SDN-Based IP and Layer 2 Services with an Open Networking Operating System in the GÉANT Service Provider Network

Pier Luigi Ventre, Stefano Salsano, Matteo Gerola, Elio Salvadori, Mian Usman, Sebastiano Buscaglione, Luca Prete, Jonathan Hart, and William Snow

ABSTRACT

The migration of service providers' wide area networks toward SDN is a challenging task. In this article, we consider the critical requirements of GÉANT, the 500 Gb/s pan-European provider interconnecting 38 national research and educational networks, for a total of 50 million users. A long-term evolution path toward the *softwarization* of GÉANT is discussed, consisting of four steps to be realized in future years, from providing SDN-based connectivity, to the so-called software defined infrastructure (SDI). As a first step, the softwarization of some basic services currently offered by GÉANT is considered: *GÉANT IP*, *GÉANT plus*, and *GÉANT Open*. This article reports the concrete experience in the SDN-based design and implementation of these services, which have been called L3-SDX and L2-SDX. Both use cases have been addressed with the use of the open source Open Network Operating System (ONOS®). The L3-SDX service has been developed on top of an existing ONOS application, called SDN-IP. SDN-IP allows interconnections between SDN and legacy networks through BGP. The L2-SDX service has been realized as a new ONOS application. Both services are currently deployed on the GÉANT Testbed Service, a continental facility offering geographical virtual testbeds to the research community. The article reports the experience gained from this experimental deployment and discusses the benefits for a service provider like GÉANT.

INTRODUCTION

Software defined networking (SDN) is a recent paradigm [1] potentially able to transform the design of both data center and wide area networks. The promise of SDN is to foster innovation and flexibility thanks to centralized network control and standard interfaces. The fundamentals of the SDN approach are:

- The separation of control and data planes
- The logical centralization of the former as a software layer called controller or network operating system (NOS)
- The introduction of a flexible forwarding paradigm (based on filtering matches and actions)
- The direct control of the hardware through common management interfaces (e.g., OpenFlow)

SDN can be seen as part of an even wider trend toward the softwarization of networks [2, 3], which implies a complete rethinking of how service provider networks are now structured. It is expected that this process will greatly increase the flexibility and efficiency of networks, reducing equipment and operational costs.

In this article, we start from the analysis of current services offered by GÉANT, the 500 Gb/s pan-European network interconnecting 38 national research and educational networks (NRENs), for a total of 50 million users. We refer to the NRENs as the *customers* of GÉANT. We identify the GÉANT needs and requirements toward the upgrading of its infrastructure. A long-term evolution path toward the softwarization of GÉANT is discussed, consisting of several steps to be realized in future years, from providing SDN-based connectivity services to the so-called software defined infrastructure (SDI) [4, 5], which is also able to dynamically offer a wide range of computing/storage/network resources.

The first step of the GÉANT migration process consists of the *SDNization* of some operational services. In particular, we consider *GÉANT IP*, which is the basic service providing Internet connectivity to the NRENs, and two layer 2 connectivity services called GÉANT plus and GÉANT open. These services are currently delivered through 26 points of presence (PoPs) located in Europe and 2 open exchange points (OXPs) in London and Paris (see the next section for further details). The OXPs are similar to the standard Internet exchange points (IXPs), allowing NRENs to exchange traffic with external (non-GÉANT) networks. The introduction of SDN technologies in an IXP is referred to as software defined (Internet) exchange (SDX) [6]. In this article, we give a wider meaning to the SDX concept, extending its potential applicability not only to the exchange points (IXPs or OXPs) but also to the PoPs. We designed and developed two SDN-based services called L3-SDX and L2-SDX (L3 and L2 stand for layer 3 and layer 2). These services represent the fundamental building blocks of the augmented

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The GÉANT infrastructure offers extensive links to networks in other world regions. External peers (other NRENs and external Autonomous Systems) are interconnected through 26 POPs, located all over Europe, and two Open eXchange Points (OXPs). GÉANT offers a wide range of connectivity and network management services

