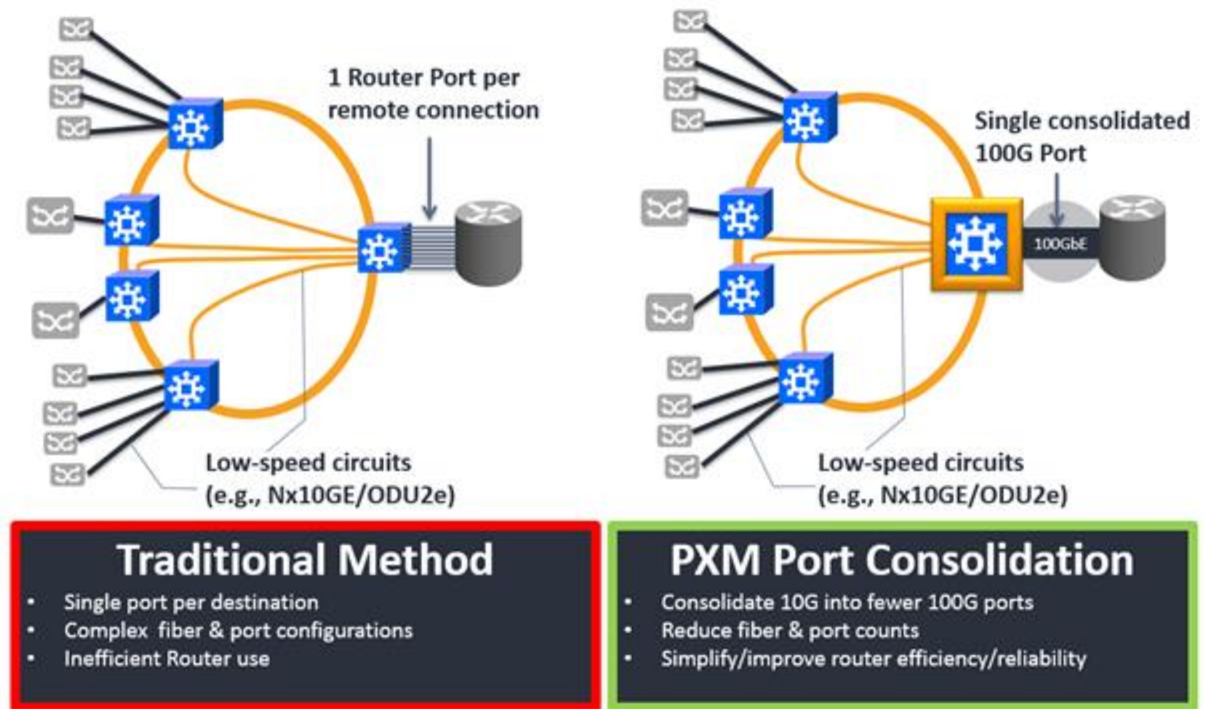

1 Router Port per remote connection
Low-speed circuits (e.g., Nx10GE/ODU2e)
Single consolidated 100G Port
100GbE
Low-speed circuits (e.g., Nx10GE/ODU2e)
Traditional Method
Single port per destination
Complex fiber & port configurations
Inefficient Router use
PXM Port Consolidation
Consolidate 10G into fewer 100G ports
Reduce fiber & port counts
Simplify/improve router efficiency/reliability

Figure 2.10: Using PXM card as aggregation for 10G interfaces into one 100GE interface

### 2.4.1.2 *Use Cases*

JRA2 has identified two use cases for transport SDN:

- Use case 1: Use of the PXM to deliver a L1 VPN for users such as the Large Hadron Collider (LHC) community. This would be supported using the ELAN service over OTN, making use of the functionality of the PXM card. This scenario was presented to the LHC community [INFINERA-PXM]. This use case is on hold, as the current version of the PXM card does not support the ELAN function. Use case 1 will be re-visited once the ELAN capabilities become available.

- Use case 2: Use of the PXM during multi-layer provisioning. In this use case, a common SDN controller is used to control both the packet layer and the OTN layer of the network. By being aware of both layers, the SDN controller can make intelligent decisions when allocating bandwidth on the OTN layer. This approach was presented at the CESNET CEF workshop [CEFWORKSHOP].

Figure 2.11 shows a standard multi-layer network architecture. Here the SDN application is used to create EVPL circuits between aggregated router interfaces. Router bypass can be created on demand to support either elephant flows or to optimise the transmission layer configuration to save on router interfaces.

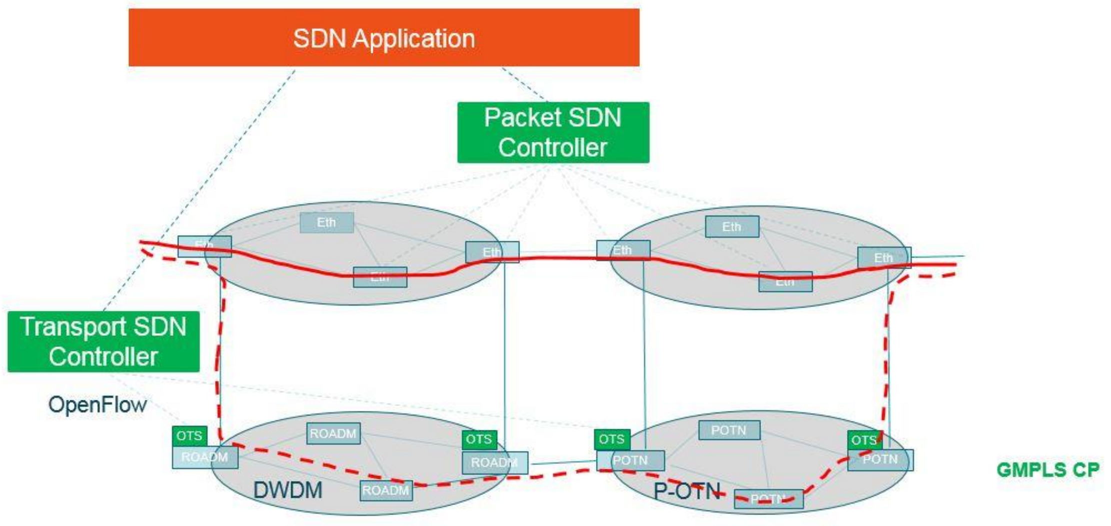


Figure 2.11: Standard multi-layer network architecture

The list of requirements for the Transport SDN use case and more particularly the PoC involving Infinera equipment and eligible SDN controllers have been identified and are presented in [JRA2TRANS].

## 2.4.2 Proof of Concept Scenario

This section provides a high-level design for the introduction of SDN control into the GÉANT transmission layer.

In the current GÉANT network Architecture, shown in Figure 2.12, routers are interconnected by fixed 100G circuits 'IP trunks'. Routers are connected in a chained architecture – each router is connected to the nearest router following the dark fibre. The chaining of routers means that the traffic follows the fibre and uses more router interfaces than necessary.

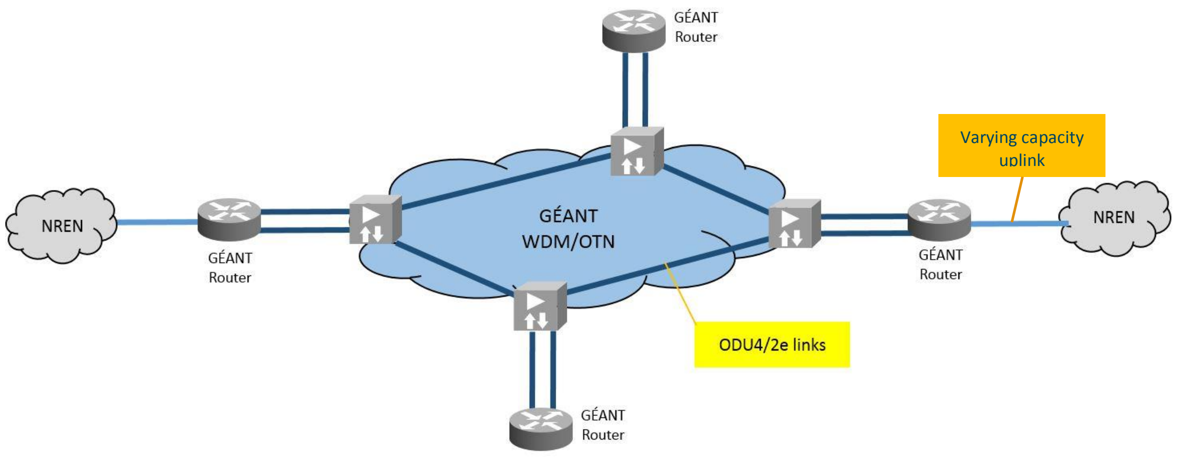


Figure 2.12: Current GÉANT architecture

The introduction of PXM cards into the network is shown in Figure 2.13. A PXM card is a 200G Ethernet switch on a blade that can be used for edge aggregation. GÉANT routers are connected to the WDM/OTN cloud via a 100GE port on a PXM card (shown in blue in this diagram). The IP trunks (red dashed line on Figure 2.13) are built between PXM cards using ODUflex circuits, which are static (not OTS controlled). These trunks support router bypass and IP trunk capacity management. Some legacy locations will retain TIMs with ODU4/2e circuits.

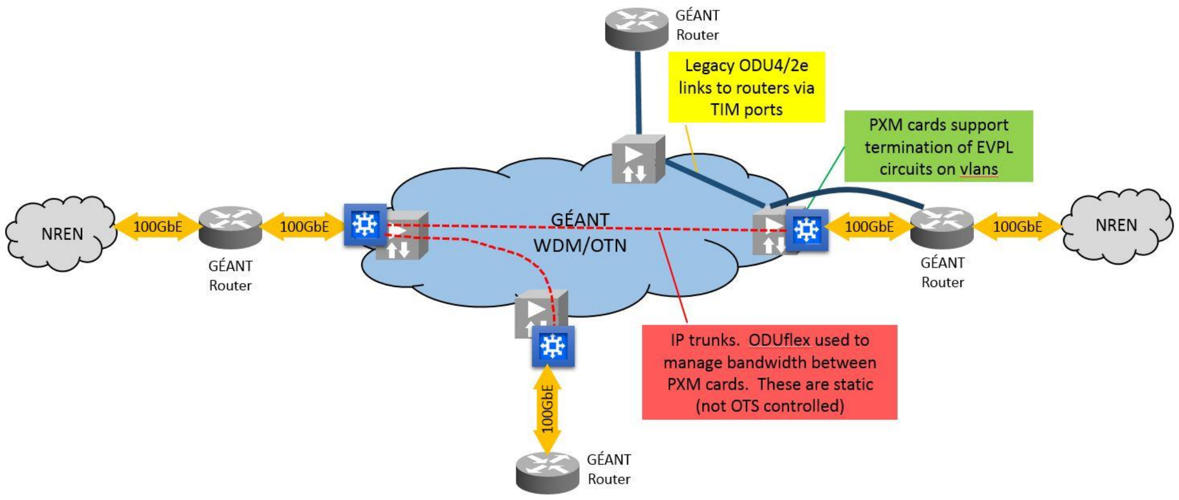

GÉANT Router
Legacy ODU4/2e links to routers via TIM ports
PXM cards support termination of EVPL circuits on vlans
NREN
100GbE
100GbE
GÉANT Router
GÉANT WDM/OTN
100GbE
100GbE
NREN
GÉANT Router
IP trunks. ODUflex used to manage bandwidth between PXM cards. These are static (not OTS controlled)
100GbE
GÉANT Router

Figure 2.13: Envisioned GÉANT architecture with PXM cards for port consolidation

### 2.4.2.1 *Phase 1 of SDN Introduction to the GÉANT network*

This first phase will introduce SDN into Layer 2 using white box switches and fixed trunks (see the use case in Section 2.2). No transport SDN is supported at this stage. The SDN controller (e.g. ONOS) and white boxes (e.g. Corsa switches) will be used to build Layer 2 point-to-point circuits, with the SDN controller managing the white boxes. Existing Infinera IP trunks can be used in two possible ways:

- Static ODUflex links between layer 2 SDN switches via router (red dotted line on Figure 2.14).
- Static 10G ODU2e links between 10G TIM ports (blue dotted line on Figure 2.14).

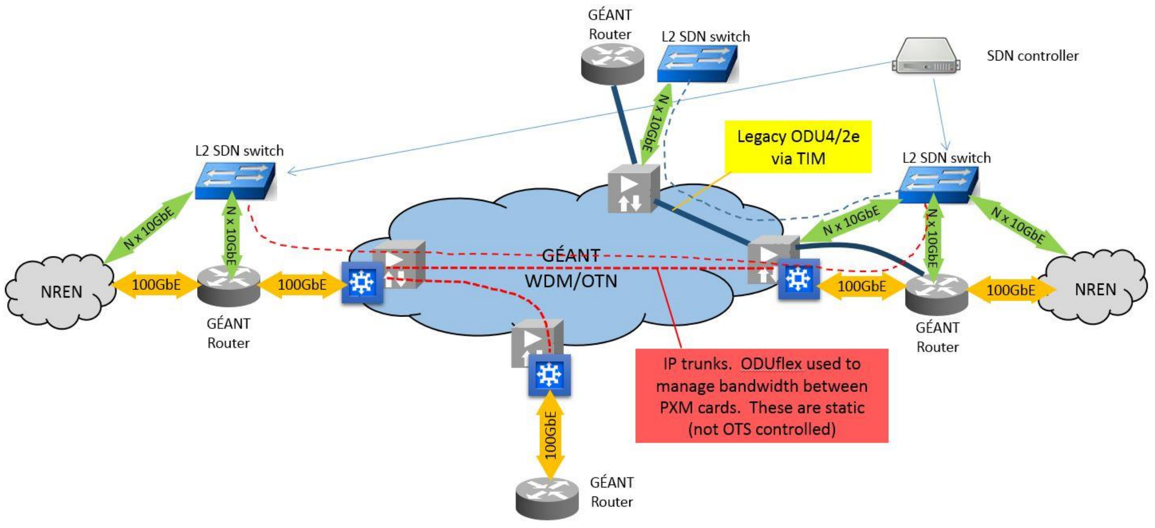


Figure 2.14: Phase 1 of introducing SDN in GÉANT transport layer

### 2.4.2.2 *Phase 2 of SDN Introduction to the GÉANT Network, Multi-Layer SDN*

This phase will result in a layer SDN solution with transport bandwidth management. In addition to the SDN controller (e.g. ONOS) and white boxes (e.g. Corsa switches) being used to build new Layer 2 point-to-point circuits, OTSv will be used to signal new trunks to OTSc. There are two scenarios for OTSv (see Figure 2.15):

- Dynamically create new EVPL services over the ODUflex capacity. This will provide guaranteed bandwidth for the associated Layer 2 user service.
- Modifying the VLANs mapped to existing ODUflex capacity. This will provide statistical multiplexing gains by sharing IP trunk capacity.

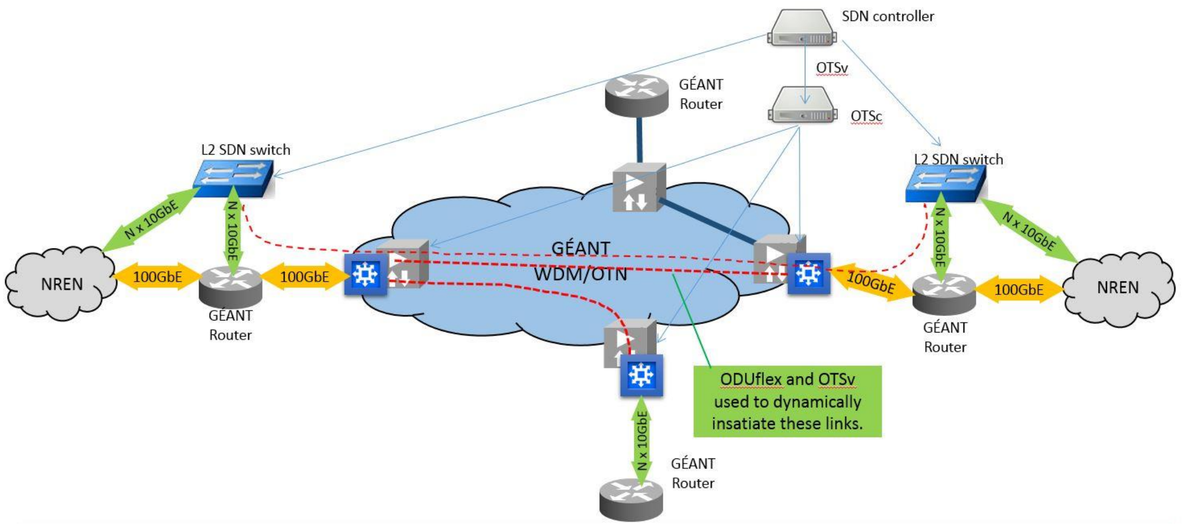


Figure 2.15: Phase 2 of introducing SDN in GÉANT transport layer

## 2.4.3 Proof of Concept Set-up

The purpose of the PoC is to show that L1 (OTN) circuits can be provisioned on the Infinera equipment via an SDN controller (in this case ONOS), as shown on Figure 2.16. The SDN controller requests EVPL circuits of up to 100Gbps. These will be used as IP trunk links between GÉANT routers. In the demonstration, the 100G links will be built.

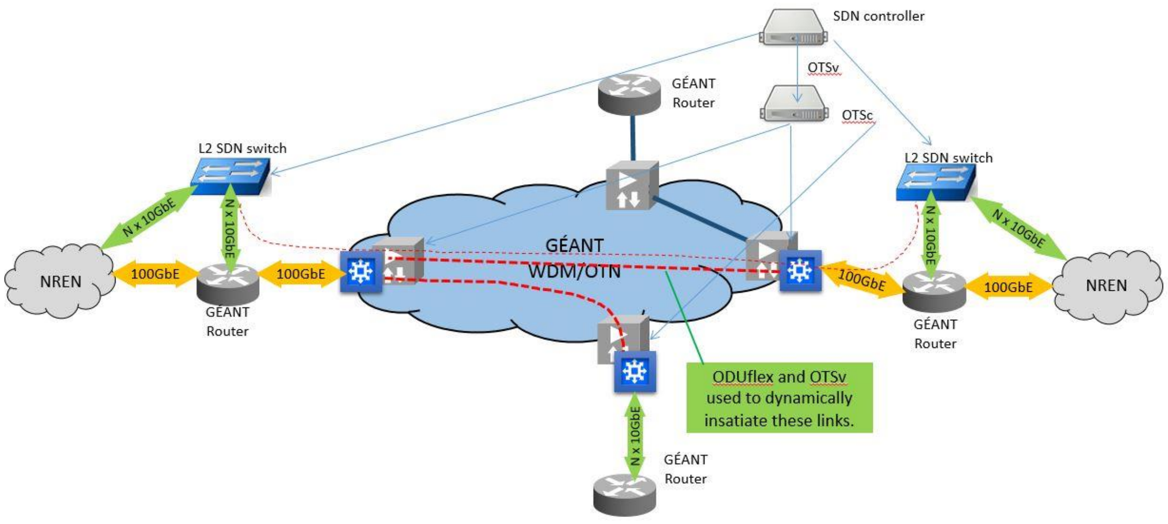


Figure 2.16: Transport SDN Proof of Concept scenario

### 2.4.3.1 *Physical and Logical Demo Setups*

Figure 2.17 illustrates the physical demo setup. 100GE tester is connected in 'Dublin' DTN-X to 100GE PXM interface. Terminal loopback on PXM card is created in 'Ballinesker' DTN-X. Request for 100G circuit is sent from ONOS to OTSv using REST interface. OTSv controller configures the 100G Ethernet Private Line service. Figure 2.18illustrates the logical demo setup. The 100G tester can be viewed in the demo via RDP.