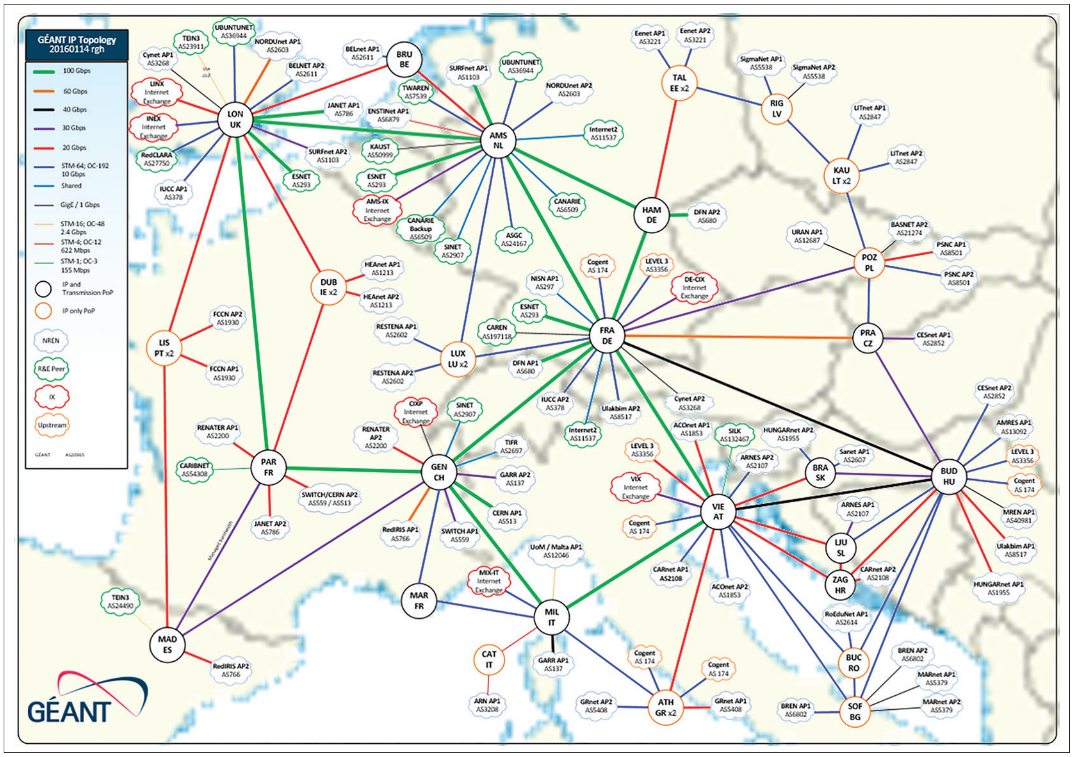

Figure 1. GÉANT IP topology and GÉANT OXPs.

SDX mentioned above and have been developed using Open Network Operating System (ONOS) [7], a promising open source solution for the SDN control plane.

GÉANT Network and Services

As one of the largest and most complex research and education networks in the world, GÉANT needs to support different services, such as standard IP transit connectivity and ultra-high-capacity data center interconnections. The GÉANT infrastructure offers extensive links to networks in other world regions. External peers (other NRENs and external autonomous systems) are interconnected through 26 POPs, located all over Europe, and two OXPs (Fig. 1). GÉANT offers a wide range of connectivity and network management services as described in [8]. We focus on a subset of them, called GÉANT IP, GÉANT plus, and GÉANT Open.

GÉANT IP provides IP transit services to interconnect participating NRENs together and with other approved research organizations and providers. It provides a peering service for IP traffic, isolated from general-use Internet access. GÉANT plus offers the NRENs point-to-point L2 (Ethernet) circuits among endpoints at GEANT PoPs [8]. The PoPs constitute the backbone of the dual (optical transmission and packet) layer network through which GÉANT supplies connectivity to its customers. From the GÉANT perspective, the PoPs are the endpoints of GÉANT IP and GÉANT plus. Finally, with the GÉANT Open service, NRENs can connect with external (non-GÉANT) networks through the OXPs. Inside an OXP, the customers (NRENs or external participants) request the establishment of L2 circuits between endpoints, which are manually provisioned through virtual LAN (VLAN) tunnels. The customers can use the L2 circuits for whatever reason, including private Border Gateway Protocol (BGP) peering. Therefore, OXPs are different from traditional IXPs, which provide a switched L2 infrastructure used by multiple participants to exchange traffic through public BGP peering.

Toward a New Service Development and Provisioning Approach

The current *connectivity and network management services* of GÉANT are mostly based on traditional IP/MPLS (multiprotocol label switching) control plane architectures running on top of complex and expensive proprietary equipment. In most cases, the services rely on proprietary software and specific vendor solutions, making it hard to innovate and offer new services. The management of a large-scale network like GÉANT is largely based on proprietary (and expensive) tools, which again constitute a barrier to innovation. A second issue is that the service provisioning phase often includes manual operations, resulting in provisioning times on the order of days. In such a scenario, the introduction of SDN and in general of *softwarization* can bring substantial benefits:

- Provisioning procedures can be drastically simplified.
- Cheaper hardware could replace current equipment.
- The openness of the SDN approach avoids the need for complex distributed control plane architectures and reduces the number of running protocols.
- Proprietary implementations can also be avoided or reduced, mitigating interoperability problems and migration issues.