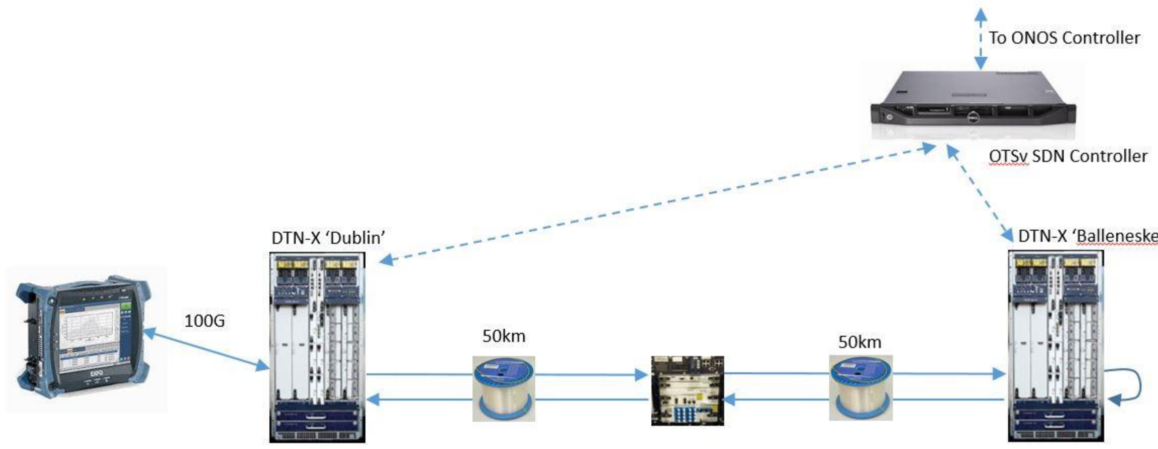


Figure 2.17: Physical demo setup

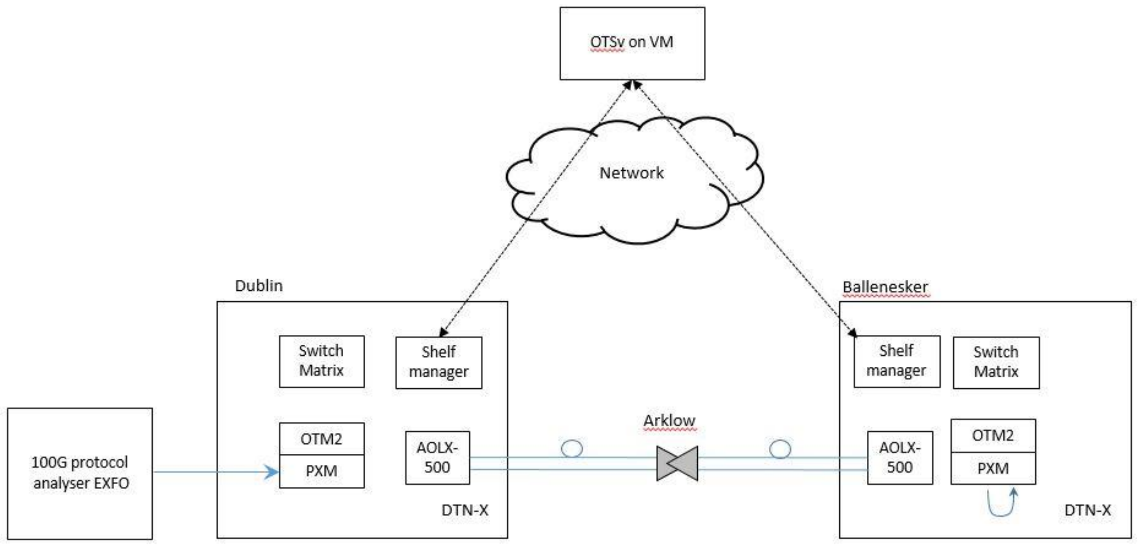


Figure 2.18: Logical demo setup

#### 2.4.3.2 *Workflow*

Two workflows are described here. The first is the instantiation of a new IP trunk circuit. The second is related to varying the bandwidth on this IP trunk.

Circuit instantiation:

- The multi-layer SDN controller has decided that more IP trunk bandwidth is needed.
- The ONOS controller sends a request for a new trunk circuit between Dublin and Ballinesker The request is for a ODU-Flex circuit of 50G.
- REST message is sent to OTSv describing the new circuit.
- The OTSv sets up the path by sending a request to the network elements (Infinera DTN-X).
- When the new trunks appear, these are detected by the MXs and the traffic begins to flow.

Capacity management:

- When the IP trunk capacity needs to be increased, ONOS signals to the OTSv to increase the IP trunk capacity.
- Capacity is increased from 50G to 100G.

### 2.4.4 Findings and Conclusions

At the moment of writing, the transport SDN in GÉANT is not yet functional. This is mostly due to late arrivals of the lab equipment (PXM cards) and OTSv implementation from Infinera.

A number of steps were completed within this PoC. The DTN-X equipment has been installed in the Cambridge Lab. It has also been tested and verified ready for operation. The PXM cards have been installed and tested and there is successful EVPL service between 100G ports. In addition, the PXM buffers were also tested and 100ms of buffering has been verified, which is crucial for TCP to work over transatlantic distance. The OTSv software is now installed on a VM in the lab and communication established with the DTN-Xs. Communication of the REST messages to the OTSv has also been established remotely from a PC, along with the verified request of information and configuration of Network Emulators (NEs).

In future, next steps include the identification of the correct REST syntax to create an EVPL service. In addition, an ONOS plug-in will also need coding in order to request EVPL services from the OTSv. A robustness test for circuit provisioning and deletion also needs to be carried out.

## 2.5 Infrastructure and Network as a Service Proof of Concept

### 2.5.1 Problem Statement and Objective

The goal of the Infrastructure and Network as a Service (INaaS) use case is to automate the process of connecting legacy L2 networks in a data centre to a VXLAN overlay network running on an OpenStack environment. There are a number of use cases for connecting L2 networks to cloud environments, and vice versa. These include connecting bare metal servers directly to virtualised tenant environments, or directly connecting hardware firewalls or routers to overlay networks. In the longer term, L2 networks can be extended beyond the data centre, utilising L2 connectivity services delivered by the upstream network provider. However, focusing on extending L2 overlays to legacy L2 networks within the data centre has been the primary goal of this use case.

An automated process for creating such configurations can provide a quicker provisioning of the network service and greater flexibility for end users, since they do not depend on network staff to handle the provisioning of their network and compute resources.

One method of facilitating this kind of connectivity is called ‘hardware VTEP’, which is a switch running software that communicates through the OVSDB protocol, and maintains a database containing VXLAN to VLAN mappings and lookup tables for local and remote MAC addresses [VTEP]. The described PoC demonstrates a use-case based on this solution.

Hardware VTEPs provide a solution for connecting the virtualised environment with the physical, where the services running on this network can share the same network access policies, since all services effectively exist within the same Layer 2 domain.

### 2.5.2 Consideration and Limitations from Testing of Requirements

#### 2.5.2.1 *Requirement Considerations*

A long list of requirements for integrating Network and IaaS was created by participating parties (GRNET, HEAnet and SURFsara) in the early stages of the project [JRA2INAAS]. From this list, a decision was made to focus on a subset of these requirements, and in particular, overlay networking in IaaS environments. Key requirements are detailed in Section 5 of [JRA2INAAS], namely those listed under “OVS & Overlay networking”. Testing has shaped the PoC design, as described in the next section.

To test and implement the requirements, a number of possible tools and technologies were considered. There have been a few preferences while identifying the most suitable technologies:

- Open-source: The solution needs to be open-source, so that it is easier to make adaptations or to contribute to the code in case of issues.
- Widely used: Well-known applications have a track record of usage. This means that there are likely to be fewer issues during deployment.
- Community support: Applications that have community support often provide an online knowledge base where possible issues can be tracked and solved.

Based on these preferences, the following tools were chosen:

- **OpenStack**: This is a well-known and widely used open-source Cloud Management Platform [OpenStack]. It has a high development momentum, a large user community, and has full support for multi-tenant overlay networking. This is mainly achieved by the Neutron networking component of OpenStack [ODL-NEUTRON].
- **OpenDaylight**: This is a widely used, open source SDN controller, it supports many applications using a range of SDN technologies. It has a well-implemented OSVDB southbound protocol implementation. ODL has also been used by other projects in the GÉANT community [ODL].
- **MidoNet**: This is a framework that is used as an overlay network controller. It provides many applications for IaaS and overlay networks to provide multi-tenancy, redundant external network connectivity and a VTEP implementation. MidoNet is mainly open-source [MIDONET].

These tools leverage a number of technologies, which are used to implement the PoC. The most important are:

- **Open vSwitch (OVS)**: A commonly used virtual switch in overlay environment.
- **Open vSwitch DataBase (OVSDB)**: The management protocol used for managing Open vSwitch.
- **Virtual eXtensible Local Area Network (VXLAN)**: A tunnelling technology used for creating overlay networks in cloud environments.
- **Hardware VXLAN Tunnel End Point (VTEP)**: A Hardware switch used for facilitating crossover from overlay to underlay environment.

Based on the use case requirements and technology considerations, a set of tests were conducted. An overview of these is presented in Appendix C.

#### 2.5.2.2 *Testing Limitations*

During testing, it became apparent that, while OpenDaylight had been chosen as an SDN controller to implement the L2 gateway requirements, the controller is currently not mature enough to support the northbound functionality towards OpenStack Neutron or to implement the required actions to set up and manage the hardware VTEP. This only became apparent through direct contact with the OVSDB developers of OpenDaylight. OVSDB contact indicated that support for our requirements would only be ready with the OpenStack release of Mitaka, and the ODL release of Boron. This would not be available before June 2016. Therefore, a decision was taken to use MidoNet as an alternative solution to be used as overlay controller and the tests that had been defined using this controller were successfully executed.

### 2.5.3 Proof of Concept Scenario

The lab presented in Appendix B.2 has been set up and used for the purposes of the PoC. The PoC entails connecting SURFsara internal L2 networks to the OpenStack overlay environment as tenant networks, and automatically provisioning the L2-gateway.

Using a hardware VTEP as a L2-gateway, tenant networks existing in the overlay network can be extended to a layer 2 environment (bridging the cloud to legacy L2). A hardware VTEP could also be used to extend the Layer 2 environment to overlay networks (bringing legacy L2 to the cloud), or to extend an L2 light path to a tenant network for the provision of external connectivity.

A vendor-independent approach was adopted to implement and automate the L2 gateway. A switch based on the Cumulus operating system or Pica8 switches were deemed to be the most appropriate. Both switches can be managed by OVSDB, since they are actually a Linux server running on a switching chassis, which can be controlled through the MidoNet overlay controller.

This is a more favourable approach for building a L2 gateway, compared to other hardware vendors (e.g. Juniper/Arista), as the latter would impose an additional southbound protocol (e.g. NETCONF). In this way, the L2-gateway can be managed by the same network controller as used for the overlay network.

Part of the PoC introduces an integrated interface that can manage overlay networks, virtual instances and L2 gateways. The interface is included in the MidoNet controller package.

#### 2.5.3.1 *Possible Network Technologies Involved in the Scenarios*

##### Neutron L2-Gateway Service Plugin

Recently, a service plugin for managing a L2-gateway through Neutron, was announced at the OpenStack summit in Vancouver [OSVAN]. The plugin was introduced in the Kilo distribution of OpenStack [OSKILO].

The plugin allows to easily provision VXLAN tunnels between software VTEPs (Neutron) and hardware VTEPs (Arista). When the tunnels are created, one can add a mapping from tenant networks in the OpenStack environment to legacy VLANs connected on physical Arista switches. In this way, traffic can be bridged between overlay and physical networks. The plugin was tested on Arista 7050X, 7150, 7280 and HP ToR switches. However, it should support any switch that supports the OVSDB hardware_vtep schema.

The solution is well documented and multiple resources can be found how to set this up, mainly using Arista and HP switches.

##### Neutron and OpenDaylight

OpenDaylight is a well-known SDN controller, which also provides support for OpenStack through the OVSDB southbound protocol.

The OpenStack Neutron integration with OpenDaylight consists of the ML2 MechanismDriver which acts as a REST proxy and passes all Neutron API calls into OpenDaylight. OpenDaylight contains a northbound REST service (called the NeutronAPIService) which caches data from these proxy-ed API calls and makes it available to other services inside of OpenDaylight. One current user of the southbound side of the NeutronAPIService is the OVSDB code in OpenDaylight. OVSDB uses the neutron information to isolate tenant networks using GRE or VXLAN tunnels.

### Neutron and MidoNet

MidoNet is an open source overlay controller, with significant support for OpenStack and hardware VTEP. It uses an agent, which replaces Open vSwitch on the Hypervisor. It is called Midolman agent and runs on API, gateway, and compute nodes [MIDOLMAN]. It creates a logical network topology on top of the physical one, using VXLAN (or GRE) encapsulation. The network state is distributed in the Network State DataBase (NSDB) and stored mostly in Zookeeper and Cassandra.

Last year MidoNet was released as open source. There is a Community Edition, and an Enterprise Edition with paid support.

MidoNet is well documented on the Internet. There is information available for hardware VTEP implementations for multiple vendors, including Pica8 and Cumulus.

Based on the aforementioned technologies, Table 2.2 presents an ML2 plugin comparison:

| | **Neutron L2-Gateway Service Plugin** | **Neutron and OpenDaylight** | **Neutron and MidoNet** |
|---|---|---|---|
| Supported tenant network types | VXLAN | VXLAN, GRE | |
| Southbound protocol | OVSDB | | |
| Used ML2 mechanism_driver | Open vSwitch (service plugin: networking-l2gw) | OpenDaylight | No ML2 mechanism driver, MidoNet has its own Neutron plugin |
| Minimum required OpenStack version | Kilo | Mitaka (not released yet) | Kilo |
| Supported Hardware VTEP vendors | Arista, HP, others (not tested) | Any OVS based platform supporting the hardware_vtep schema | Any OVS based platform supporting the hardware_vtep schema |
| OpenDaylight required? | No | Yes, ODL beryllium (only full support in Boron) | No |
| Pros | • Vendor independent<br>• No additional controller required | • Vendor independent<br>• Very flexible<br>• Support for non OpenStack overlay topologies | • Vendor independent<br>• Solution well documented<br>• Easy setup (compared to ODL) |

| | Neutron L2-Gateway Service Plugin | Neutron and OpenDaylight | Neutron and MidoNet |
|---|---|---|---|
| Cons | • Limited automation options<br>• Overlay topology limited to OpenStack | • Complex to set up<br>• development support required for automation process | • Cannot function as a SDN OpenFlow controller to support non overlay networking scenarios<br>• Non-OVS based network agent |

Table 2.2: ML2 plugin technology comparison

### 2.5.4 Proof of Concept in SURFsara Lab

A PoC of the use case was deployed on the SURFsara Lab, as a data centre environment with relevant requirements. The network topology of the PoC scenario is as follows:

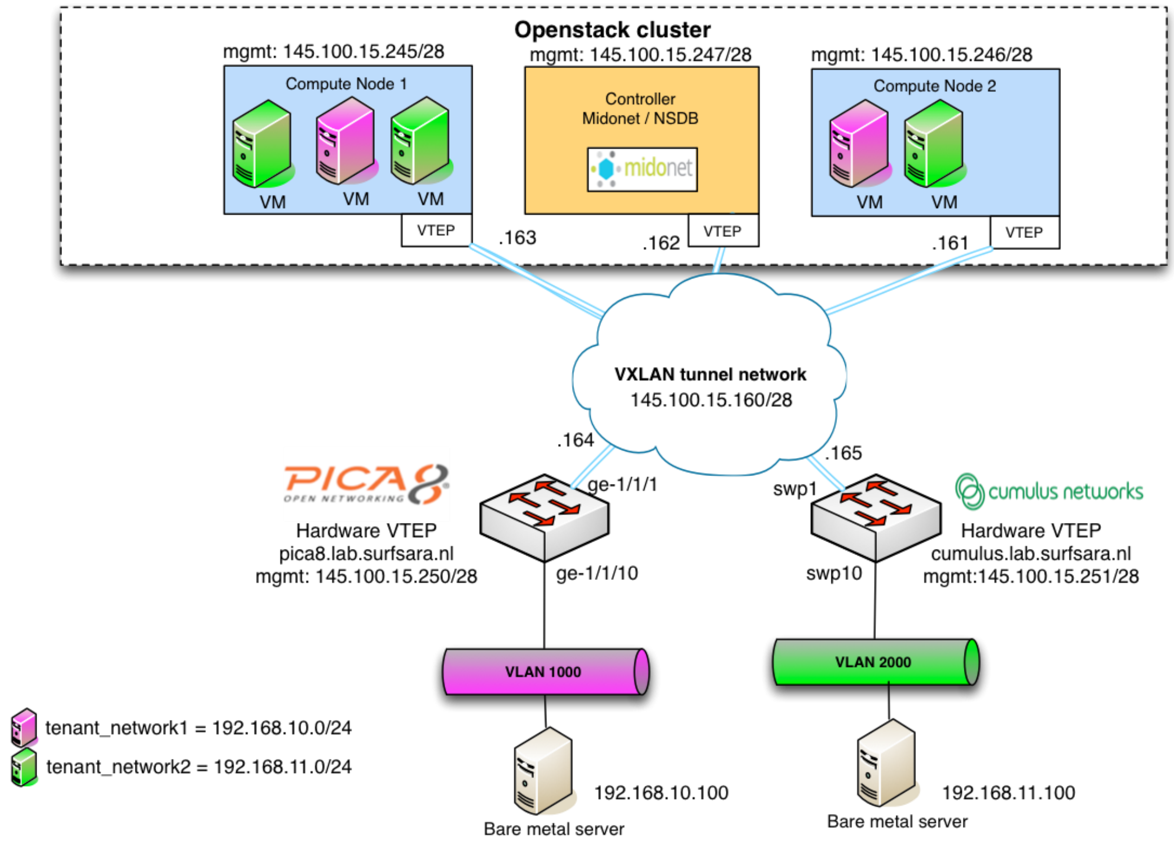


Figure 2.19: INaaS PoC network topology

#### 2.5.4.1 *Components in the Scenario*

**OpenStack controller node**

Manages the OpenStack cluster, provides a dashboard to instantiate compute instances, manage hard drive space, and network components.

**OpenStack Compute nodes**

These servers host virtual machines which are provisioned and managed through the control node.

**OpenStack Network node running SDN controller + Neutron**

The network node hosts the OpenStack Neutron application. Manages all network-related items in OpenStack, such as switching, routing, management of provider/tenant networks, etc. Neutron can be extended with additional plugins using the ML2 framework, to provide support for third-party hardware and software. In this case the network node and controller node are integrated on the same machine.

**Hardware VTEP**

This is a switch performing the translation between VXLAN and legacy L2 networks. This can be either a Pica8 or a Cumulus switch. It is used to extend a tenant network towards a physical L2 network.

**SDN Controller**

The SDN controller (such as MidoNet or OpenDaylight) sits in between Neutron and the VTEP. It acts as a proxy for Neutron, by means of executing neutron commands using a northbound protocol. It also manages the VTEP using an OVSDB southbound protocol.

#### 2.5.4.2 *User Story / Flowchart*

1. The client wants to launch a VM and connect his/her own network to the VM.
2. Initially the external network needs to be created.
3. Client logs in to the Horizon dashboard.
4. Client creates new network, and fills in all required network name, subnet, and other fields.
5. MidoNet Neutron plugin takes care of L2 provisioning on Cumulus or Pica8 switch.
6. This user story assumes the external network is already configured in Neutron, and MidoNet configured the hardware switch accordingly using OVSDB.
7. Client Logs in Horizon dashboard.
8. Client start Launch new instance wizard.
9. Client selects his own network from the network tab, fills in other normally required parameters and boots the VM.
10. In case no DHCP server is available, the client logs into the VM through a console to configure IP.
11. Client connects to newly launched VM using SSH, to test the connectivity.

### 2.5.5 Findings and Conclusions

Multiple approaches for managing overlay networks and hardware VTEPs were tested. The main conclusion is that the technology is not yet sufficiently mature. For instance, at the time of writing (April 2016), it is not possible to implement the envisaged scenario using OpenDaylight, as was initially anticipated. The required driver is still not released, which makes it impossible to manage a VTEP using ODL. User and design documentation for certain features is often also limited. The alternative approach using MidoNet has been more successful. This included participating in an evaluation test where direct support was provided by engineers from Midokura. This allowed for a fast deployment to carry out the required testing. Much better documentation also proved itself.

In addition, the hardware VTEP implementation on the switches varies by vendor, and introduces a number of issues. For instance, Juniper switches will only communicate using the OVSDB protocols through TLS/SSL, which is not supported on many of the SDN controllers. The hardware VTEP implementation on tested Cumulus OS based switches introduced some issues, mainly based on availability of the management of the VTEP. The required processes on the switch and on MidoNet had to be restarted from time to time to ensure proper functionality.

There are many options to provide greater flexibility and automation in the area of overlay networking and IaaS environments. Most of the testing in the area of managing overlay network topologies has been successful, and there is much momentum in the development of the used SDN controllers.

## 2.6 Network in the Campus Proof of Concept

### 2.6.1 Problem Statement and Objective

Some of the GN4-1 NRENs' users (labs, researchers, etc.) within universities are requesting enhanced networking service provisioning, with easier and more time-efficient provisioning mechanisms. Currently, such requirements are handled by campus NOCs (Network Operations Centres), requiring considerable amounts of manpower investment, special treatment and manual configuration. The process of receiving such enhanced services usually involves a great deal of administrative and human interaction, which is further increased in most of the cases where the upstream NREN is involved in order to leave the campus.

It would be desirable to have the means to obtain differentiated network services on demand and through fast and simple allocation mechanisms, which should also be available to any user (usually researchers) in the campus. In addition, it should be also taken into account that some users may request non-standard connectivity services that differentiate from the TCP/IP paradigm and thus, they cannot coexist with it. One of these non-standard connectivity cases are SDN-enabled labs, which are already being deployed in many campuses. In a number of cases, these SDN labs need to extend their points of presence over the campus, and require the transparent transport of their communications traffic over the production infrastructure. In many cases, these labs federate with other labs, which involve the upstream NREN in delivering non-IP, special purpose connectivity.

The goal of the NitC use case is to use SDN to enable extending special purpose connectivity services from the upstream network into the campus network, specifically to the end user. Differentiating from other approaches such as Science DMZ [SCIENCE-DMZ], the approach presented here does not require the use of dedicated systems for specialized data/flow handling within the campus. It focuses less-intrusive options.

There are two actors involved in the NitC use case.

- The researcher (user): The person that consumes enhanced network services and/by performing experiments with it. The researcher desires a way to reserve the resources in isolation.
- The NOC: The Networks Operations Centre of the campus. It manages the network by monitoring, operating and troubleshooting the university's network infrastructure.

NOC admins are reluctant to change hardware that is still operational, especially those with paid maintenance contracts. The separation of the production/standard traffic from the research/enhanced traffic needs to be done easily, using the actual equipment and available technologies. The possibility of running parallel SDN and legacy equipment is a realistic possibility for campuses in a mid-term time frame, and probably will occur since a massive, at-once replacement of existing hardware is not foreseen.

A potential researcher/user could be someone requesting for a BoD service to access a real time streaming resource which cannot be recovered afterwards. Another example that could fit into this use case is the Large Hadron Collider (LHC), which produces very large amounts of data that cannot be processed in a single place, and so must be disseminated to multiple processing centres. In such a case, it is clear that the bandwidth needs to be maintained to avoid data loss. Within campuses, network labs do usually try to break with actual network architectures introducing new terms such as SDN, Internet of Things (IoT) or Future Internet, among others, that would not interfere with the production network but that are also unable to run in parallel to it.

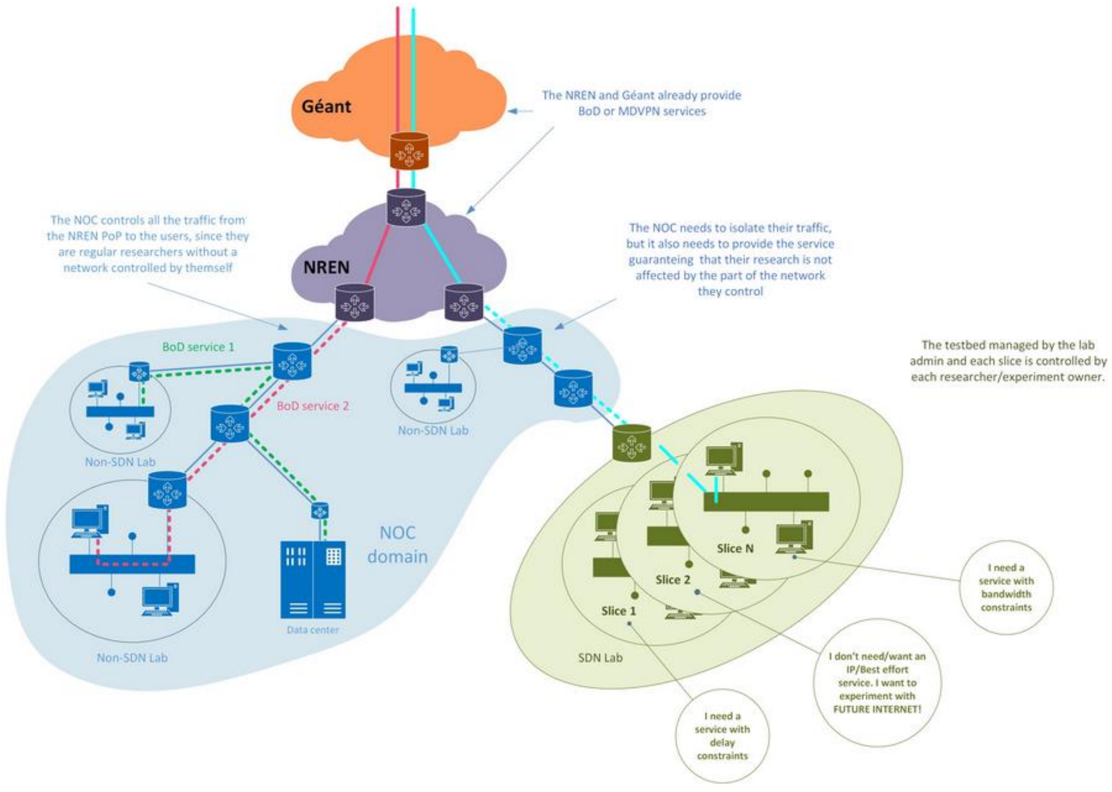

Géant
The NREN and Géant already provide BoD or MDVPN services
The NOC controls all the traffic from the NREN PoP to the users, since they are regular researchers without a network controlled by themself
NREN
The NOC needs to isolate their traffic, but it also needs to provide the service guaranteing that their research is not affected by the part of the network they control
The testbed managed by the lab admin and each slice is controlled by each researcher/experiment owner.
BoD service 1
BoD service 2
Non-SDN Lab
Non-SDN Lab
Non-SDN Lab
NOC domain
Data center
Slice N
Slice 2
Slice 1
SDN Lab
I need a service with bandwidth constraints
I don't need/want an IP/Best effort service. I want to experiment with FUTURE INTERNET!
I need a service with delay constraints

Figure 2.20: A hybrid campus infrastructure composed of a legacy and SDN-enabled segments

As shown in Figure 2.20, specialised traffic handling requirements (light green circles to the right, the 'SDN side') co-exist in campus environments together with BoD-related requirements (blue shape to the left, the 'legacy side'), the latter being addressed utilising enhancements over the NOC's already provided services.

Traffic in the SDN side of Figure 2.20 could be TCP/IP agnostic on demand, this means that no firewall, Network Address Translation (NAT), tunnel or any other mechanism designed to control or shape user behaviour can be in the path. This traffic should be also possible to identify and deliver or receive from other universities or research centres via the upstream NREN. The requirements are often similar to those of Science DMZ (Demilitarized Zone), however, the approach is more dynamic, without the restriction of being applied on the border of the campus network. A single SDN controller is introduced to enable the required functionality and expose a single point of entry for users to declare their NitC requests. Specialised flow handling can be introduced to segments of the campus network; these segments should also be shared among concurrent users through management policies and restrictions.

A detailed listing of the requirements emerging from the use case is presented in [JRA2NITC].

### 2.6.2 Considerations, Limitations and Implementation of Requirements

#### 2.6.2.1 *L2 Connectivity*

The NitC use case requires the creation of logical networks on demand based on legacy and SDN devices. In order to achieve proper Layer 2 connectivity, the handling of special cases such as Layer 2 broadcasts (ARP) must also be taken into account. This is handled seamlessly in the legacy side using VLANs to create separate broadcast domains, whereas in the SDN side we rely on flow rules instructing an OpenFlow device to direct a packet out of multiple egress ports. Complications arise when there are one or more hosts on the legacy side and two or more hosts on the SDN side (and specifically when at least one of the SDN hosts is on the EdgeBorder switch). Essentially, a broadcast packet originating from the SDN side must be handled differently based on the egress port; packets sent to the legacy trunk port need the appropriate VLAN tag pushed, without sending tagged packets to SDN hosts. Broadcasts arriving from the legacy side normally should not cause such problems, because we only need to strip the header and forward to SDN hosts. However, it seems that the mechanism used to perform multicast/broadcast (ONOS single-multi-intent) does not support the pop VLAN actions as expected.

The following workaround is proposed to resolve that problem:

Switches supporting OpenFlow version 1.3 [ONFSPECv1.3], offer a multi-table pipeline processing. Hence, the packet can be forwarded in all the SDN hosts, and later, using another pipeline table, the appropriate tag will be pushed in order to reach the legacy side. In recent versions of OpenFlow (version 1.5 [ONFSPECv1.5]), the multi-table pipeline can be split between ingress and egress flow tables. Egress flow tables may process a packet after the output port is specified by an ingress flow table, thus allowing us to push VLANs based on a packet's egress port.

In order to account for devices running older versions of OpenFlow, a dedicated switch as the edge SDN switch is considered. The switch must not have any hosts connected to it, so that VLANs can be pushed/popped, without having to worry about SDN hosts receiving tagged packets.

An entire switch is dedicated to act as an edge device and as an alternative, a loop mechanism is placed in the switch. Two ports (A, B), instead of the entire switch, are then dedicated to act as a bridge. Ports A and B, are cabled with each other so traffic sent out through A will enter B, which allows handling of L2 broadcasts by multicasting to every SDN host port, plus to port A. Then a separate flow rule pushes a VLAN tag to packets arriving in port B (after being outputted from A) and forwards them to the legacy side.

After setting up logical isolated networks it is important to ensure sufficient network resources. This can be achieved by rate limiting/guaranteeing bandwidth on specific ports. A rate-limiting scheme[4] was tested without success, therefore, further investigations are required. Ideally, we would like to shape the traffic based on the logical networks (VLANs), although in a way access ports represent only one VLAN.

#### 2.6.2.2 *NETCONF/ONOS Imitations and Remedies*

A requirement imposed by the use case on the legacy side is that the devices have to support NETCONF. The team experimented with three different Cisco devices:

- ISR (Integrated Service Router) 2911
- Catalyst switch 2960-S
- SM-X-ES3-24-P5 (Switching Module for the ISR)

Configuring/enabling NETCONF is the first step. The desired actions also needed to be formulated in XML messages. These XML messages are used to perform various RPC (Remote Procedure Call) operations, and must conform to the NETCONF schema supported by each device.

Such operations are: <get>, <get-config>, <edit-config>, <close-session>. NETCONF offers the functionality of exchanging RPC operations. It is up to the client (or in our case the SDN controller, ONOS) to properly formulate a message or modify a template, and then sent an XML to the device.

The CLI commands offered by the router/switch software are the upper bound of what can be done with NETCONF, and cannot be replaced entirely. During experimentation it was not possible to create new VLANs/add new descriptions to them, retrieve different types of information in XML format (i.e. <show> operations for: interface/port status, mac address-table, vlan). Generally, operations involving the modification of configuration files can be performed using NETCONF. However it is important to note that neither the structure of a configuration file nor that of the XML Device Configuration message is vendor agnostic.

The following functionalities were successfully achieved with NETCONF:

- Retrieving switch data:
  - Running configuration (RPC <get-config>, equivalent to show running-configuration command) in XML format.

[4] Policy Map each-port-limit
```
        Class class-default
        police 1000000 125000 exceed-action drop
```
# The snippet above should limit the traffic on 1 mbps.

[5] Cisco IOS Software, C3560E Software (C3560E-UNIVERSALK9-M), Version 15.0(2)EJ, RELEASE SOFTWARE (fc1).

    - Performing other *show* operations in plain text, not XML format (i.e. show mac-address table, show interfaces, show vlan).
- Configuring a switch port as Access/Trunk.
- Removing the configuration on a switch port.

NETCONF protocol is supported by ONOS as part of its southbound interfaces set. However, currently the controller only provides some basic functionality for the implementation of the initiation and establishment of a NETCONF session towards a given device.

In order to support a particular NETCONF operation towards a given device, the following features are necessary within ONOS:

- This operation should be included in the behaviours API exposed by ONOS core for the operations on devices.
- A driver implemented for this specific device type should implement this behaviour.

Since NETCONF support in ONOS is in its early stages, not all of the desired operations are included in the ONOS core API. Moreover, the implementation of drivers only includes a limited set of devices, most notably, no driver for CISCO IOS devices was included in ONOS and should be implemented from scratch.

The operations required by ONOS core that had to be implemented in the context of the NitC use-case PoC are the following:

- Behaviour interface for directly sending NETCONF XML to a specific device.
- Behaviour interface for administering VLANs and trunk mode on device ports.

As previously mentioned, a Cisco IOS driver had to be introduced in ONOS southbound in order to implement the above behaviours for this specific type of device.

A notable limitation concerns the behaviour for port discovery which is not supported for CISCO IOS. Port discovery takes place after the device discovery and NETCONF session setup. During this operation, ONOS interrogates the devices about their ports. In the case of CISCO IOS devices, NETCONF implementation on devices is not able to provide a reply structured in XML format and therefore parsing of the reply is not possible within ONOS. The consequence of this limitation is that the device ports are not available in ONOS core and thus no further manipulation can be performed on these ports (e.g., they are not visible in the ONOS GUI or cannot be auto-completed/cross-checked in ONOS CLI commands).

Apart from above features, three new CLI commands where introduced in ONOS to make use of the introduced behaviours previously mentioned, namely:

- Device-setconfiguration: For the sending of raw NETCONF XML messages to a given device.
- Device-add-interface: For the configuration of an interface on a device, i.e., addition to a VLAN and setting to trunk mode.
- Device-remove-interface: For the removal of the configuration from a device interface.

All of the above features have been approved by ON.Lab and are already included into ONOS code-base, release 1.5 [ONOS1.5].

### 2.6.2.3 *Dynamic Human Friendly Resource Mapping*

One of the challenges to be faced in this PoC was to provide the user with a human-friendly way to identify the resources that are available for the user. An application to store the relation between the real resource and its description has been developed. This application uses the ONOS persistenceService to store the data so that can be easily accessible.

The term "human friendly" is widely used but many times is not defined. In this case, a geographical meaning for network devices is proposed. A user might not have any kind of technical knowledge and thus, terms such as 'switch' should be avoided. However, a user knows exactly where his/her end-station/lab is located, the building, the floor, and can easily locate the wall port where the cable is plugged. Taking this information into account it is possible to provide a location-based structure and a rough description. The idea is that the description can be as long/short or descriptive as needed, e.g., "Wall port below window in Bob's office with tag #36". This system also has to work the other way around. Once a port is selected for provision, it needs to be translated from its human friendly identifier to a machine-understandable one, such as dpid:port for SDN or ip:port networkport for NETCONF.

It is important to emphasise that this topological way of representing the information is also very handy when assigning privileges for the users. Even more levels could be designed and dynamically created, although this is outside of the scope for this PoC.

### 2.6.2.4 *Overlay Technologies*

Overlay networks were introduced to overcome the limitations of traditional technologies in modern datacentres. Multi-tenancy and the need for isolation between the tenants was severely diminished by the limited number of VLANs in a physical network. As a consequence, technologies were designed to implement virtual networks on top of existing IP networks. Examples of such technologies are STT, VXLAN, and GENEVE [STT], [VXLAN], [GENEVE]. In general, the aforementioned operate in unison by encapsulating traffic at the source and de-capsulating at the destination. In other words: by establishing tunnels that provide Layer 2 connectivity between the tunnel termination points.

Despite the emerging overlay technologies, for the purposes of the PoC, the JRA2 team adopted and tested the IEEE 802.1q protocol [802.1q] as an overlay technology (VLANs over an Ethernet network), as it is most widely accepted in legacy environments and is supported by all vendors. Furthermore, network administrators in campuses are more familiar with this type of technology and for this reason, more willing to adopt it as an overlay technology.

The main drawback of the 802.1q overlay technology is the restricted number of supported VLANs to 4096. This can be alleviated by alternative approaches such as the QinQ approach which is standardized by IEEE at 802.1ad. Adopting this approach, it is possible to increase the number of supported VLANs quite significantly i.e. from 4096 to 4096×4096=16777216. Thus in this way, greater networking needs can be accommodated and served.

All the above aspects and implementation choices have emerged as an evolution of the initially defined requirements and the results of the initial testing. The following section describes the integrated view of all NitC components and capabilities.

### 2.6.3 Proof of Concept Scenario

The PoC scenario (implemented in the GÉANT Lab, see Section B.1, also Figure 2.21) consists of an SDN side with two PICA8 P3922 devices (with one host connected to each one) and a legacy side with two Cisco SM-X-ES3-24P (again with one host connected to each one). Both sides are connected through a Gigabit connection.

The PoC is managed with three ONOS applications providing an ONOS integrated UI. The user (NOC or researcher) interacts with the system only through this interface. The GN4Auth application is in charge of providing authentication and authorisation services to the PoC. GN4Storage application is in charge of storing the resources in a human friendly way and organising the information. The GN4NetICUI application allows the definition of the overlays by the user and enforces the changes into the network.

The SDN side is managed using ONOS intents. The intent service enforces the flows into the devices through the OpenFlow module. The pair dpid:port is used to define the connectivity. The legacy side is managed using the NETCONF module of ONOS. Connectivity in the legacy side is defined using VLANs. Therefore, there is a translation from VLAN to dpid:port mechanism. Unfortunately, it is not possible at this stage to direct traffic based on VLAN and dpid:port and untag the messages at the same time, so the only limitation for the user is to use the MAC addresses of the hosts in the legacy side.

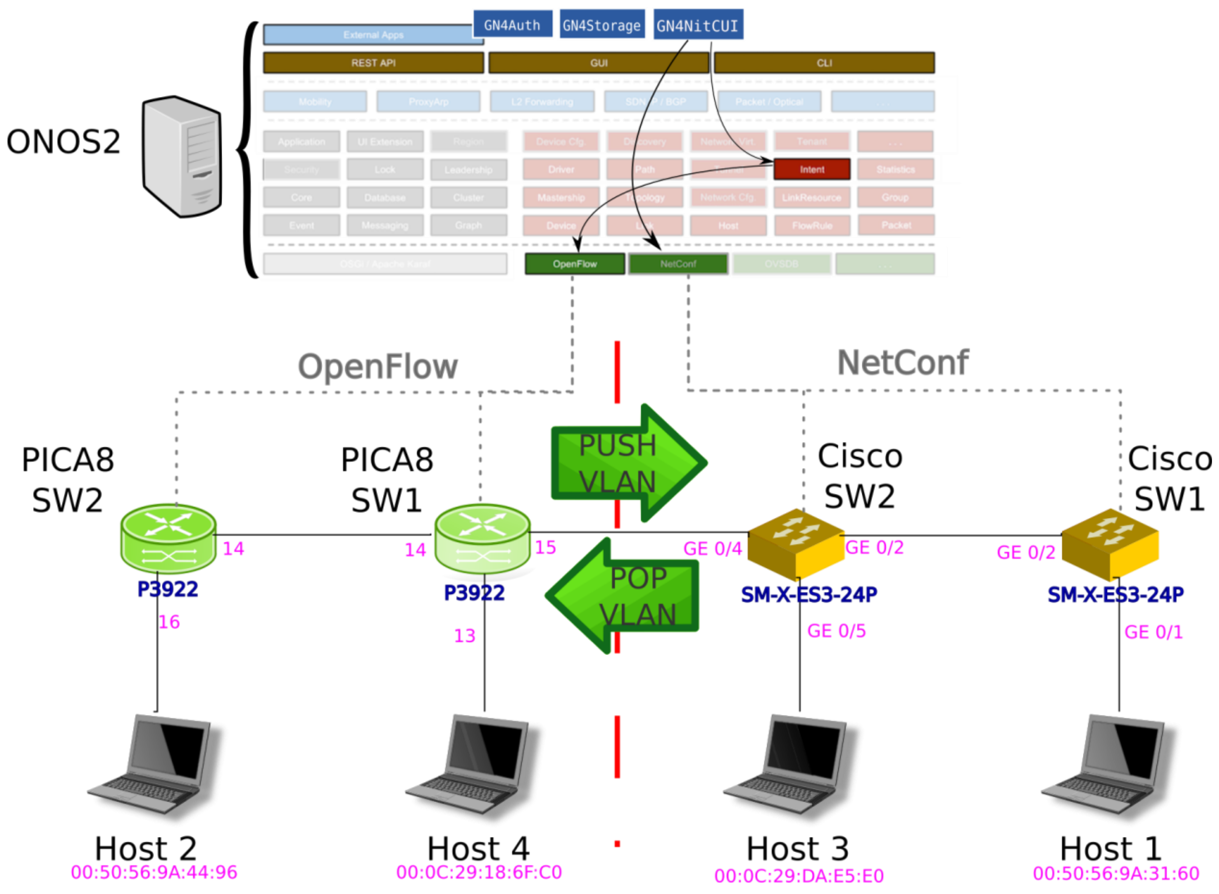


Figure 2.21: NitC PoC scenario

The actual configuration of the PoC in the GÉANT Lab is shown in Figure 2.22. The MX devices visible in the datapath have been used to reduce the 10G ports of Pica8s to 1G ports of the Cisco switches.