Softwarization facilitates the development and introduction of new services of strong interest

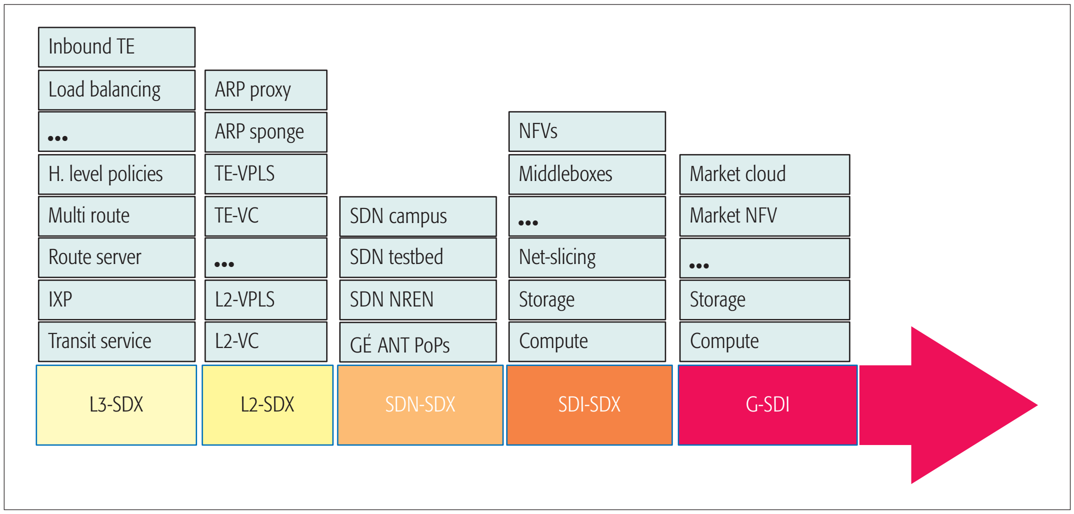

Figure 2. Softwarization path.

The migration of the GÉANT network and its services toward an SDI is a challenging task, which cannot happen overnight. We decomposed the transition of GÉANT to the SDN paradigm in incremental steps. Each step enhances the GÉANT infrastructure, making it more sustainable, more manageable, and less expensive, and introduces new services/functionalities to the portfolio.

to GÉANT but difficult to implement using the current technologies, such as application- specific peering, inbound traffic engineering, load balancing, and steering of traffic for service function chaining [9].

GÉANT Softwarization Path

The migration of the GÉANT network and its services toward an SDI is a challenging task, which cannot happen overnight. We decomposed the transition of GÉANT to the SDN paradigm in incremental steps, as shown in Fig. 2. Each step enhances the GÉANT infrastructure, making it more sustainable, more manageable, and less expensive, and introduces new services/functionalities to the portfolio. The transition path also takes into account the operational requirements of a production network. This migration strategy rationalizes and extends some ideas already presented by Monga in [5]. The idea behind the strategy is to initially introduce the concept of SDX, replacing the current architecture based on PoPs and OXPs, and then to progressively enhance its functionality. The first step of the path is the realization of the L3–SDX and L2–SDX, referred to as *pure connectivity* SDX [5, 10]. L3-SDX supports GÉANT IP, while L2-SDX represents the SDNization of GÉANT plus and GÉANT Open. With this first step, there is no full migration to SDN technology, because NRENs can run legacy technologies without direct interaction with the GÉANT SDX operations.

Assuming that the NRENs will set up their own SDN infrastructures, the next step, called SDN–SDX, consists of the interconnection and harmonization of the SDN infrastructures between GÉANT and the NRENs. To understand the advantages of this step, consider that the NRENs have their customers (research organizations), which requires connectivity toward other research organizations in the same NRENs, in remote NRENs, or outside the GÉANT's NRENs. Thanks to the SDN-SDX, the NRENs and the research organizations could fully exploit the advantages of the SDN paradigm, leveraging end-to-end SDN-based services spanning the GÉANT backbone and the NRENs.

The next step, denoted as SDI–SDX, refers to a GÉANT SDN infrastructure augmented with cloud resources: an NREN can request not only networking services, but also compute and storage resources, outsourcing some of its computations to the SDX cloud.

The final step is referred to as G-SDI, for global SDI. It foresees a wider adoption of the full softwarization (SDN augmented with storage and computing resources) by all NRENs. Following this approach, an end user (research organization) can obtain compute and storage resources from other NRENs or from GÉANT, leveraging the resources offered through a logically global GÉANT SDX. At this step, considering GÉANT's position in the European scenario, it will be possible to exploit the Buyya vision of market-oriented cloud computing [11]. GÉANT's role fits well as a "super party" that manages the market. This evolution of the GÉANT infrastructure encompasses an economic model, useful for the auto-sustainability of the GÉANT project and its participants (the NRENs themselves).

GÉANT Requirements for SDN-Based IP and Layer 2 Services

L3-SDX and L2-SDX have been identified as the first step of the GÉANT softwarization path. We carried out a thorough analysis of the requirements on these services from the perspective of the GÉANT service provider, summarized in Table 1. The requirements are classified as functional, non-functional (i.e., referring to performance or reliability), and operational (e.g., related to monitoring or logging).

Based on this requirement analysis, we selected ONOS [7] as the controller platform. In particular, the existing SDN-IP ONOS application provided a very good fit with the functional requirement of L3-SDX, and the ONOS resilience and distribution features provided a good match with the identified non-functional requirements.

ONOS: SDN Network Operating System for Service Providers

ONOS is an open source SDN control plane platform, meeting service provider requirements, released in 2014 as an open source project by

ON.Lab. ONOS provides a stable implementation of a scalable, highly available, and resilient network operating system (NOS).

The overall system has been conceived as a distributed system in the form of a cluster, composed of multiple instances, all functionally identical to each other. The architecture (Fig. 3) can be structured in three tiers: a protocol-aware southbound (SB) layer, a protocol-agnostic distributed core layer, and an application layer. Each tier is a collection of pluggable modules/subsystems realizing specific functionalities that make up the ONOS platform. An application programming interface (API) is exposed at each tier, providing isolation and modularity.

The distributed core is responsible for synchronization and coordination between the instances in the cluster. It builds a global network view based on information learned on the SB API and offers services to the application layer. In order to achieve scalability and provide resiliency, various distribution mechanisms are available through a set of primitives. Each core subsystem uses these primitives in different ways according to the consistency requirements of the state it is managing. On top of the distributed state, a logically centralized network view is constructed and presented to applications. In addition, work is partitioned among the instances in the cluster. For example, each instance is elected to be responsible for managing a subset of the devices in the network, while the other instances are ready to step in if the primary instance fails. In the case of data plane failures, built-in mechanisms for traffic rerouting are activated.

The SB layer consists of a collection of software modules called "providers," which interact with data plane devices using different southbound protocols. Providers gather information about network state and pass it to the distributed core, and receive instructions from the core to program the devices.

On the northbound side, ONOS presents abstractions to the applications, including Network Topology, Flow Objectives, and Intents. Intents provide applications with a network-centric programming abstraction that allows developers to program the network through the usage of high-level policies that capture *what* needs to be done, rather than how to do it. The Intent framework determines how to implement an intent based on what other policies are in the system, and abstracts low-level details of this implementation. Intents make network policy configuration easier, speed up management procedures, and tend to reduce the occurrence of configuration errors. Intents are backed by a dedicated subsystem that:

- Translates Intents into device instructions
- Coordinates and ensures the installation of the generated instructions
- Reacts to network changes and modifies paths accordingly
- Permits optimization across intents' translations

The Intent framework has been widely used for developing the L3-SDX and L2-SDX applications.

ONOS is supported by an active open source community. Different ONOS applications have been developed over the years by ON.Lab and by the community as listed in the documentation of the project. For example, the SDN-IP application allows SDN islands to seamlessly interconnect with external networks using standard BGP. Among the applications, we mention CORD™ (Central Office Re-Architected as Datacenter) [12]. It aims to revolutionize the way service provider central offices are built and operated. It brings in the principles of SDN, network functions virtualization (NFV), cloud technologies, and disaggregation, thereby making the central offices more manageable and agile.

Requirement	Service	Type	Priority	Status
L2 virtual circuit between two edge ports or VLANs	L2-SDX	Functional	Must	Completed
MPLS encapsulation of L2-SDX circuits	L2-SDX	Functional	Must	Completed[1]
VLAN and Stacked-VLANs (802.3ad) encapsulation	L2-SDX	Functional	Must	Completed[2]
IP transport between BGP peers	L3-SDX	Functional	Must	Completed
Custom route selection process	L3-SDX	Functional	Desirable	Planned
IPv6 support	Both	Functional	Must	Completed
Control plane resiliency	Both	Non-functional	Must	Completed
Control plane failure recovery	Both	Non-functional	Must	Completed
Network status after control plane failure	Both	Non-functional	Must	Completed
BGP control plane resiliency	L3-SDX	Non-functional	Must	Completed
Traffic rerouting after data plane failures	Both	Non-functional	Must	Completed
Control BGP attributes for each BGP peer	L3-SDX	Functional	Desirable	Not needed[3]
Apply separate policies for each BGP peer	L3-SDX	Functional	Desirable	Not needed[3]
Add, remove or shutdown BGP peers without impacts	L3-SDX	Functional	Must	Completed
Scale up to 100 BGP peers	L3-SDX	Non-functional	Desirable	Planned
Scale up to 100K routes	L3-SDX	Non-functional	Must	Planned[4]
Data plane statistic collection	Both	Operational	Desirable	Completed
Export of statistics to standard NMSs (SNMP, IPFIX)	Both	Operational	Optional	Ongoing[5]
Logging facilities	Both	Operational	Must	Completed

[1] Not fully supported in all switches [2] Stacked-VLANs not fully supported in the switches [3] Realized in the BGP peer [4] Tested up to 15K routes [5] SNMP not supported

Table 1. GEANT SDX requirements.