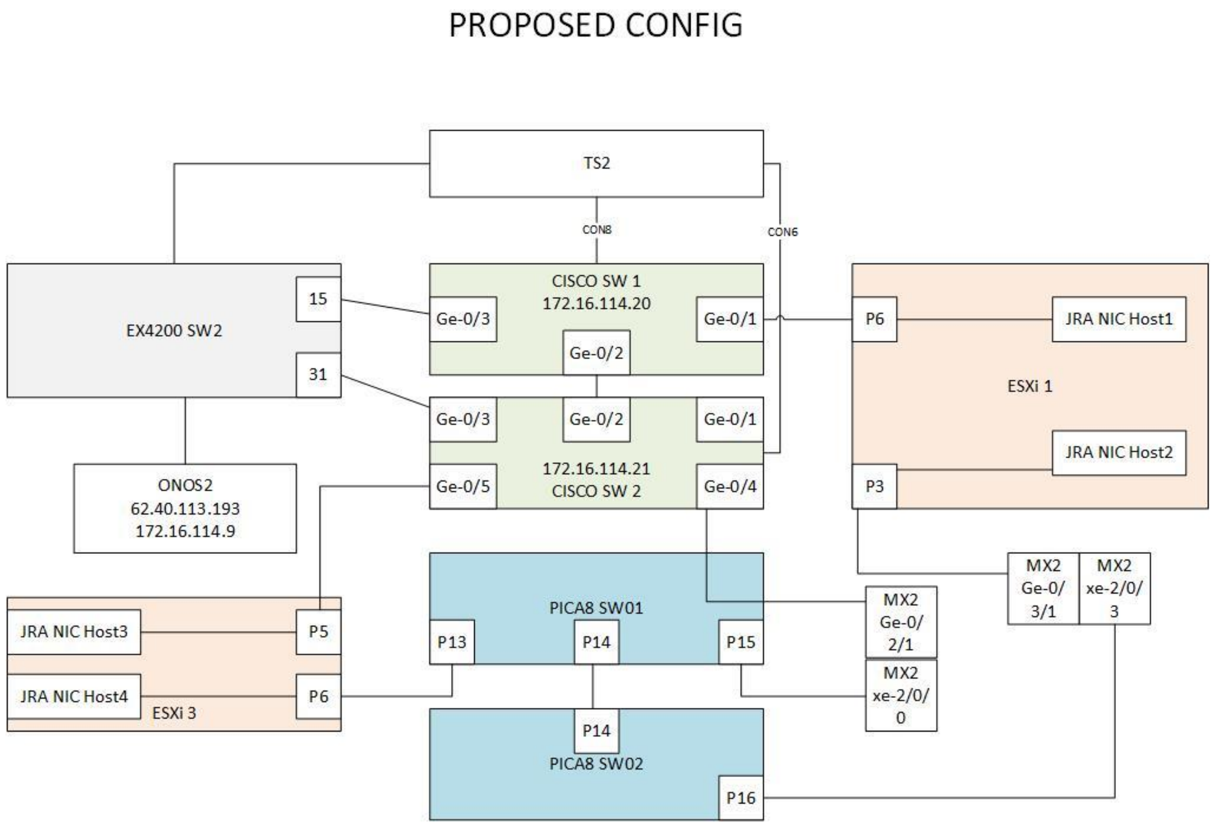


Figure 2.22: Detailed wiring view of NitC PoC scenario

This PoC shows how the NOC manages users (creation/removal/…) that are afterwards assigned to profiles, which can be trusted with some capabilities that will allow the profile to perform certain actions. The provisioning part is also taken into account by allowing the registration of resources that will be related with the geographical position in the campus (building, floor and wallport), so that the final user is provided with a meaningful description of the resources while operating the system.

Finally, the user's point of view is demonstrated by allowing the user to create network overlays and assign ports to the overlays in an intuitive way.

## 2.6.4 Proof of Concept Set-up

The components of the PoC are:

- ONOS: The SDN controller that allows to control an OpenFlow domain. It provides a set of basic services and features that applications can use. Within this use case work has been done to extend NETCONF functionality in ONOS.
- GN4Auth: App running in ONOS providing with users and profile capabilities.
- GN4StorageService: App running in ONOS that stores the relation between network devices and human friendly descriptions related to where they provide functionality, i.e.: dpid:port is mapped to building, floor, wallport.

- GN4NetICUI: App that takes information from GN4Auth and GN4StorageService to allow users to deploy services by themselves when enough permissions are granted by NOC.

#### 2.6.4.1 *PoC workflow*

- Step 1:
  - The NOC login in the GN4Auth application.
    - The NOC user is the only one created upon installation and that cannot/should not be removed, as well as the ADMIN profile.
- Step 2:
  - The NOC creates the buildings, floors and ports within GN4StorageService app.
    - The relation between geographical position of the resources and the resources themselves are stored in a distributed storage service within ONOS that would allow multiple instances of ONOS access the same information.
- Step 3:
  - The NOC creates a profile for Layer 2 users in GN4Auth.
    - Profiles are the grouping mechanism that will finally be assigned with the capabilities.
- Step 4:
  - The NOC assigns wallport capabilities, MAC address selection and in campus circuit creation capabilities to the Profile for Layer 2 users.
    - Capabilities are not configurable, they depend completely in implementation and what is embedded in but can be assigned to different profiles dynamically.
  - The NOC creates a User.
- Step 6:
  - The NOC assigns the user with the Layer 2 profile.
- Step 7:
  - The NOC authorises the user to utilise specific ports.
    - The NOC is presented with a list of the provisioned ports. At this stage, the NOC can allow the user with a specific port, a whole floor or the whole building.
- Step 8:
  - The User logs into the system and gets into the NetICUI App.
- Step 9:
  - The user creates a Layer 2 Network.
    - At this point a VLAN id is assigned for the network. Each Layer 2 network is assigned with a VLAN id upon creation.
- Step 10:
  - The user adds one of the ports that were allowed by NOC to the Layer 2 Network.
- Step 11:
  - The user adds more ports to the network.
- Step 12:
  - The user sets MAC addresses for ports in the legacy side.

        - This is a restriction due to the inability to use multi-table on the SDN side. This restriction could be removed if multi-table is used or using multiple links between the legacy and the SDN side.
- Step 13:
    - The user clicks the Apply button and connectivity is provided.
        - At this point, the intents are created for the SDN side, and NETCONF commands are sent to the devices to create the VLANs. Also the edge port in the legacy side is set to trunk mode.

#### 2.6.4.2 *NETCONF Interaction*

Figure 2.23 depicts the messages exchanged in a typical configuration scenario.

In order to connect a device with ONOS, both counterparts exchange NETCONF <hello> messages with which they announce the supported capabilities (schemas). After the negotiation phase is complete, ONOS can sent XML messages to the Cisco device.

- Specific interfaces can be configured as trunk or access be sending the appropriate <edit-config> messages. In case the desired setup is no longer needed other <edit-config> messages are sent to remove the configuration lines. From here the cycle can be repeated, as long as there is an active NETCONF session.
- If there is no need to interact with the device at all, the NETCONF session may be terminated with the <close-session> operation.

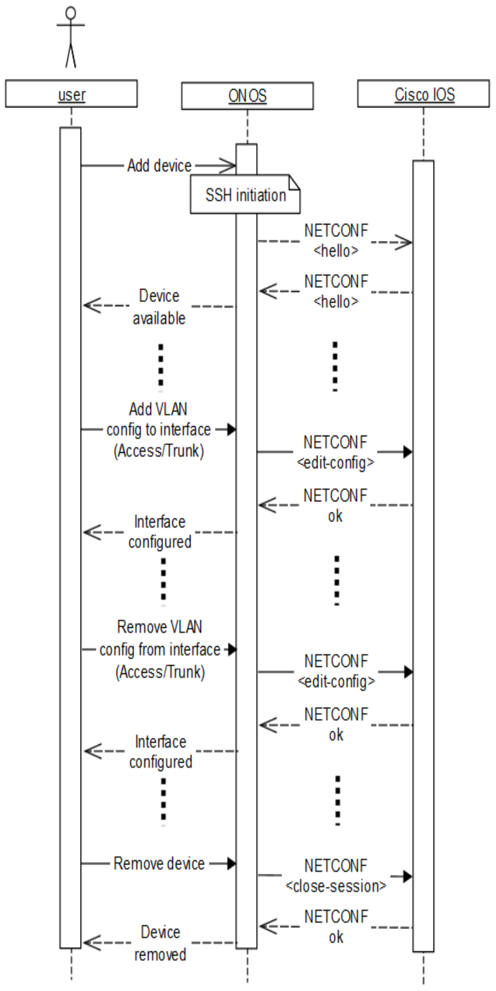


Figure 2.23: NETCONF Interaction sequence

Note that, in order to remove the trunk configuration from an interface the process needs to be broken down into two parts. This detailed interaction is presented in Figure 2.24.

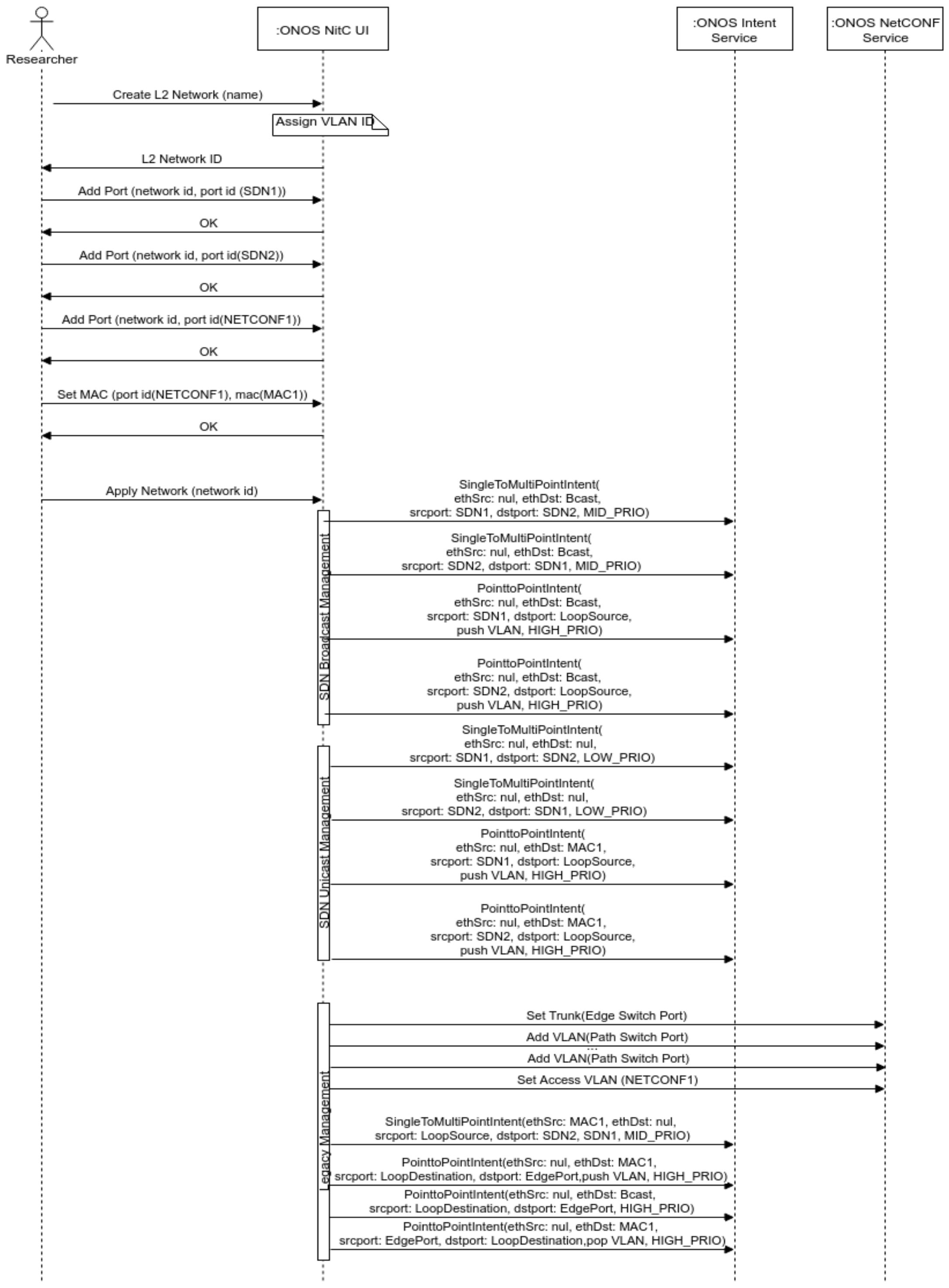

Researcher
:ONOS NitC UI
:ONOS Intent Service
:ONOS NetCONF Service
Create L2 Network (name)
Assign VLAN ID
L2 Network ID
Add Port (network id, port id (SDN1))
OK
Add Port (network id, port id(SDN2))
OK
Add Port (network id, port id(NETCONF1))
OK
Set MAC (port id(NETCONF1), mac(MAC1))
OK
Apply Network (network id)
SDN Broadcast Management
SingleToMultiPointIntent( ethSrc: nul, ethDst: Bcast, srcport: SDN1, dstport: SDN2, MID_PRIO)
SingleToMultiPointIntent( ethSrc: nul, ethDst: Bcast, srcport: SDN2, dstport: SDN1, MID_PRIO)
PointtoPointIntent( ethSrc: nul, ethDst: Bcast, srcport: SDN1, dstport: LoopSource, push VLAN, HIGH_PRIO)
PointtoPointIntent( ethSrc: nul, ethDst: Bcast, srcport: SDN2, dstport: LoopSource, push VLAN, HIGH_PRIO)
SDN Unicast Management
SingleToMultiPointIntent( ethSrc: nul, ethDst: nul, srcport: SDN1, dstport: SDN2, LOW_PRIO)
SingleToMultiPointIntent( ethSrc: nul, ethDst: nul, srcport: SDN2, dstport: SDN1, LOW_PRIO)
PointtoPointIntent( ethSrc: nul, ethDst: MAC1, srcport: SDN1, dstport: LoopSource, push VLAN, HIGH_PRIO)
PointtoPointIntent( ethSrc: nul, ethDst: MAC1, srcport: SDN2, dstport: LoopSource, push VLAN, HIGH_PRIO)
Legacy Management
Set Trunk(Edge Switch Port)
Add VLAN(Path Switch Port)
...
Add VLAN(Path Switch Port)
Set Access VLAN (NETCONF1)
SingleToMultiPointIntent(ethSrc: MAC1, ethDst: nul, srcport: LoopSource, dstport: SDN2, SDN1, MID_PRIO)
PointtoPointIntent(ethSrc: nul, ethDst: MAC1, srcport: LoopDestination, dstport: EdgePort,push VLAN, HIGH_PRIO)
PointtoPointIntent(ethSrc: nul, ethDst: Bcast, srcport: LoopDestination, dstport: EdgePort, HIGH_PRIO)
PointtoPointIntent(ethSrc: nul, ethDst: MAC1, srcport: EdgePort, dstport: LoopDestination,pop VLAN, HIGH_PRIO)

Figure 2.24: Detailed interaction diagram

### 2.6.5 Findings and Conclusions

Despite the preliminary status of the PoC, the results demonstrated two of the most-requested features in campus environments: management capabilities and user-driven provisioning of Layer 2 connectivity in the least intrusive way.

Although the use case focused on the integration of SDN and legacy hardware, the solution is also valid for legacy equipment only, which means that each entity can introduce the SDN equipment progressively, as required.

Bandwidth reservation and guarantees had to be postponed due to the various problems encountered in interacting with legacy equipment (Cisco IOS) through NETCONF and the amount of effort involved in developing the needed extensions for the controller.

Regarding NETCONF, although a good choice to integrate other vendors to our system, the integration of new devices is not straightforward, and some work needs to be done for each specific hardware.

Finally, it is important to emphasise that although using flows instead of intents would provide a more fine-grained interaction with the devices, the intents present three advantages:

- Network errors are transparent for the user and for the NOC.
- The NOC can more easily understand what the system is doing.
- Assuming NETCONF devices get integrated in the intent framework, no special treatment would be needed for them, thus simplifying the whole approach.

# 3 Proof of Concept Key Points

There are a number of key points from the five proof of concept use cases that are important to reiterate.

- In order to bring the SDXL2 and SDXL3 applications to production, some additional concerns related to security and integration with management systems need to be addressed.
- Future work will also include the integration of the missing requirements (for example, the realisation of a custom route selection process for SDXL3), the development of new services, such as VPLS, and the continuation of white box switch testing.
- The developed SDN-based capabilities can bring considerable savings in the operational costs and can dramatically reduce the service provisioning time, as they automate many tasks. Similar improvements in service provisioning and management are also affordable.
- Multiple approaches for managing overlay networks and hardware VTEPs were tested. The main conclusion is that the technology is not yet sufficiently mature.
- There are many options to provide greater flexibility and automation in the area of overlay networking and IaaS environments. Most of the testing in the area of managing overlay network topologies has been successful, and there is much momentum in the development of the used SDN controllers.
- A robustness test is needed for circuit provisioning and deletion.
- Two of the most requested features in campus environments: management capabilities and user-driven provisioning of Layer 2 connectivity, were addressed by the INaaS PoC in the least intrusive way.
- Although focus has been placed on the integration of SDN and legacy hardware, the solution is also valid for legacy equipment, which means that each entity can introduce the SDN equipment progressively, as required.
- Although NETCONF has been a good choice for vendor integration, the integration of new devices is not straightforward and some work needs to be done for each specific hardware.
- Although using flows instead of intents would provide a more fine-grained interaction with the devices, network errors are transparent for the user and for the NOC, the NOC can easily understand what the system is doing and assuming NETCONF devices are integrated in the intent framework, no special treatment would be needed thus simplifying the whole approach.
- The DynPaC framework could effectively foster the migration to an SDN-based BoD service provisioning. This framework could be used as the Network Resource Manager (NRM) of OpenFlow domains, thanks to its compatibility with the NSI-CS protocol. As such, the SDN-based approach ensures that future BoD deployments can utilise a standards-based southbound interface (i.e. OpenFlow) to the data plane instead of custom-made technology specific proxies.
- This solution does not only facilitate the integration of OpenFlow domains in the wider, multi-domain BoD solution, but also enables a future migration to an SDN-based BoD service provisioning to keep strategic connections with other NRENs.
- Future migration to an SDN-based BoD solution will make the BoD service more automated, flexible and powerful. This solution will benefit GÉANT as a service provider by enhancing

network resource utilisation. It will also benefit current network operators, automating many of the tasks that are currently done manually. And most importantly, it will benefit end-users by increasing the service request acceptance ratio and by providing more robust services with failure recovery guarantees.