High-Level Architecture for GÉANT SDX

The proposed SDX architecture is based on SDN enabled networking equipment, controlled by a cluster of ONOS controllers. The ISP services, such as L3-SDX and L2-SDX, are designed as northbound applications running simultaneously on top of the NOS, offering both L2 and L3 connectivity services. Coexistence of different services in the data plane can be enforced through slicing mechanisms (e.g., VLAN tagging). As for the networking equipment, their integration is possible through open APIs, like OpenFlow, or by vendor-specific APIs implemented in ONOS in the form of pluggable drivers. The use of so-called *white box* devices is currently under investigation and testing in GÉANT as they could replace traditional equipment to achieve relevant cost savings.

An SDX can span a single location (e.g., replacing an OXP or PoP) or multiple locations (e.g., federating PoPs in a single logical PoP, or creating a distributed OXP). This issue is further discussed in the section about the practical experience. The L3-SDX has been developed on top of an existing ONOS application, called SDN-IP, while L2-SDX has been realized as a new ONOS application.

L3-SDX/SDN-IP IN GÉANT

SDN-enabled networks still need to interoperate with traditional networks on the Internet. The ONOS SDN-IP application interconnects an SDN island with external networks leveraging the BGP protocol. The solution allows:

- External ASs to exchange routes and transit traffic through an SDN network
- The SDN network to advertise routes to the external networks
- A service provider to scale its SDN control plane by segmenting an AS into multiple SDN domains, which communicate through BGP

Besides the technical advantages, the service providers also gain benefits in reduced capital expenditures (CAPEX) and operational expenditures (OPEX), since they can use a single set of devices to manage L2 and L3 connectivity (and possibly L0/L1).

The high-level architecture of SDN-IP is shown in Fig. 4. The SDN network is composed of different data plane devices controlled by ONOS, which are directly connected to the BGP-speaking border routers of the external ASs. Finally, one or more internal BGP speakers peer with the external routers and act as bridges between the external domains and the SDN-IP application. From the legacy networks' perspective, the SDN domain appears as a standalone AS, as though it was running legacy BGP routers at the edges. Within the SDN network, SDN-IP has two main roles. The first is to install flows for BGP traffic between the external routers and the internal BGP speakers, thus allowing BGP sessions to be established. The second is to translate received routes into ONOS Intents, which are compiled down into flows on the SDN switches. In order to transport the data traffic in the SDN network, ONOS makes use of *multipoint to single-point* tunnels, avoiding the use of $n \times n - 1$ tunnels to connect the endpoints, thus reducing the flow table entries in the data plane.

SDN-IP provides a feasible migration path toward the softwarization of ISP networks. It can be integrated with networks that already use BGP both externally and internally. From an operational point of view, SDN-IP guarantees flexibility in the covered use case, as it does not make any assumptions on the deployment scenario. The application can run on one or multiple ONOS instances. Moreover, the BGP settings can be changed dynamically with the addition or removal of peers. SDN-IP provides high availability (HA) within the application itself: the service keeps working seamlessly, as long as there is at least one instance of the SDN-IP application running. In addition, SDN-IP leverages the HA mechanisms provided by ONOS for maintaining a consistent forwarding state in the data plane. SDN-IP provides a scalable solution able to control large-scale of SDN networks by using BGP-based confederations and ONOS clusters of different sizes.

L3-SDX extends SDN-IP, adding support for new deployment scenarios and providing facilities to monitor the BGP and transit traffic in the network. L3-SDX improves the flexibility of SDN-IP, making it possible to deploy multiple peers belonging to the same AS and interconnected through different connection points controlled by ONOS. The application supports the typical IXP scenario where all the BGP routers as well as the route server belong to the same subnet [6]. An integration with the ONOS IPFIX application allows exporting the counters related to the BGP sessions and to the L3 tunnels using the standardized IPFIX protocol. This can be used to realize

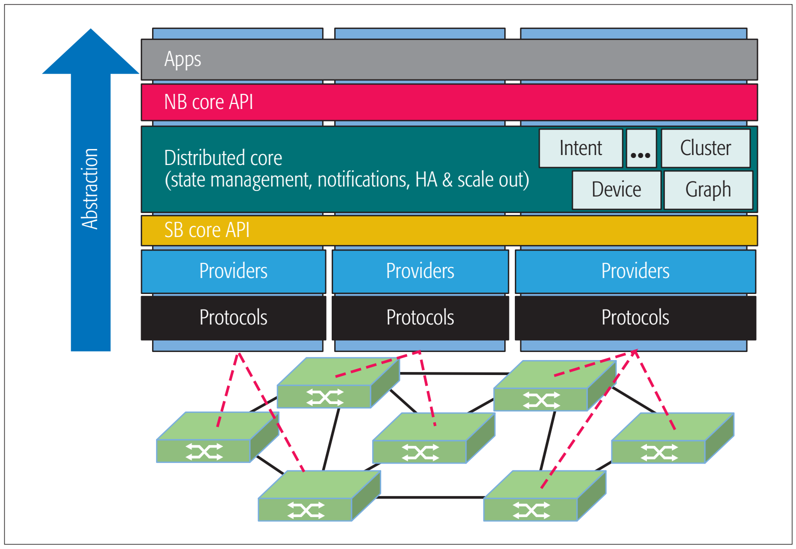

Figure 3. ONOS architecture.

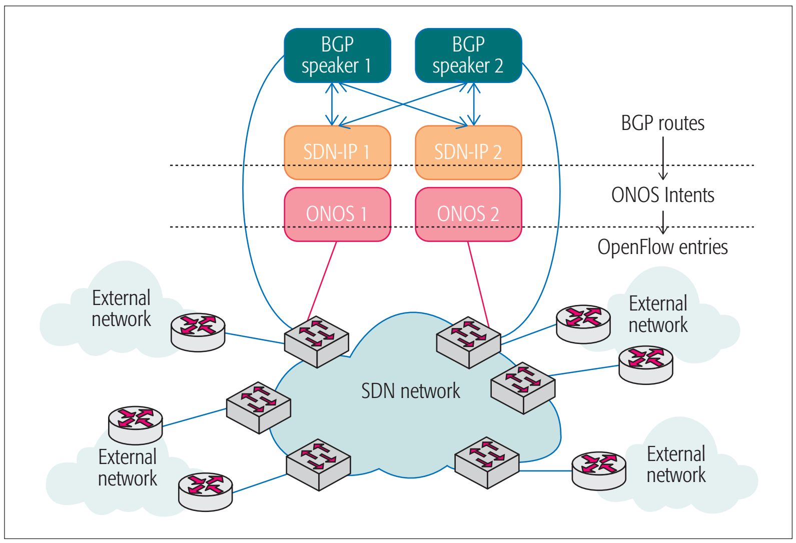

Figure 4. High-level representation of the SDN-IP architecture.

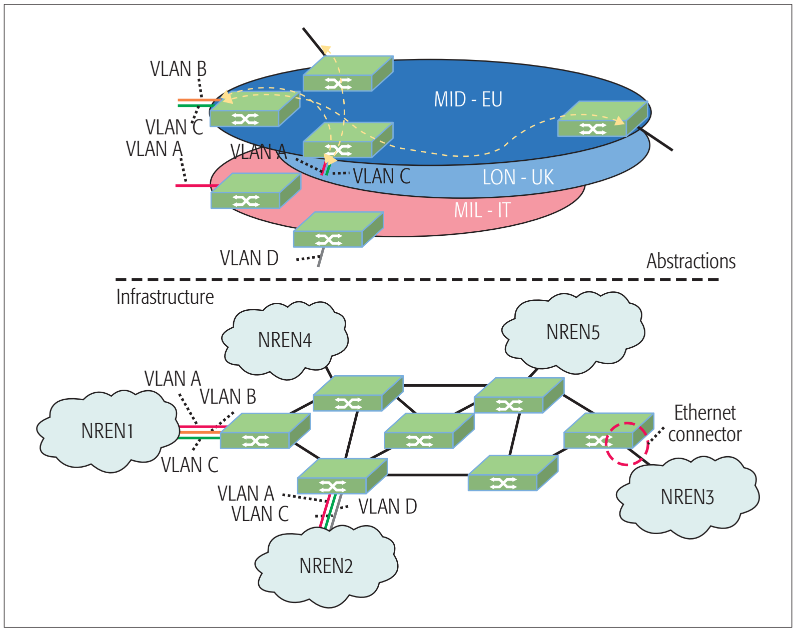

Figure 5. L2-SDX application and its abstractions.

advanced monitoring tools. L3-SDX and SDN-IP are both available under a liberal open source license.

L2-SDX Service in GÉANT

L2-SDX is an ONOS application that allows the automated provisioning of L2 tunnels between endpoints, which can be physical Ethernet interfaces or VLANs. The offered L2 services belong to the class of IP virtual leased line services (IP VLL) or virtual private LAN services (VPLS), which are a fundamental part of the service portfolio offered by large-scale ISPs. At the time of writing, only IP VLL has been integrated in the L2-SDX application, but VPLS can be provided with a straightforward extension of the current implementation. From a customer perspective, the L2-SDX appears as a black box that transports traffic from the source to the destination endpoint, as if they were in the same Ethernet LAN. Inside the SDX infrastructure, the L2-SDX application provides the necessary mechanisms for the service provisioning and monitoring. The human operators can manage and monitor the application through a command line interface (CLI) and a graphical user interface (GUI), which accepts high-level customer requests and translates them into ONOS *point-to-point intents*.