- Standardisation on the northbound (e.g. controller northbound) interfaces is still an open issue in the SDN global activities. It is not a significant hurdle in SDN-based services adoption as it is left to each SDN-enable domain to implement differently. However, standardised east-west interfaces across SDN enabled domains are very important in a multidomain (i.e. multi-NREN) environment. NSI can undertake that role as demonstrated by the SDN BoD PoC.

# 4 Dissemination

The dissemination work of GN4-1 JRA2 was conducted by Task 3 and has been very important throughout the activity. It has enabled awareness creation for the SDN-based future network service capabilities that have been proposed, but also collection of feedback on the different use cases and PoCs presented, as well as additional “must-have” and “nice-to-have” features that would be interesting to incorporate to the design as part of future work.

Even though most of the PoCs have been demonstrated during the project duration, the complexity of some implementation and testing aspects of selected features have prevented us from submitting details of the work done earlier than the issue of this deliverable. The concepts and achievements on the NitC, SDN-IP/SDX L3 and L2 and SDN BoD use cases have recently been submitted to international conferences and events for dissemination purposes. Meanwhile, dissemination of further information on the transport SDN and INaaS use cases should take place in the near future. Additionally, internal dissemination actions within GÉANT and NREN community have been carried out.

The list of the dissemination events in which JRA2 has participated with of PoC demonstrations and the feedback received from the audience and attendees are presented in the following sections.

## 4.1 SDN-Based Bandwidth on Demand Proof of Concept Dissemination

### 4.1.1 Scientific Publications

| No. | Title | Main Author | Title of Periodical or Series | Publisher | Status |
|---|---|---|---|---|---|
| 1 | Providing multi-domain Bandwidth on Demand services in Software-Defined Networks | Alaitz Mendiola | Communications Magazine, special issue feature topic on “SDN use cases for Service Provider networks” | IEEE | Submitted |

Table 4.1: SDN-based BoD PoC publications

### 4.1.2 Dissemination Events

| No. | Type of Activities | Main Leader | Title | Name of Event | Date/ Period | Place | Type of Audience | Size of Audi-ence | Coun-tries Addressed | Status |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Workshop | Mian Usman | BoD service plans in GÉANT | LHCOPN-LHCONE meeting | 28-29 Oct-15 | Amster-dam Nether-lands | Scientific Community (Research) | 30 | Global | Accepted |
| 2 | Workshop | Alaitz Mendiola | DynPaC: A Path Computation Framework for SDN | 4th European Workshop on SDN - EWSDN | 1-3 Oct-15 | Bilbao, Spain | Scientific Community (Research) | 100 | Europe | Accepted |
| 3 | Symposium | Alaitz Mendiola | Multi-domain Bandwidth on Demand service provisioning using SDN | GN4-1 Symposium | 8-9 Mar-16 | Vienna, Austria | GÉANT Community | 200+ | Europe | Accepted |
| 4 | Conference | Alaitz Mendiola | SDN-enabled AutoBAHN. Envisioning future BoD services | TNC 2016 | 12-16 June-16 | Prague, Czech Republic | Scientific Community (HE, Research), Industry, Policy Makers, Media, GÉANT Community, EC | 700+ | Global | Planned |

Table 4.2: SDN-based dissemination events

### 4.1.3 Received Feedback

For the moment, all the papers submitted have either been accepted or are still under review. In the case of the accepted proposals, most of the reviewers have agreed that the SDN BoD solution based on the DynPaC framework could actually be applied to real scenarios in order to solve real problems, due to the benefits that it can provide to the network operations teams, the end users and the service providers.

## 4.2 SDN IP/SDX at Layers 3 & 2 Proof of Concept Dissemination

With regards the dissemination of the results, top-ranked journals and highly qualified conference venues in the SDN and NFV research areas have been considered.

### 4.2.1 Scientific Publications

| # | Title | Main author | Journal / Conference | Publisher | Status |
|---|---|---|---|---|---|
| 1 | SDN-based IP and Layer 2 services with Open Networking Operating System in the GÉANT Service Provider Network | Pier Luigi Ventre | Communication Magazine, special issue feature topic on "SDN use cases for Service Provider networks" | IEEE | Submitted |
| 2 | Revisiting Open eXchange Points with Software Defined Networking | Pier Luigi Ventre | 22nd IEEE International Symposium on Local and Metropolitan Area Networks - LANMAN 2016 | IEEE | Under preparation at the moment of writing |
| 3 | SDN based Open eXchange Point: the prototype of an hybrid OXP in the GÉANT project | Pier Luigi Ventre | 2nd IEEE Conference on Network Softwarization - NETSOFT 2016 | IEEE | Under preparation at the moment of writing |

Table 4.3: Publication list

### 4.2.2 Dissemination Events

| # | Title | Main Leader | Event | Date | Audience | Size of audience |
|---|---|---|---|---|---|---|
| 1 | **GÉANT SDN Experimentation - Introducing SDN capabilities in backbone** | Mian Usman | SDN & OpenFlow World Congress 2015 (SDN+NFV Innovation track) | 12-16 October 2015 | Scientific Community (Higher Education, Research), Industry, Civil Society, Policy Makers, Media | 1000+ Global |
| 2 | **DREAMER and GN4-JRA2 on GTS** | Pier Luigi Ventre | GTS Tech + Futures Workshop | 20 – 22 October 2015 | Scientific Community | 50 + remote |

| # | Title | Main Leader | Event | Date | Audience | Size of audience |
|---|---|---|---|---|---|---|
| 3 | **SDN in GÉANT backbone** | Mian Usman | 7th STF meeting | 24–25 February 2016 | GÉANT Access Port Managers, Ops engineers | 45 + remote |
| 4 | **SDN based Internet eXchange Point** | David Schmitz | GÉANT Symposium 2016 | 07–10 March 2016 | NREN community | 200 |
| 5 | **Investigating New Services for GÉANT Using Open Networking Operating System** | Matteo Gerola | Open Network Summit: Conference | 14–17 March 2016 | Scientific Community | 1000 + remote |
| 6 | **Global SDN deployment powered by ONOS** | Pier Luigi Ventre (European deployment) | Open Network Summit: Conference | 14–17 March 2016 | Scientific Community | 1000 + remote |

Table 4.4: Event list

#### 4.2.2.1 *Feedback received*

At time of writing, the GÉANT SDN IP / SDX use case has been presented twice: at the 2015 GTS workshop and at the Open Networking Summit. Moreover, it has been demonstrated at the Open Networking summit conference as part of the “Global SDN deployment powered by ONOS” (two presentations and one showcase).

Several service provider operators found the applications very useful for the agile management of both Layer 3 and Layer 2 services. The PoCs were found to be very interesting and ambitious for large scale deployments.

In general, the audience appreciated:

- The design of the GÉANT SDX, that allows a smooth transition from the current OXP/PoPs infrastructure towards more flexible and less expensive points of presence and a seamless integration with the rest of the GÉANT infrastructure.
- The modularity of the architecture, that allows independent start and stop of the Layer 3 and the Layer 2 services without impact on the infrastructure.
- The Realisation of the solution in a short time/limited resource consumption.

However, the audience also expects GÉANT to deploy these services in production to demonstrate their resiliency and scalability in real deployment and real workloads.

## 4.3 Transport SDN Proof of Concept Dissemination

### 4.3.1 Dissemination Events

| No. | Type of Activities | Main Leader | Title | Name of Event | Date/ Period | Place | Type of Audience | Size of Audi-ence | Countries Addressed | Status |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | GÉANT meetings | Mian Usman | SDN in GÉANT backbone | 7th STF meeting | 24-25 February 2016 | Amsterdam | GÉANT Access Port Managers, Ops engineers | 45+ remote | Europe | Accep-ted |
| 2 | Sympos-ium | Mian Usman | GÉANT Network evolution | GN4-1 Symposium | 8-9 March 2016 | Vienna, Austria | GÉANT Com-munity | 200+ | Europe | Accep-ted |

Table 4.5: Transport SDN PoC dissemination events

### 4.3.2 Received Feedback

Infinera attended the GÉANT network evolution workshop at the symposium, endorsing the approach upon which the GÉANT team and Infinera work collaboratively. The feedback from Infinera was that the R&E community needs to consider the multiple standardisation efforts for Management information Bases (MIBs). Infinera is making use of the YANG model and recent work coming out of IETF [YANG]. The key here is to encourage coordination of information model selection so that interoperation between vendors and network providers is facilitated.

## 4.4 Infrastructure and Network as a Service Proof of Concept Dissemination

### 4.4.1 Dissemination Events

| No. | Type of Activities | Main Leader | Title | Name of Event | Date/ Period | Place | Type of Audience | Size of Audi-ence | Countries Addressed | Status |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Sympos-ium | Erik Ruiter | INaaS Developments Overview | GN4-1 Symposium | 8-9 March 2016 | Vienna, Austria | GÉANT Community | 200+ | Europe | Accepted |

Table 4.6: INaaS PoC dissemination events

## 4.5 Network in the Campus Proof of Concept Dissemination

### 4.5.1 Dissemination Events

| No. | Type of Activiti es | Main Leader | Title | Name of Event | Date/ Period | Place | Type of Audience | Size of Audience | Countries Addressed | Status |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Demo Session + Poster | Jordi Ortiz | SDN Integration and Manage-ment Solutions for Campus Network Enhanced Services | Innovations in clouds, Internet and Networks - ICIN 2017 | 02-03--2016 | Paris, France | Scientific Community Research | 80 | Global | Accepted |
| 2 | Demo Session | Jordi Ortiz | SDN Integration and Manage-ment Solutions for Campus Network Enhanced Services | GN4-1 Symposium | 08-03-2016 | Vienna, Austria | GÉANT Com-munity | 200+ | Europe | Accepted |
| 3 | Lightning talk | Jordi Ortiz | | TNC 2016 | 12/16-06-2016 | Prague, Czech Republic | Scientific Com-munity (HE, Re-search) Industry, Policy Makers, Media, GÉANT Community, EC | 700+ | Global | Planned |

Table 4.7: NitC PoC dissemination events

### 4.5.2 Received Feedback

During the PoC dissemination activities, there was great interest on how the proposed enhanced network services within the campus could be extended with those provided by the NREN and how the user could provision himself those services when trusted by the NOC. Although neither the poster nor the demo focused on extra-campus connectivity, the audience was interested to know how such intra-campus capabilities could be extended.

Regarding VLAN selection as an overlay mechanism, there were questions regarding dropping the VLAN tag at the SDN side instead of maintaining it to direct traffic to destination. Performance issues were indicated as a reason, without always being convincing to the audience.

Overall, the audience was pleasantly surprised by the functional PoC.

# 5 Summary and Next Steps for Future Network Services

Overall, the work on SDN-enabled future network service capabilities during GN4-1 JRA2 has resulted in:

- Significant knowledge development for the GÉANT software and network engineers, as well as operations teams.
- Significant insight on community-supported SDN-controller frameworks.
- First-hand assessment of SDN support in legacy and white box hardware.
- Collaboration with industry and collaborative developments to deliver SDN capabilities.
- Contribution to the core code of ONOS controller with functionality relevant for backbone service providers and campus providers.
- Visibility of GÉANT SDN activities and evolution path.

The next step for the use cases presented in this document is their further development and deployment in pre-production environments for further validation and testing, with the ultimate goal being their deployment as service capabilities in operational environments.

Based on the work reported in this document, a number of functional and operational aspects need to be further developed to lead to stable solutions that can form part of service offerings. A series of pilots will be required to advance the PoCs to pre-production solutions. The challenges are to  work on the developed SDN applications but also to evolve the maturity of the overall ecosystem, including the community SDN controllers and vendors' support of SDN.

The SDN-based BoD use case is considered mature enough to be deployed in pilots early in the process. Application functionalities to be further developed include fine-grained handling of constraints, dynamic handling of all types of topology updates and support for VLAN translation. The application's capability to interoperate with any NSI-compliant domain will also be verified, based on the limited domain interoperation that was demonstrated via the PoC. Introducing the NitC application to solve the last mile issue is also anticipated.

SDX Layer 2 capabilities are also quite mature to be deployed in pilots. In this case, identifying the tunnelling modes (MAC, VLAN or MPLS-based) that are relevant and efficient operationally, and verifying that they scale to the requirements of GÉANT exchange points will be the main goal.

The functional prototype of the Transport SDN use case will be made available after the end of GN4-1 and will then have to be deployed in a pilot using the Infinera equipment available in GÉANT. Further ahead, in conjunction with the SDN-IP application, it will be used to enable multi-layer coordination through a single SDN controller.

The SDXL3 application will follow, with the primary goal of verifying its scalability against the requirements set by GÉANT. After ensuring scalability, the SDN-IP/SDXL3 applications will be evaluated in pilots for pre-production deployment, in conjunction with the GÉANT network evolution planning.

Finally, interconnection of L2 legacy networks to multi-tenant cloud environments will be further investigated and evaluated as part of integration with e-Infrastructures and cloud providers, as proposed for future work.

# Appendix A Testing of the Requirements: Methodology

In GN4-1 JRA2, a testing strategy was put in place to guide testing as well as the implementation of the proposed use cases' Proofs of Concept (PoCs). The testing strategy enabled the team with technical coherence, categorisation of the tests performed, identification of the required testing resources and timely/efficient testing execution.  A testing plan template was prepared for each of the proposed use cases. Later, the template was customised to the specifics of the concrete use case PoCs. The most important aspects of the testing methodology are provided in this Appendix.

## A.1 Requirements Traceability Matrix

The traceability matrix enables to track the development, status and execution of the tests. The main purpose of Requirement Traceability Matrix is to ensure that no functionality is left out of testing and it is a live document that must be properly updated as the testing progresses. One traceability matrix per use case was created in the JRA2 wiki space. The different fields of the table are detailed here:

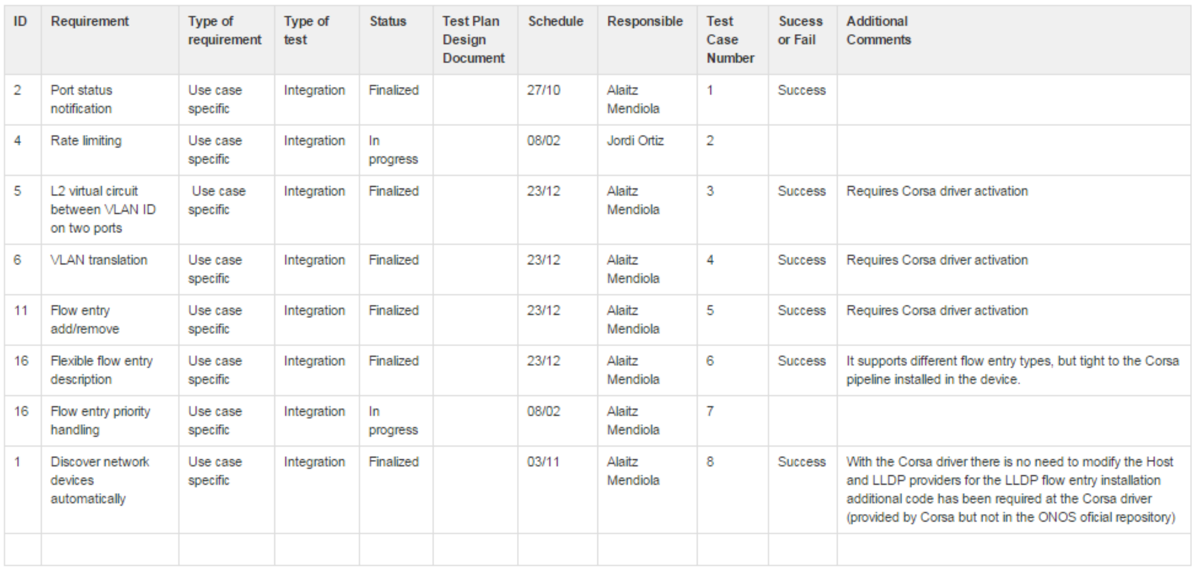
- **ID**: A unique ID number used to identify the traceability item in the requirements traceability matrix.
- **Requirement**: This column should be populated with a short technical description of the requirement.
- **Type of requirement**: It can be a general requirement linked to some others, or use case specific:
    - Use case specific.
    - Generic requirement.
- **Type of test**:  To identify the type of test that is intended to be run:
    - Unit/component testing.
    - Integration testing.
    - Performance testing.
    - Stress testing.
- **Status**: This column should be populated with the current status of the functional requirement:
    - Designing,
    - Preparing

  - Execution ongoing.
  - Finalised.

- **Test plan design document**: This column should be populated with a LINK to the test plan design document (separate document for each of the requirements). It must include:
  - Requirement ID.
  - Approach.
  - Requirement testing tasks.
  - Input: Determine the test entry.
  - Output and describe the exit criteria. (What is the expected outcome/verification mean once the test has finalized). Pass / Fail criteria.
  - Facilities: Scenario (resources, components, equipment, required software).
  - Procedure.
  - Schedule.
  - Responsible.
  - Observations.
  - Success or Failure Type.
- **Schedule**: You can book here the time slot(s) when each requirement will be tested (high level). It must match the schedule set in the test plan design document.
- **Responsible**: This column should be populated with the responsible of testing each of the requirements of the use cases.
- **Test case number:** This column should be populated with the test case number linked to the requirement.
- **Success or Fail**: Specify is the requirement test passed or failed.

Additional comments:

Figure A.1 shows a screen shoot of a partial view of a traceability matrix for the SDN-based BoD use case. As it can be shown, the purpose of the traceability matrix is to provide a quick view on the up-to-date status of each of the requirements to be tested at a glance.



| ID | Requirement | Type of requirement | Type of test | Status | Test Plan Design Document | Schedule | Responsible | Test Case Number | Sucess or Fail | Additional Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | Port status notification | Use case specific | Integration | Finalized | | 27/10 | Alaitz Mendiola | 1 | Success | |
| 4 | Rate limiting | Use case specific | Integration | In progress | | 08/02 | Jordi Ortiz | 2 | | |
| 5 | L2 virtual circuit between VLAN ID on two ports | Use case specific | Integration | Finalized | | 23/12 | Alaitz Mendiola | 3 | Success | Requires Corsa driver activation |
| 6 | VLAN translation | Use case specific | Integration | Finalized | | 23/12 | Alaitz Mendiola | 4 | Success | Requires Corsa driver activation |
| 11 | Flow entry add/remove | Use case specific | Integration | Finalized | | 23/12 | Alaitz Mendiola | 5 | Success | Requires Corsa driver activation |
| 16 | Flexible flow entry description | Use case specific | Integration | Finalized | | 23/12 | Alaitz Mendiola | 6 | Success | It supports different flow entry types, but tight to the Corsa pipeline installed in the device. |
| 16 | Flow entry priority handling | Use case specific | Integration | In progress | | 08/02 | Alaitz Mendiola | 7 | | |
| 1 | Discover network devices automatically | Use case specific | Integration | Finalized | | 03/11 | Alaitz Mendiola | 8 | Success | With the Corsa driver there is no need to modify the Host and LLDP providers for the LLDP flow entry installation additional code has been required at the Corsa driver (provided by Corsa but not in the ONOS oficial repository) |
| | | | | | | | | | | |

Figure A.1: Screenshot of the SDN-based BoD use case traceability matrix taken in January 2016

## A.2 Test Plan

### A.2.1 Purpose of the Test Plan

The purpose of the test plan is to guarantee that all the necessary elements to carry out the testing of the requirements are in place before executing the testing, to identify whether the testing has failed or succeeded and to enable, with the means to restructure, the testing of a requirement in case the test failed. The test plan should be understood as a tool to keep the test environment under control and guide the preparation process in advance of the testing execution. One test plan for each of the requirements of the use cases was created at the JRA2 wiki space.

### A.2.2 Test Strategy and Performance

The test strategy and performance has been planned considering the other involved tasks of the activity - Task 1 Future Network Services' requirements and architectures and Task 2 Future Network Services' software solutions – to synchronise and align the efforts towards the implementation of the use cases' PoCs. Figure A.2 shows the test strategy conceived in Task 3, including the different parts that compose the testing activity (including: the traceability matrix, the test plan, text execution and documentation and test analysis and feedback) and the relation to Task 1 and Task 2.