The application is fully integrated in ONOS and implemented as a callable service. In the next release, its services will be exposed through a REST API, allowing integration with orchestration platforms. Monitoring is achieved through the ONOS IPFIX application. L2-SDX can run over a single ONOS instance or on a cluster of ONOS instances that share common state information. The multi-instance deployment is useful to control large-scale SDXs made up of many SDN devices. L2-SDX leverages the high availability mechanisms provided by ONOS in order to maintain a consistent state in both the control and data planes. Failures in the control plane are managed through the redundancy of the ONOS cluster. Instead, data plane failures are automatically resolved through transparent re-routing mechanisms provided by ONOS.

L2-SDX provides users with powerful APIs and abstractions as shown in Fig. 5. A virtual SDX (e.g., MID-EU, LON-UK in the figure) contains a number of endpoints modeled as edge connectors, which can be interconnected through virtual circuits. Customers manage only the edges of the SDN network controlled by ONOS. The L2-SDX application eases service management and provisioning (e.g., enforcing isolation and avoiding several types of conflicts):

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

L2-SDX is available under a liberal open source license.

Proofs of Concept and Worldwide Experimental Deployment

We realized two proofs of concept (PoCs). The first PoC was deployed in a laboratory at the University of Rome Tor Vergata and used mainly for validation and testing. It is based on virtual machines (VMs) and Open vSwitch (nine VMs emulate the data plane, a cluster of three VMs makes up the ONOS control plane).

The second PoC was realized in the GÉANT Testbed Service (GTS) [8]. The GTS delivers virtual testbeds powered by several facilities, co-located with GÉANT PoPs, offering different types of resources like VMs, SDN devices, and virtual circuits. Using GTS, we have built a large-scale PoC with seven HP OpenFlow switches deployed in seven PoPs (Fig. 6). This data plane is controlled by a cluster of three ONOS instances located in three of the PoPs. Three VMs, working as BGP peers, and two stub networks with perfSONAR hosts have been deployed. PerfSONAR is a performance measurement and troubleshooting tool for multi-domain scenarios.

The SDX PoC on GTS was integrated into 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. The network spans over 5 continents, interconnecting 9 RENs and more than 30 universities and research centers

Deployment Experience and Benefits for GÉANT

Overall, the SDX PoC on GTS worked according to our expectations; L2-SDX and L3-SDX passed all the functional tests we performed. The *status* column in Table 1 reports the coverage assessment of the input requirements. The scalability and efficiency of L2-SDX and L3-SDX are tightly related to ONOS performance, and it has been demonstrated in [7] that the platform can meet carrier grade requirements in specific deployment conditions. L3-SDX and SDN-IP can scale up to 15,000 routes, achieving the current GÉANT requirement of 12,000 announced routes.

The SDX deployed in the GTS represents a single geographically distributed SDX, spanning seven PoPs, with three ONOS instances running in different countries. During the execution of the functional tests, we gained feedback (e.g., the mastership election duration) that drove us not to further stress the SDX under critical events like controller instance failure or data plane failures. Therefore, we believe that having single-location SDXs, spanning a single OXP or PoP, is a safer approach to start the migration toward SDN. OXPs are good candidates for early deployment of SDX due to the complexity of the services that are offered, which makes the introduction of the SDN-based approach attractive. Moreover, with single-location SDXs, the devices can keep their independence and troubleshooting capabilities. In the current GÉANT network, each PoP is seen as a "hop" by the IP traffic, while in a geographically distributed L3-SDX, simple troubleshooting tools like traceroute would no longer be useful. Incidentally, we observe that there is a gap to be filled with troubleshooting tools for SDN-based networks, because L3 tools based on ICMP (ping, traceroute) do not work hop by hop in a network of SDN controlled switches.

The transition toward geographically distributed SDX could start with federations of nodes controlled by the same NOS instance. We have done some preliminary work on this issue with ICONA [14], an application to interconnect multiple ONOS clusters seamlessly through an "East-West" interface. Initially, OXPs could be interconnected, creating a geographically distributed L2 fabric controlled by ONOS. Likewise, geographically close PoPs could be federated in small clusters.

From the point of view of the development costs, it was possible to release the L2-SDX and L3-SDX in the PoCs with relatively little effort (on the order of three man months) thanks to the possibility of relying on the ONOS code base and documentation.

Let us now provide a high-level analysis of the benefits achievable by GÉANT with the softwarization of the infrastructures, in terms of operational costs like services provisioning and services management. The deployment of an SDX in place of an OXP will automate most of the configuration operations, reducing the efforts of the human operators. Currently, in order to set up a GÉANT OPEN service between two access points (ports or VLANs) inside an OXP, the customer has to contact the operators who manually configure the connection [8]. These operations (creation of virtual interfaces, VLAN id selection on both endpoints, VLAN id rewriting) are error-prone and require coordination between the interested parties. Any arising issue requires further manual intervention of the operators. A typical target for the provisioning time of these services is five days. Using the L2-SDX, it will last minutes instead [15]. Moreover, most failure cases are automatically resolved by L3-SDX/L2-SDX using ONOS built-in mechanisms (e.g., a failure of a controller is solved using redundancy of controller instances, a switch failure is solved by ONOS with re-computation of data plane paths around the faulty switch).