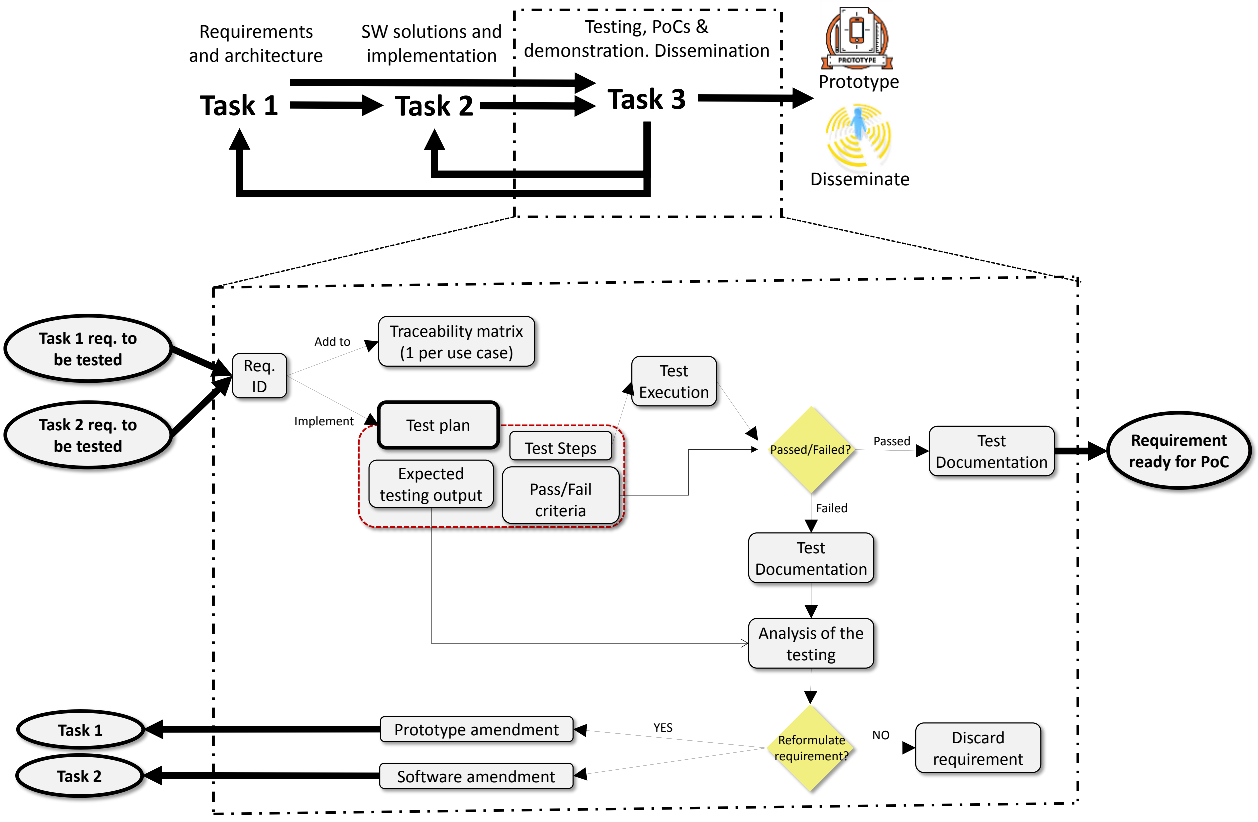


Figure A.2: Detail of the Task 3 test strategy in the context of the overall JRA2 activity

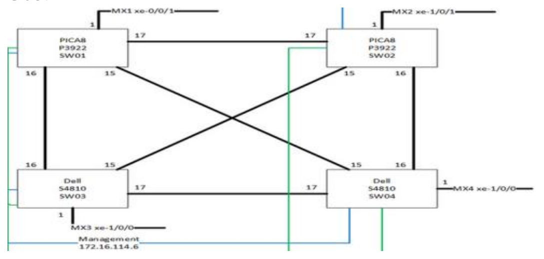
## A.2.3 Test Plan Design

The test plan design followed a general approach to enable the preparation of different types of testing (mainly physical equipment, software and integration testing). Each use case comprises a test plan per each of their requirements that includes the following items:

- Requirement ID: ID of the requirement given for identification purposes.
- Requirement name: Name given to the requirement.
- Linked to: It may be the case that the requirement is also addressed in other use cases. In case the testing has already been done, there is no need to repeat it. Indicate the link to the site, the use case, and requirement ID of the one that has been tested and there is no need to complete the whole testing process.
- Approach: Describe the overall approaches to testing. The approach should be described in sufficient detail to permit identification of the major testing tasks and estimation of the time required to do each task. Identify the types of testing to be performed along with the methods and criteria to be used in performing test activities. Describe the specific methods and procedures for each type of testing.

- Requirement testing tasks/procedure/steps: Identify the set of tasks necessary to prepare for and perform testing activities. Identify all inter-task dependencies and any specific skills required.
- Input: Identify the inputs required to trigger each test.
- Output and Exit (Pass/Fail criteria): Identify the outputs from each type of testing. What is the expected outcome/verification mean once the test has finalized. Also specify the criteria to be used to determine whether each item has passed or failed testing. The test of the requirement is considered as successful, once the "output" and the "pass criteria" are the same.
    - Approval Criteria: Specify the conditions that need to be met to approve test results.
    - Fail Criteria: Specify the conditions that indicate that the test has not been successfully accomplished.
    - Test output: Specify the output of the test.
- Facilities: Identify the resources allocated for the performance of testing tasks. Identify the components, the equipment, the required software, tools, etc.).
- Test scenario figure that includes the physical scenario set up with all the involved equipment and software.
- Responsible and participants: Responsible person of executing and documenting the test of the requirement and other involved participants.
- Schedule: Specify the concrete date(s) when the test execution will take place.
- Observations: Include any relevant additional considerations.
- Success or Failure Type: Choose among one of the following categories: Critical, High, Medium, Low.
- Test plan summary table: The table contains a summary of previous items to prepare the test of each of the requirements. The summary tables of each of the requirements that have been tested have been included in the wiki space of each of the UCs. Table A.1 represents an example of a test plan summary table for a concrete requirement.

| | |
|---|---|
| Requirement ID: | *#45* |
| Requirement Name: | *Change Password – Normal State* |
| Linked to: | *wiki.geant.org/pages/xxxxx Requirement #33 of use case "BoD".* |
| Requirement testing tasks/procedure/ steps | 1. *Launch software application Login Screen*<br>2. *Type in test username and password, click "Login"*<br>3. *Click on link for "Settings"*<br>4. *Click on link for "Change Password"* |

| | |
|---|---|
| | *5. In pop-up text box, type existing password in "Existing Password" field using numbers, letters and symbols*<br>*6. In pop-up text box, type new password in "New Password" field*<br>*7. In pop-up text box, type new password in "Confirm New Password" field*<br>*8. Click "Ok"*<br>*9. Click "Exit Application"*<br>*10. Launch software application Login Screen*<br>*11. Type in test username and modified password, click "Login"* |
| Setup/input | • Introduce username and previous password. |
| Exit (Pass/Fail criteria) | • Approval criteria: The password has been successfully changed.<br>• Fail Criteria: The password has not changed |
| Expected Output(s)/Result(s): | *1. Login Screen appears*<br>*2. System accepts login and launches Main Screen*<br>*3. Settings screen appears*<br>*4. Change Password pop-up text box appears*<br>*5. Text box accepts numbers, letters and symbols*<br>*6. Text box accepts numbers, letters and symbols*<br>*7. Text box accepts numbers, letters and symbols*<br>*8. System accepts the password change*<br>*9. Application closes*<br>*10. Login Screen appears*<br>*11. System accepts login and launches Main Screen.* |
| Facilities | *Detail the required facilities to carry out the testing*<br>• *Hardware*<br>• *Software*<br>• *Other tools, techniques, methodologies, etc.* |
| Test scenario Figure | • *A figure including the testbed performance, equipment, software, etc.*<br> MX1 xe-0/0/1<br>MX2 xe-1/0/1<br>PICA8 P3922 SW01<br>PICA8 P3922 SW02<br>Dell S4810 SW03<br>Dell S4810 SW04<br>MX3 xe-1/0/0<br>MX4 xe-1/0/0<br>Management 172.16.114.6<br>1<br>15<br>16<br>17 |
| Responsible and participants | • *Responsible: José Aznar*<br>• *Participants: José Aznar, John Doe, etc.* |
| Schedule | *03/02/2016* |

| | |
|---|---|
| Observations | *No other observations* |
| Success or Failure Type (Critical, High, Medium, Low) | Critical |

Table A.1: Example of a test plan summary table

### A.2.4 Test Execution and Documentation

Once the test of a requirement has been planned and the resources are in place, the test execution follows. The execution should be executed according to the steps which have been established in the "procedure" field of previous test plan summary table.

One requirement may need one or more tests. All of them are documented and include a "test case number" to differentiate among the different tests of the same requirement. Additionally, the test is validated/rejected by comparing the "Expected Output(s)/Result(s)" specified in the test plan summary table with real outcomes of the testing.

### A.2.5 Analysis of the Testing and Feedback

The analysis of the tested requirement involves two possibilities:

- In case the testing has succeeded, the requirement is ready to be part of the functionalities that will demonstrate the proposed use case in a later stage.
- In case the testing failed, the reason why it failed is analysed. During the testing phase, several reasons for test failure have been identified:
  - In the case of a software implementation test, the implementation does not satisfy the expected performance.
  - In the case of equipment testing, the equipment does not support some specific features that are required to match the expected outcome.
  - In the case of an integration testing requirement, the interfaces or connectors among the resources and or the software managing the resources do not behave as expected.

For each concrete test, a decision on the next steps is taken. In the case of software testing, the possibility of re-implementing or modifying the functionality is evaluated. For equipment and integration tests, the possibility of reformulating the testing, or including some alternative equipment that may satisfy the test is analysed. In case alternative ways to address the requirement have been identified, then the testing wheel suggests to repeat the cycle. Otherwise, the requirement is marked as "not achievable" and removed from the list of functionalities.

### A.2.6 Testing Methodology Outcomes

As the planning and execution of JRA2 PoC tests progressed, it became apparent that the resulting methodology challenges should be captured and addressed in a more systematic way for the benefit of future testing activities, particularly those conducted during the transition to operational use. In addition, establishing a common understanding of testing work and terminology between JRA and SA activities would help both, particularly when some technology or solution that was successfully assessed for possible future application is eventually migrated to the operational infrastructure. Although the tests conducted within JRAs are more limited in terms of scope and resources than the highly formal tests required before the launch of actual services, both types of testing would benefit from a closer alignment of their approaches and documentation.

Inspired by the ongoing work of JRA2, GN4-1 SA4 Task 1 “Quality validation and testing” produced a Testing Framework as part of SA4 Task 1 public knowledge base. Starting from the live documentation and specifications of its JRA2 use cases, requirements, test plans, environment descriptions and execution logs, this document outlined a structured approach to testing, dealing with testing best practices, management, enactment, documentation and tailoring. It also provides a source of common terminology. The highlights from this document and its glossary were incorporated into the GN4-1 deliverable D8.1 “Service Validation and Testing Process” [D8.1].

This Testing Framework is aligned with the major standards in the field, such as ISO/IEC/IEEE 29119, IEEE 829 and BS 7925, complements ITIL recommendations and processes, but is, at the same time, in line with the common language and practices of testing.

Although it is primarily meant to support the GÉANT validation and testing practices for software-based services and the related infrastructure (the mentioned standards are primarily related to testing of software systems), the developed framework was prepared also with hardware and system testing in mind. It therefore may help in strengthening of the common ground between networking engineers, software developers, testers and end-users. It can be used to help consolidating evaluation of various externally developed products and solutions, those developed and by GÉANT community, and even throughout the service lifecycle - that is, before upgrades or enhancements of GÉANT services.

# Appendix B Testbed Facilities

For the purposes of the PoC design and deployment, advanced testbed facilities were implemented. In this section, a summary of the facilities utilised and developed for the purposes of JRA2 PoCs are presented.

## B.1 GÉANT Lab

The GÉANT Lab in Cambridge was made available for the JRA2 activity to use for the deployment of SDN equipment and the development, testing and validation of use cases. The presence of a physical Lab has been a fundamental driver providing a centralised location for use by the whole activity. Having a centralised environment greatly simplified the coordination of testing activities and the sharing of information and findings across teams.

The GÉANT Lab provides a large amount of equipment and space. It is also well maintained and connected, as it is regularly used by the GÉANT Operations team for software and product testing, and validation. The Lab includes a number of routing, switching and optical transmission nodes as well as several virtual machines servers.

Figure B.1 below shows the non-SDN part of the Lab. The available equipment in the lab includes:

- 3 x Juniper MX-480
- 1 x Juniper MX-960
- 1 x Juniper M120
- 4 x Cisco routers

The above equipment is used to emulate the GÉANT production network, which helps with PoC testing. The topology of the equipment is connected is shown below:

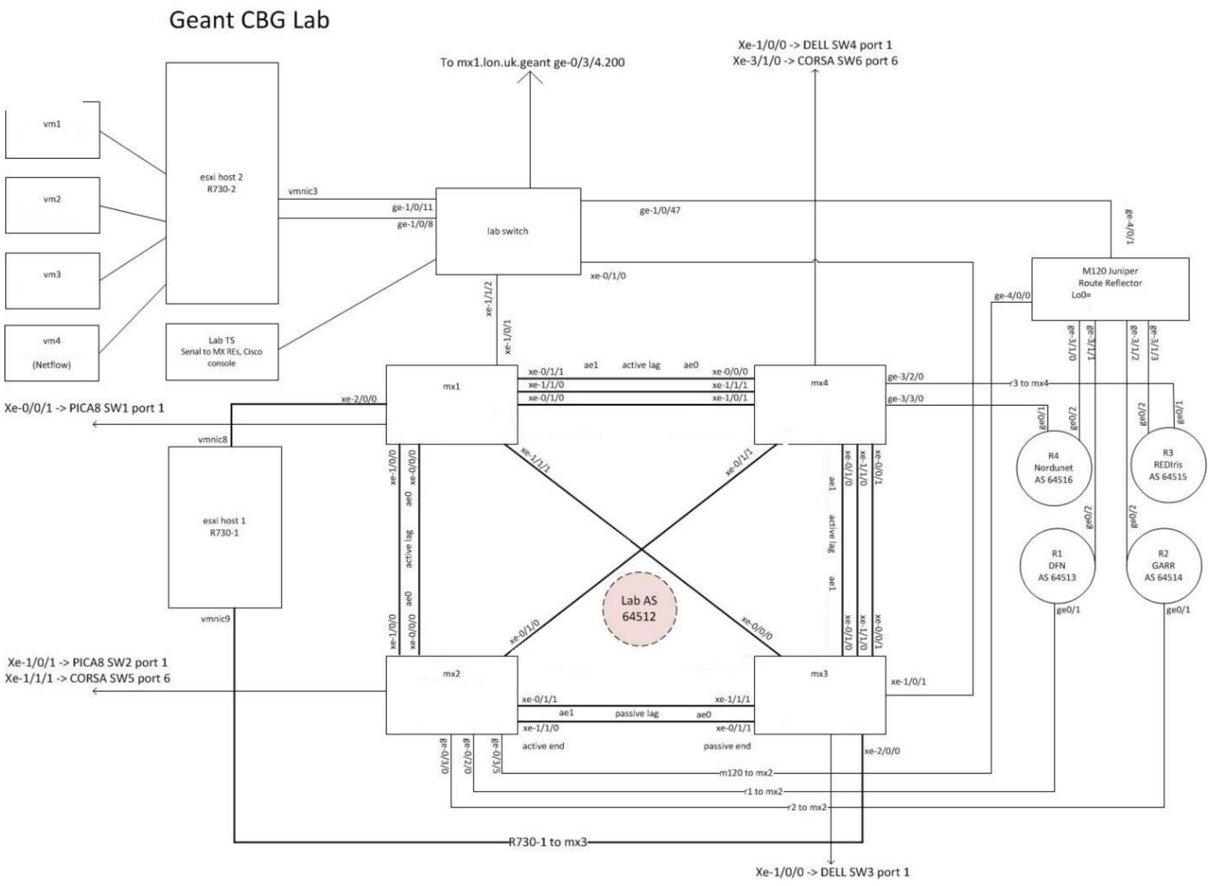


Figure B.1: LAB in Cambridge testbed facilities – non-SDN part

As part of the JRA2 work, a number of hardware SDN switches from different Dell, Pica8 and Corsa vendors were also deployed to complement the already rich set of equipment and provide a complete environment for SDN testing.

The SDN-specific part of the Lab is shown in Figure B.2: . Figure B.3:  shows the SDN lab topology in Cambridge, with management IP addresses. It consists of the following equipment:

- 2 x Corsa 6410 Switches.
- 2 x PICA 8 Switches.
- 2 x Dell S4810 Switches running Cumulus Linux.
- 1 x Dell Server for VMs.

It also connects to the GÉANT Juniper MX lab which is shown in Figure B.3: . The topology can be changed by shutting down any ports that are not needed.

The SDN-specific part of the Lab is shown in Figure B.2:

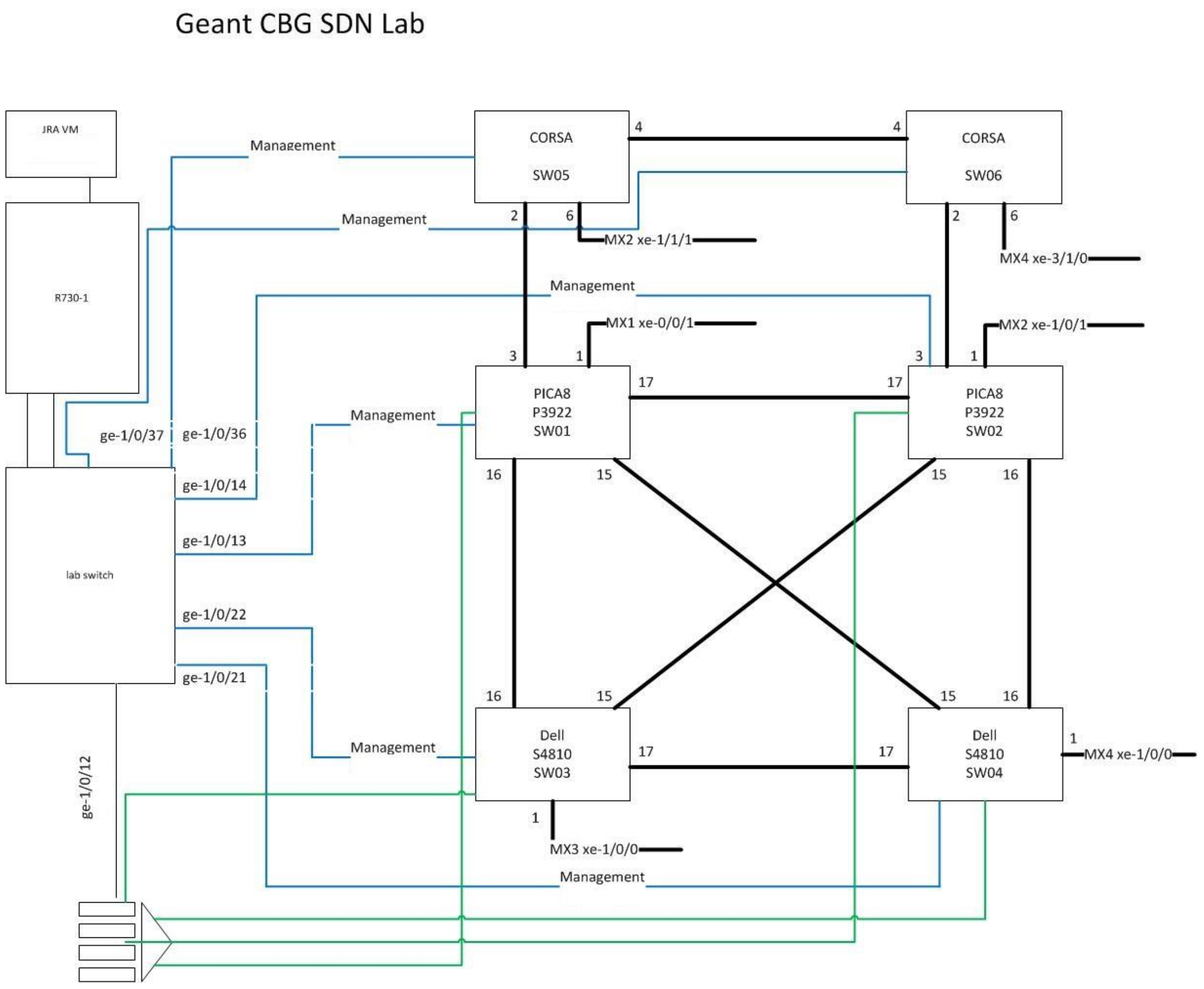


Figure B.2: LAB in Cambridge testbed facilities - SDN part

Virtualisation in the Lab played a key role as it allowed for the provisioning of multiple "slices" for testing. More than 30 virtual machines, a number of virtual routers and several slices of SDN switches were instantiated, allowing for the creation of the complex overlay topologies required for supporting the JRA2 activities.

The following diagrams show some of the JRA2 use-case topologies instantiated in the GÉANT Lab.

### B.1.1 GÉANT Lab Setup for the NitC Use Case

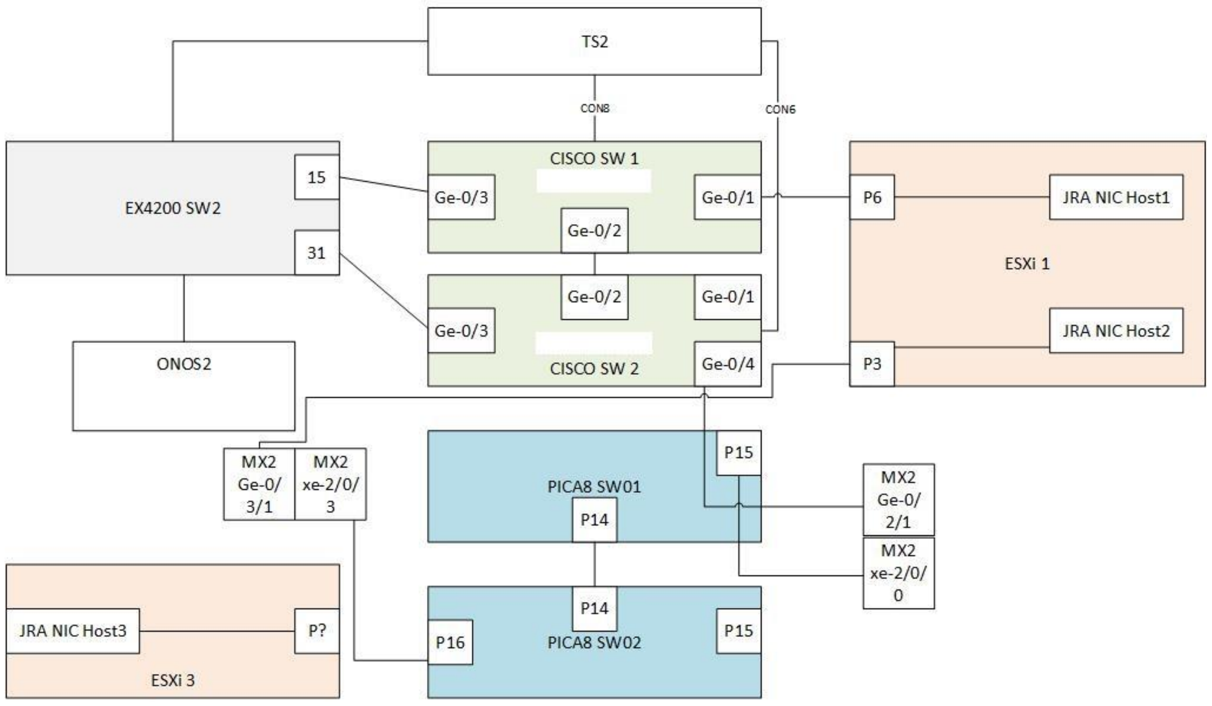


Figure B.3: Slice of the GÉANT Lab facilities dedicated to the NitC use case PoC implementation and demonstration.

### B.1.2 GÉANT Lab Setup for the SDN Use Case

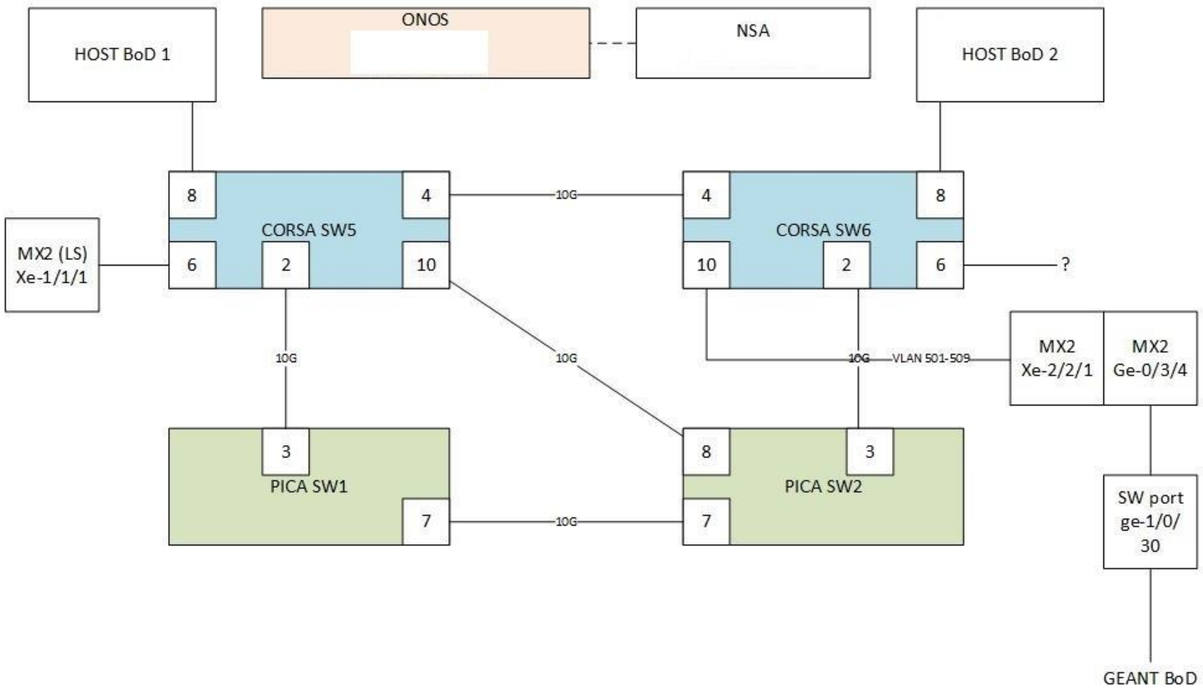


Figure B.4: Slice of the GÉANT Lab facilities dedicated to the SDN BoD use case PoC implementation and demonstration

### B.1.3 GÉANT Lab Setup for the SDN IP Use Case

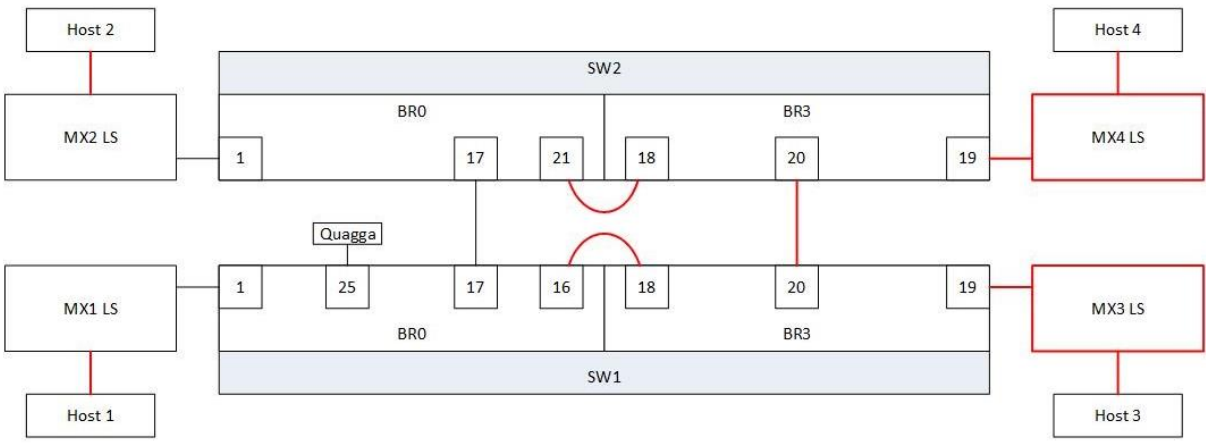


Figure B.5: Slice of the GÉANT Lab facilities dedicated to the SDN use case PoC implementation and demonstration

Apart from general-purpose SDN equipment and software testing, the Lab was primarily used for instantiating the PoC demonstrators at various events. Isolation among the PoC deployments was ensured, to allow for different PoC demos to be run in parallel at the relevant events. All demos were run live, directly from the GÉANT Lab.

## B.2 SURFsara Facilities

SURFsara operates a test lab in Amsterdam that has been devoted to test and validate the INaaS use case [SURFsara]. This lab hosts a number of physical compute servers and various brands / types of networking equipment. It runs a Mirantis OpenStack deployment based on Ubuntu 14.04, on three nodes [MIRANTIS].

This setup has been made available for the INaaS workgroup as part of GN4_JRA2 by means of a intermediate host stepping stone, which is connected to the firewall connected to the internet, using a SURFnet link. A number of networks are configured to be able to operate the OpenStack environment in multi-tenant setup using Neutron and VXLAN tunnelling. This also provides segmentation between management and production networks.

In addition to the available servers, there is also networking equipment available from various vendors, including Dell, Juniper and Pica8. This can be used to build networking scenarios to test external connectivity for the OpenStack cluster.

Figure B.6 shows SURFsara testbed overview:

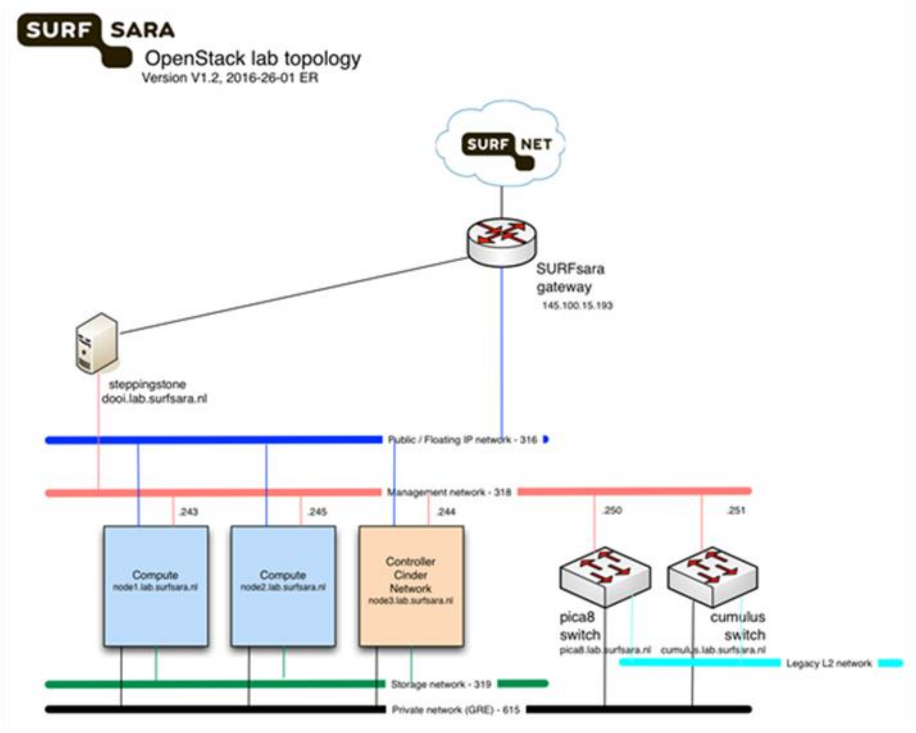


Figure B.6: SURFsara OpenStack lab topology

# Appendix C Summary of Testing Results for the INaaS Use Case

| Requirement | Type of test | Success or Fail | Additional Comments |
|---|---|---|---|
| OpenDaylight (and / or Neutron) can identify resources in an OVS | Component Testing | Success (with ODL xSQLsql) | Follow up on relating VM to OVS interface by REST interface |
| OpenDaylight (and / or Neutron) can create new resources in an OVS<br><br>a. Create a new virtual port in an OVS<br>b. Create a VLAN in OVS | Component Testing | Success (with ODL REST) | |
| OpenDaylight (and / or Neutron) can configure VLANs on ports, access and trunk | Component Testing | Success (with ODL REST) | Requires Corsa driver activation |
| OpenDaylight (and / or Neutron) can present port information such as state, traffic statistics, VLAN assignment | Component Testing | Mostly Success (with xSQLsql) | Follow up to check whether the VLAN assignment can also be queried with REST calls |
| OpenDaylight (and / or Neutron) can configure L2 protocols on OVS ports. Protocols to be tested LACP and STP | Component Testing | | Current status: Only interface to query current state of LACP and STP in ODL |
| OpenDaylight (and / or Neutron) can create a virtual port in OVS of VXLAN type IP address of remote tunnel end point should be provided as an argument | Component Testing | Success | |

| Requirement | Type of test | Success or Fail | Additional Comments |
|---|---|---|---|
| OpenDaylight (and / or Neutron) can orchestrate the two servers/nodes in order to acquire the VXLAN tunnel and use it as a L2 pipe between desired running OVS instances | Component Testing | Success | |
| OpenDaylight (and / or Neutron) can create a virtual port in OVS of GENEVE type. IP address of remote tunnel end point should be provided as an argument | Component Testing | – | GENEVE is not supported in Lab |
| OpenDaylight (and / or Neutron) can orchestrate the two servers/nodes in order to acquire the GENEVE tunnel and use it as a L2 pipe between desired running OVS instances | Component Testing | – | GENEVE is not supported in Lab |
| Implement network topology in a single VLAN using Neutron<br>Attach vmA in ovsA port 1 running in host A<br>Configure port 1 on ovsA as access to vlan RED<br>Attach vmB in ovsB port 1 running in host B<br>Configure port 1 on ovsB as access to vlan RED<br>Attach vmC in ovsC port 1 running in host C<br>Configure port 1 on ovsC as access to vlan RED | Component Testing | Success | |
| Create VXLAN tunnels between hosts A,B and C. Verify that no loop is created using Neutron and OpenDaylight | Component Testing ODL + Neutron | Success | |
| Create OF rules for learning MACs in data plane | Component Testing ODL | – | OpenFlow rules are created by Open vSwitch |

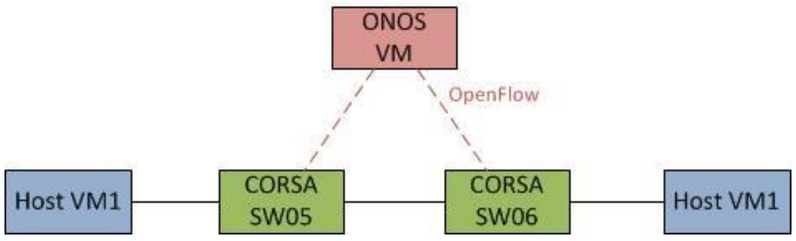
| Requirement | Type of test | Success or Fail | Additional Comments |
|---|---|---|---|
| Create OF rules for broadcast traffic forwarding between the VMs belonging to broadcast domain RED | Component Testing ODL | – | OpenFlow rules are created by Open vSwitch |
| Create OF rules for unicast traffic forwarding between the VMs belonging to broadcast domain RED | Component Testing ODL | – | OpenFlow rules are created by Open vSwitch |
| Implements / supports an NBI and can be managed either by ODL/MidoNet or Neutron. NB protocols should be OVSDB and/or OF | Component Testing MidoNet | Success | |
| Supports VXLAN, be able to operate as VTEP | Component Testing MidoNet | Success | Supported by MidoNet / Neutron using a Cumulus switch as HW VTEP |
| The HVXLANGW should be able to maintain 2 VXtunnel interfaces towards the 2 compute nodes, and carry traffic belonging to multiple VNIs | Component Testing MidoNet | Success | Supported by MidoNet / Neutron using a Cumulus switch as HW VTEP |
| Regarding the VLAN side (or legacy side) the gateway should behave like a typical bridge. Combining VXLAN and VLAN sides the HVXLANGW should support mapping VNI-to-VLAN, which should be configurable via the NBI mentioned in [PEPELNJAK] and mainly bridge (Only L2) the mapped VNI to VLAN | Component Testing MidoNet | Success | Is supported by MidoNet / Neutron using a Cumulus switch as HW VTEP |

Table C.1: Summary of testing results for the INaaS use case

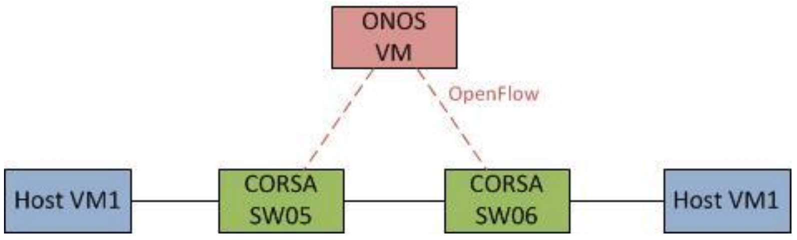
# Appendix D SDN-Based BoD Testing

In the following summary tables, the test results of the PoC are presented.

| | |
|---|---|
| **Requirement Name:** | Port status notification |
| **Requirement testing tasks/procedure/steps** | 1. Tear down one of the ports.<br>2. Check if the controller receives a notification about the new port status.<br>3. Re-establish the port.<br>4. Check if the controller receives a notification about the new port status. |
| **Setup/input** | Following inputs are needed:<br>• Ports and switches where two hosts are connected. |
| **Exit (Pass/Fail criteria)** | Approval criteria: The ONOS controller is notified with the new port status.<br>Fail Criteria: The ONOS controller is not notified with the new port status. |
| **Expected Output(s)/Result(s):** | 1. Check if after tearing down the port the switch sends the OFPT_PORT_STATUS message.<br>2. Check if ONOS receives correctly the port status notification.<br>3. Check if after restoring the switch sends the OFPT_PORT_STATUS message.<br>4. Check if ONOS receives correctly the port status notification. |
| **Facilities** | Testing will be conducted with the hardware Corsa switches available at GÉANT Lab.<br>Hardware description:<br>• 2 Corsa switches.<br>• 2 VMs for hosts: 1 core and 512MB RAM, Linux distribution. Software: tcpdump, Iperf.<br>• 1 VM for ONOS: 2 cores and 4GB RAM, Linux Kernel 3.19.0-25-generic (Ubuntu 14.04 LTS). Software: ONOS 1.4, wireshark. |