As regards GÉANT IP and GÉANT Plus, similar improvements in the services provisioning and management are an affordable objective with single-location SDX. They represent a tangible result when compared to the current procedures (five days to obtain IP connectivity or to set up an L2 circuit).

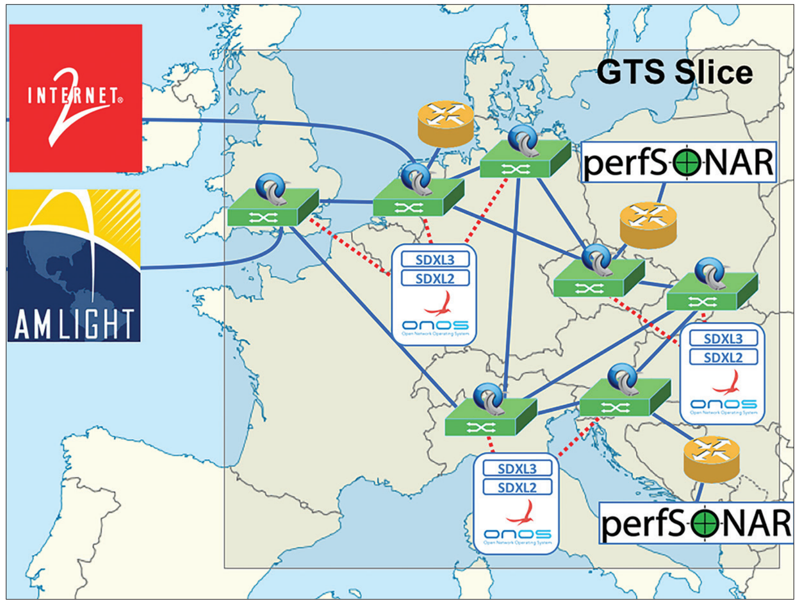

Figure 6. Proof of concept over the GÉANT testbed service.

When considering geographically distributed SDXs, having a centralized view of the network potentially brings further benefits like more efficient traffic management, but the challenges for a wide area SDN deployment still need to be solved. In particular, a first issue is the impact of the latency and unreliability of the control plane connections between controllers and remote network nodes. A second issue arises when the controller instances are distributed in a geographical way, in order to reduce the latency toward the controlled nodes. The mechanisms used to achieve a consistent view across all the distributed controllers works well in LANs, where the latency is low and the capacity is high. The performance of these consistency mechanisms can become critical in geographically distributed wide area networks; a careful assessment of these aspects is still needed.

Finally, let us consider an NREN that would like to establish L2 connectivity with a third party (not GÉANT). Different configurations have to be in place in order to have the connectivity operational:

- L2 configuration of the PoP where the NREN is located
- L2 configuration of the PoP where the target OXP is located
- Steering of the NREN flow into a label switched path (LSP), provided by MPLS/BGP, toward the destination PoP
- Establishment of L2 connectivity inside the OXP

Despite the services being logically similar, the provisioning procedure can require up to 10 days, because they are managed in two completely separated infrastructures, with specific hardware, and different policies and configuration mechanisms. Moreover, coordination is needed between all the operators (GÉANT, NREN, and

In order to bring the L2-SDX and L3-SDX services to production, some additional concerns related, for example, to security and integration with management systems need to be addressed. The GÉANT team is committed to working on these issues in the near future.

the third party). Instead, within an SDX environment, the separation is blurred, and these services can be managed through a single platform, reducing coordination efforts, manual intervention of the network operators, and complexity of the procedures. SDX allows a network engineer to provision an L2 circuit without prior technical coordination with the other network teams [15]. Moreover, they are delivered using a unique infrastructure, with reductions in terms of OPEX and future hardware investments.

Conclusions

In this article, we have first considered the long-term softwarization path of a service provider network like GÉANT. Then we have described the prototypes of two services, called L3-SDX and L2-SDX, that have been deployed in a proof of concept over the GÉANT Testbed Service. The development has been based on the open source ONOS controller platform for SDN. We have performed a functional evaluation of the PoC and an analysis of the potential benefits, which have been very satisfactory. The developed services can bring considerable savings in the operational costs and can dramatically reduce the service provisioning time, as they automate many tasks that are manually performed. From the point of view of performance, the SDX solution is ready for a "local" deployment, that is, considering a single location (even if composed of a large number of nodes). It has to be further assessed if geographically distributed locations can be combined in single logical instances of the SDX.

In order to bring the L2-SDX and L3-SDX services to production, some additional concerns related, for example, to security and integration with management systems need to be addressed. The GÉANT team is committed to working on these issues in the near future.

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