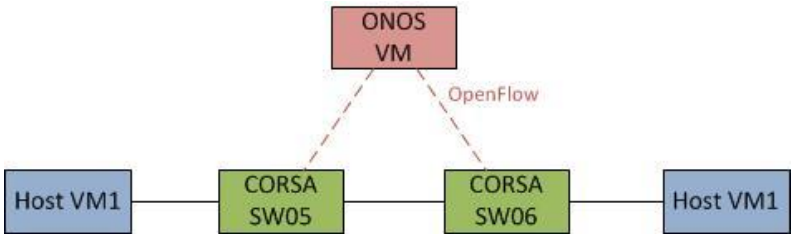
| | |
|---|---|
| **Test scenario Figure** |   ONOS VM<br>OpenFlow<br>Host VM1<br>CORSA SW05<br>CORSA SW06<br>Host VM1 |
| **Observations** | To teardown a port in the corsa switch use the following command:<br>port <port_number> disable<br>To restore a port in the corsa switch use the following command:<br>port <port_number> enable<br>To check in ONOS the port status use the following command:<br>ports |
| **Success or Failure Type (Critical, High, Medium, Low)** | Success |

| | |
|---|---|
| **Requirement Name:** | Rate limiting |
| **Requirement testing tasks/procedure/steps** | Check OpenFlow generic approach with QoS queues.<br>Interconnect 3 machines with OVS.<br>Establish BW limit between two of them.<br>Check that BW limit only affects communication between those two machines.<br>http://openvswitch.org/support/config-cookbooks/qos-rate-limiting/ , http://archive.openflow.org/wk/index.php/Slicing , https://n40lab.wordpress.com/2013/05/04/openvswitch-setting-a-bandwidth-limit/<br>Alternative to Queues with meters not supported with Open vSwitch. Possible alternative to check locally with ofsoftswitch13.<br>Interconnect 3 machines with ofsoftswitch13.<br>Establish BW limit between two of them using Meters.<br>Check that BW limit only affects communication between those two machines. (Iperf?).<br>Replicate with ONOS.<br>Try to create two intents replicating first part of experiment.<br>Establish BW limit to the intent between two machines. |

| | |
|---|---|
| | Check behaviour<br>https://wiki.onosproject.org/display/ONOS/Intent+Framework<br>Migrate to Cambridge Lab |
| **Exit (Pass/Fail criteria)** | Pass: Traffic between two machines in an scenario of three have limited connectivity while rest of communications stay as they are. Achieve this with ONOS.<br>Fail: Inability to produce rate limitations. |
| **Expected Output(s)/Result(s):** | Iperf should produce different results between links limited and non-limited on Open vSwitch-based scenario.<br>ONOS should register the intents for the second scenarios and send OpenFlow commands to the switches. Iperf should produce approximately the same result as with Open vSwitch. |
| **Facilities** | Open vSwitch, Virtual Machines/mininet, ofsoftswitch13, GÉANT Lab. |
| **Test scenario Figure** |  ONOS VM<br>OpenFlow<br>Host VM1<br>CORSA SW05<br>CORSA SW06<br>Host VM1 |
| **Observations** | Flows are properly installed in the Corsa switches. In order to activate the Corsa driver it is necessary to follow this procedure:<br>1. Disconnect the Corsa switches from the ONOS controller.<br>2. Run ONOS.<br>3. Use the following command to install the Corsa's configuration.<br>4. onos-topo-cfg <onos_ip> configuration_file.<br>5. Check that the Corsa devices are shown when using the following ONOS CLI command (Only the information included in the configuration file should appear).<br>6. Devices.<br>7. Connect the Corsa switches to the ONOS controller.<br>8. Check that the Corsa devices are shown when using the devices ONOS CLI command (This time, all the information about the device should appear).<br>Check at the Corsa devices that the LLDP, BDDP and ARP-related flow entries have been successfully installed in the corresponding flow tables. |

| | |
|---|---|
| **Success or Failure Type (Critical, High, Medium, Low)** | Success. |

| | |
|---|---|
| **Requirement Name:** | L2 virtual circuit between VLAN ID on two ports. |
| **Requirement testing tasks/procedure/steps** | Configure ONOS Point-to-point intent between two ports of connected switches. Command to use for configuration are:<br>• onos:add-point-intent -v vlan -p priority device1/port1 device2/port2<br>• onos:add-point-intent -v vlan -p priority device2/port2 device1/port1<br>Generate traffic between the two hosts check the connectivity. |
| **Setup/input** | Following inputs are needed:<br>Ports and switches where two hosts are connected. |
| **Exit (Pass/Fail criteria)** | Approval criteria: Traffic between the hosts connected through the switches is transported successfully through the SDN network.<br>Fail Criteria: Traffic between the hosts connected through the switches members fails. |
| **Expected Output(s)/Result(s):** | Check if the ONOS controller created point-to-point Intents to forward the traffic between the two hosts.  Command (onos:intents).<br>Check if the ONOS controller created flows corresponding to the Intents. Command (onos:flows).<br>Check if the flows from ONOS controller are installed on the OpenFlow switches.<br>Check if the flows on the OpenFlow switches are matching generated traffic. |
| **Facilities** | Testing will be conducted with the hardware Corsa switches available at GÉANT Lab.<br>Hardware description:<br>2 Corsa switches<br>2 VMs for hosts: 1 core and 512MB RAM, Linux distribution. Software: tcpdump, Iperf<br>1 VM for ONOS: 2 cores and 4GB RAM, Linux Kernel 3.19.0-25-generic (Ubuntu 14.04 LTS). Software: ONOS 1.4, wireshark |

| | |
|---|---|
| **Test scenario Figure** |  ONOS VM<br>OpenFlow<br>Host VM1<br>CORSA SW05<br>CORSA SW06<br>Host VM1 |
| **Success or Failure Type (Critical, High, Medium, Low)** | Success |

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| **Requirement Name:** | VLAN translation |
| **Requirement testing tasks/procedure/steps** | 1. Configure ONOS Point-to-point intent between two ports of connected switches. Command to use for configuration are:<br>a. onos:add-point-intent -v vlan1 -p priority --setVlan vlan2 device1/port1 device2/port2<br>b. onos:add-point-intent -v vlan2 -p priority --setVlan vlan1 device2/port2 device1/port1<br>2. Generate traffic between the two hosts check the connectivity.<br>3. Check with tcpdump that the traffic to the destination host is tagged with vlan2. |
| **Setup/input** | Following inputs are needed:<br>Ports and switches where two hosts are connected. |
| **Exit (Pass/Fail criteria)** | Approval criteria: Traffic between the hosts connected through the switches is transported successfully through the SDN network.<br>Fail Criteria: Traffic between the hosts connected through the switches members fails. |
| **Expected Output(s)/Result(s):** | 1. Check if the ONOS controller created point-to-point Intents to forward the traffic between the two hosts. Command (onos:intents).<br>2. Check if the ONOS controller created flows corresponding to the Intents. Command (onos:flows).<br>3. Check if the flows from ONOS controller are installed on the OpenFlow switches.<br>4. Check if the flows on the OpenFlow switches are matching generated traffic. |

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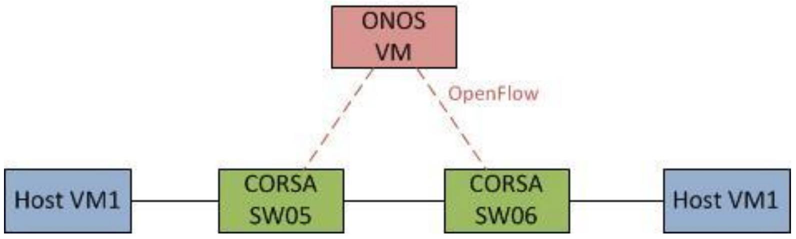
| | 5. Check it the packets' vlan tag is vlan2 at the destination host. |
| **Facilities** | Testing will be conducted with the hardware Corsa switches available at GÉANT Lab.<br><br>Hardware description:<br><br>2 Corsa switches<br><br>2 VMs for hosts: 1 core and 512MB RAM, Linux distribution. Software: tcpdump, Iperf<br><br>1 VM for ONOS: 2 cores and 4GB RAM, Linux Kernel 3.19.0-25-generic (Ubuntu 14.04 LTS). Software: ONOS 1.4, wireshark |
| **Test scenario Figure** |  ONOS VM<br>OpenFlow<br>Host VM1<br>CORSA SW05<br>CORSA SW06<br>Host VM1 |
| **Success or Failure Type (Critical, High, Medium, Low)** | Success. |

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| **Requirement Name:** | Flow entry add/remove. |
| **Requirement testing tasks/procedure/steps** | 1. Configure ONOS Point-to-point intent between two ports of connected switches. Commands to use for configuration are:<br>a. onos:add-point-intent -p priority device1/port1 device2/port2<br>b. onos:add-point-intent -p priority device2/port2 device1/port1<br>2. Check if flow entries are added to the switches.<br>3. Remove ONOS Point-to-point intent between two ports of connecte switches. Commands to use for configuration are:<br>c. onos:remove-intent -p app_id intent_id (for each intent, we need to obtain the app_id and intent_id)<br>4. Check if the flow entries are removed from the switches. |
| **Setup/input** | Following inputs are needed:<br><br>Ports and switches where two hosts are connected. |
| **Exit (Pass/Fail criteria)** | Approval criteria: Flow rules are properly installed and removed upon request. |

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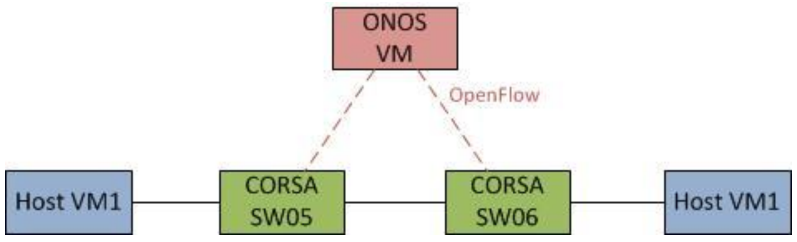
| | Fail criteria: Flow rules are not properly installed or removed upon request. |
| **Expected Output(s)/Result(s):** | 1. Check if the ONOS controller created point-to-point Intents to forward the traffic between the two hosts. Command (onos:intents).<br>2. Obtain the app_id and intent_ids.<br>3. Check if the ONOS controller created flows corresponding to the Intents. Command (onos:flows).<br>4. Check if the ONOS controller removed point-to-point Intents between the two hosts. Command (onos:intents).<br>5. Check if the ONOS controller removed the flows corresponding to the intents. Command (onos:flows). |
| **Facilities** | Testing will be conducted with the hardware Corsa switches available at GÉANT Lab.<br>Hardware description:<br>2 Corsa switches<br>2 VMs for hosts: 1 core and 512MB RAM, Linux distribution. Software: tcpdump, Iperf<br>1 VM for ONOS: 2 cores and 4GB RAM, Linux Kernel 3.19.0-25-generic (Ubuntu 14.04 LTS). Software: ONOS 1.4, wireshark |
| **Test scenario Figure** |  ONOS VM<br>OpenFlow<br>Host VM1<br>CORSA SW05<br>CORSA SW06<br>Host VM1 |
| **Success or Failure Type (Critical, High, Medium, Low)** | Success. |

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| **Requirement Name:** | Flexible flow entry description. |
| **Requirement testing tasks/procedure/steps** | 1. Generate add flow messages.<br>2. Check if flows are correctly installed. |
| **Setup/input** | Following inputs are needed:<br>• Layout of the pipeline used at the device. |

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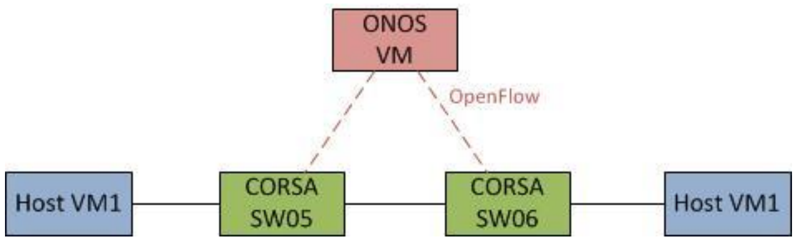
| **Exit (Pass/Fail criteria)** | Approval criteria: Flow rules are properly installed upon request.<br>Fail criteria: Flow rules are not properly installed upon request. |
| **Expected Output(s)/Result(s):** | Check if the ONOS controller created the corresponding flows at the device. Command (onos:flows). |
| **Facilities** | Testing will be conducted with the hardware Corsa switches available at GÉANT Lab.<br>Hardware description:<br>2 Corsa switches.<br>2 VMs for hosts: 1 core and 512MB RAM, Linux distribution. Software: tcpdump, Iperf.<br>1 VM for ONOS: 2 cores and 4GB RAM, Linux Kernel 3.19.0-25-generic (Ubuntu 14.04 LTS). Software: ONOS 1.4, wireshark. |
| **Test scenario Figure** |   ONOS VM<br>OpenFlow<br>Host VM1<br>CORSA SW05<br>CORSA SW06<br>Host VM1 |
| **Observations** | Flows are correctly installed at the devices, depending on the pipeline layout. As long as the matching criteria specified for the flow entry is supported by the pipeline, it will be installed. |
| **Success or Failure Type (Critical, High, Medium, Low)** | Success. |

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| **Requirement Name:** | Discover network devices automatically. |
| **Requirement testing tasks/procedure/steps** | Start ONOS. The topology discovery is done at start up. |
| **Setup/input** | Following inputs are needed: |

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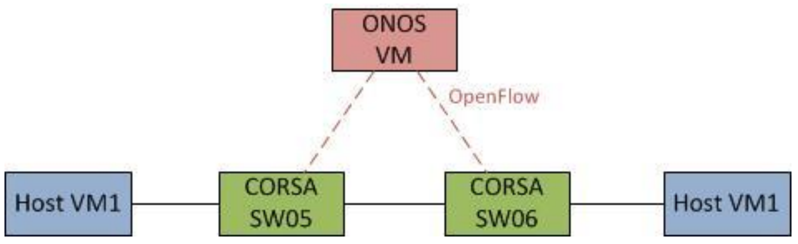
| | Number of hosts, devices and links that exist in the topology. |
| **Exit (Pass/Fail criteria)** | Approval criteria: all the network resources are correctly discovered by the ONOS controller (Nodes, links, hosts).<br>Fail criteria: network resources are not correctly discovered. |
| **Expected Output(s)/Result(s):** | Check if all the nodes are detected, with this topology 2. (Command: devices).<br>Check if all the links are detected, with this topology 1 between the switches and 2 to connect the hosts. (Command: links).<br>Check if all the hosts are detected, with this topology 2. (Command: hosts). |
| **Facilities** | Testing will be conducted with the hardware Corsa switches available at GÉANT Lab.<br>Hardware description:<br>2 Corsa switches<br>2 VMs for hosts: 1 core and 512MB RAM, Linux distribution. Software: tcpdump, Iperf<br>1 VM for ONOS: 2 cores and 4GB RAM, Linux Kernel 3.19.0-25-generic (Ubuntu 14.04 LTS). Software: ONOS 1.4, wireshark |
| **Test scenario Figure** |  ONOS VM<br>OpenFlow<br>Host VM1<br>CORSA SW05<br>CORSA SW06<br>Host VM1 |
| **Observations** | 1st. TEST<br>The pipeline installed in the Corsa switches requires a priority between 0-255 for all the flows installed in the first table, which is the case of LLDP and ARP flows. The ONOS controller uses a priority of 40000 for these control flows, resulting on the flows remaining on "pending to add" status and therefore making impossible for the ONOS controller to detect the links between the Corsa switches. To solve this problem, it is necessary to change the priority of these flows in several modules of the ONOS controller:<br>apps/proxyarp/src/main/java/org/onosproject/proxyarp/ProxyArp.java<br>Change the values for the ARP's priority to CONTROL_CORSA<br>core/api/src/main/java/org/onosproject/net/packet/PacketPriority.java<br>Add CONTROL_CORSA (<priority>) |

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| | providers/host/src/main/java/org/onosproject/provider/host/impl/HostLocationProvider.java<br>Change the values for the ARP's priority to CONTROL_CORSA<br>providers/lldp/src/main/java/org/onosproject/provider/lldp/impl/LLDPLinkProvider.java<br>Change the values of the LLDP and BDDP traffic to CONTROL_CORSA<br>2nd. TEST<br>Requires Corsa driver activation |
| **Success or Failure Type (Critical, High, Medium, Low)** | Success. |

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**[JRA2NITC]** GN4-1 JRA2 NitC Use Case Requirements http://www.geant.org/Projects/GEANT_Project_GN4-1/Documents/ (public) https://intranet.geant.org/gn4/1/Activities/JRA2/Shared%20Documents/Public%20documents/GN4-1_NitC%20Requirements.pdf (Project Participants)

**[JRA2INAAS]** GN4-1 JRA2 INaaS Use Case Requirements http://www.geant.org/Projects/GEANT_Project_GN4-1/Documents/ (public) https://intranet.geant.org/gn4/1/Activities/JRA2/Shared%20Documents/Public%20documents/GN4-1_INaaS%20Requirements.pdf (Project Participants)

**[JRA2TRANS]** GN4-1 JRA2 Transport SDN Use Case Requirements http://www.geant.org/Projects/GEANT_Project_GN4-1/Documents/ (public) https://intranet.geant.org/gn4/1/Activities/JRA2/Shared%20Documents/Public%20documents/GN4-1_Transport%20SDN%20Requirements.pdf (Project Participants)

**[JRA2IPSDX]** GN4-1 JRA2 SDN-IP/SDX (Software Defined Internet Exchange) Use Case Requirements http://www.geant.org/Projects/GEANT_Project_GN4-1/Documents/ (public) https://intranet.geant.org/gn4/1/Activities/JRA2/Shared%20Documents/Public%20documents/GN4-1_SDN-IP%20Requirements.pdf (Project Participants)

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# Glossary

| | |
|---|---|
| **AMS** | Amsterdam |
| **API** | Application Programming Interface |
| **AS** | Autonomous System |
| **BGP** | Border Gateway Protocol |
| **BoD** | Bandwidth on Demand |
| **BRA** | Bratislava |
| **CLI** | Command-Line Interface |
| **DMZ** | Demilitarized Zone |
| **DynPaC** | Dynamic Path Computation |
| **EBGP** | External Border Gateway Protocol |
| **E-Line** | Ethernet virtual private Line |
| **ELAN** | Ethernet Local Area Network |
| **EVP-LAN** | Ethernet Virtual Private Local Area Network |
| **EVPL** | Ethernet Virtual Private Lines |
| **GRE** | Generic Routing Encapsulation |
| **GTS** | GÉANT Testbed Service |
| **GUI** | Graphical User Interface |
| **HAM** | Hamburg |
| **IBGP** | Internal Border Gateway Protocol |
| **INaaS** | Infrastructure and Network as a Service |
| **ISR** | Integrated Service Router |
| **IP** | Internet Protocol |
| **IPFIX** | Internet Protocol Flow Information Export |
| **IOS** | Internetwork Operating System |
| **IoT** | Internet of Things |
| **IXP** | Internet eXchange Point |
| **JRA** | Joint Research Activity |
| **L2** | Layer 2, data link |
| **L3** | Layer 3, network |
| **LACP** | Link Aggregation Control Protocol |
| **LHC** | Large Hadron Collider |
| **LON** | London |
| **MAC** | Media Access Control |
| **MIB** | Management Information Base |
| **MIL** | Milan |
| **ML2** | Modular Layer 2 |
| **NAT** | Network Address Translation |

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|---|---|
| **NE** | Network Element |
| **NitC** | Network in the Campus |
| **NOC** | Network Operation Centre |
| **NREN** | National Research and Education Network |
| **NRM** | Network Resource Manager |
| **NSDB** | Network State DataBase |
| **NSI-CS** | Network Service Interface – Connection Service |
| **ODL** | Open Daylight |
| **OF** | OpenFlow |
| **ONF** | Open Networking Foundation |
| **OS** | Operating System |
| **OSCARS** | On-Demand Secure Circuits and Advance Reservation System |
| **OTN** | Optical Transport Network |
| **OTS** | Open Transport Switch |
| **OTSc** | Open Transport Switch (client) |
| **OTSv** | Open Transport Switch (virtual) |
| **OVS** | Open vSwitch |
| **OVSDB** | Open vSwitch DataBase |
| **OXP** | Open eXchange Point |
| **PCE** | Path Computation Element |
| **PCEP** | Path Computation Element Protocol |
| **PoC** | Proof of Concept |
| **PoPs** | Points of Presence |
| **PRG** | Prague |
| **R&E** | Research and Education |
| **REN** | Research Education Network |
| **REST** | Representational State Transfer |
| **SDN** | Software Defined Networking |
| **SDX** | Software Defined internet eXchange Point |
| **SSH** | Secure Shell |
| **STP** | Spanning Tree Protocol |
| **T** | Task |
| **TCP** | Transmission Control Protocol |
| **TS** | Topology Service |
| **VC** | Virtual Circuit |
| **VLAN** | Virtual Local Area Network |
| **VM** | Virtual Machine |
| **VPLS** | Virtual Private LAN Service |
| **VTEP** | VXLAN Tunnel End Point |
| **VXLAN** | Virtual eXtensible Local Area Network |
| **XML** | eXtensible Markup Language |