Analysis and Evaluation of Virtual Network Function Chaining in Network Softwarization Scenarios Using Segment Routing

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Abstract

Network Function Virtualization (NFV) aims to bring flexibility and programmability to the network layers, enabling the replacement of traditional network appliances for software components, running in virtual servers. Specifically, NFV decouples the network services from the underlying (dedicated) hardware infrastructure, enabling the designing, managing and execution of complex network services on software running on virtualized servers. On the other hand, Segment Routing (SR) is a new paradigm for routing in IPv6 and MPLS scenarios and relies on the source routing concept, where a source node adds to a packet an ordered sequence of segments that must be followed in order to the packet reach its final destination. As focus from ISPs and network providers stray from hardware focused network implementations, Software Defined Networks have begun to make their way into the spotlight. The presençe of SDN and SR is expanding into Database centers, and its influence is assumed to reach worldwide networks with the emergence of 5G. The benefits entailed are various, both for the providers and the customers, such as cost reduction and network speed. Still, it is common for state-of-the-art solutions to reveal some shortcomings at some point that may or may not have been thought about beforehand. The goal of this thesis is to test the implementation and deployment of Segment Routing alongside SDN, in environments where SR has gained popularity, such as Datacenters, while at the same time integrating NVF services chaining.
Keywords: SDN, SR, NFV, SREXT, Spine-Leaf, NG-SDN

1. Introduction

1.1. Motivation

The complexity of modern networks has caused enterprises to incorporate network virtualization models into their traditional networks. Such an approach offers an easier management and control of a network, along with the tempting benefit of reducing network costs, both Capital and Operational Expenses (CAPEX and OPEX, respectively) [2]. It also shows promise in regards to increasing speed, agility, flexibility, and other parameters that are desired in every network [3]. But this potential is not always fulfilled . Cases have arisen where unexpected delays have occurred, and recent research suggests that such performance incoherences can sometimes be traced back to subpar combinations of Virtual Network Functions (VNF) in Service Function Chaining environments (SFC) [15]. For these technologies to fully be able to bring about their full benefits and potential, there is a need to understand how SFC and virtual environments in general are influenced by the virtual functions running in the network.

Having found out how the presently most used SDN version of policy-based routing, SFC, can bring about limitations to the network, efforts have been and are continually made to find a way to prevent the network from being affected by these setbacks. Researchers have put forward several attempts to do so, such as altering the function chaining process or creating tools to better understand what is causing performance degradation and where it is happening [15] [**?**]. Based on the recent research gathered and the possible improvements to the identified problem, the development of this paper will revolve around the usage of Segment Routing to improve the routing capabilities of the present SFC in regards to VNF dissemination.

1.2. Goals

The goal of this work is to answer the following research questions:

- How far has Segment Routing been developed and what are its use cases presently?
- Can enterprises leverage the use of Segment Routing? How can they benefit?

- What are the advantages of using Segment Routing with NFV? Is there a performance and/or latency increase?

During this thesis, an attempt was made to study the impacts of SR in SDN environments, more specifically, how the usage of Segment Routing in an IPv4 MPLS infrastructure can impact the network. SR in IPv6 has been a target of Virtual Network Function Chaining as a possible solution for achieving a better performance, but no conclusions were drawn regarding its stability [19]. Other relevant questions may surface, and there is the possibility that this work may delve further into the advantages (or disadvantages) of using Segment Routing in the multiple scenarios in which the routing technique will be implemented.

1.3. Structure

In the second chapter, this introductory report presents an informative description of the backbone technologies and state-of-the-art of the tools and networking concepts which are essential to the development and understanding of the thesis.

The following chapter, "Segment Routing Applications" focuses on how the solutions obtained try to answer the questions raised previously. It makes use of the achievements during the implementation of the project and provides a conceptual depiction of how said solutions can be used to answer those questions.

Chapter 4, "Segment Routing Implementations", addresses the implemented solutions, tests and results obtained during the development of the thesis, as well as the setbacks and challenges faced.

The document ends with chapter 5, expanding on the significance of the thesis regarding present technological needs and achievements, as well as what can be and is being done towards the development of similar implementations and the technologies involved.

2. Background

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Network softwarization has already captured the interest of both researchers and networking enterprises all over the world. Although the speed at which its core ideas are accepted and viewed as a significant improvement when comparing with the present hardware-based networks, the research into the less obvious particularities of the subject can still be considered somewhat superficial.

One of the most obvious benefits of the migration from legacy networks into a centralized approach are the expenses an ISP will face in the long term management of said networks, regarding scalability and flexibility [1].

Although a consensus has been reached about some of the more straightforward benefits of progressing into these kinds of software-based networks, the analysis of the optimal usage of this technology is still ongoing. Researchers have fiddled with many topics such as resource management, software interoperability and cost efficiency [2], and although it is globally accepted that the usage of SDN results in the reduction of costs, scalability improvement, and provides greater ease in managing the network [3], the technology's main potential lies in the possibility of its integration with other technologies, such as Segment Routing and Network Function Virtualization.

MPLS is a tunneling mechanism used in today's networks, providing a traffic steering functionality and secure encapsulation. MPLS VPN is an example of such encapsulation, while the famous RSVP-TE (Resource Reservation Protocol - Traffic Engeneering) is responsible for steering traffic in the network [7]. ISPs have found success in providing affordable VPNs and secure connection with the usage of MPLS, and the usage of VPN usage is still growing.

Segment Routing is considered to be an improvement over the classical MPLS encapsulation. Amongst some differences that give SR a reasonable edge over the classical protocol (which will be approached later in this paper), the most obvious difference between both implementations is the absence of the Label Distribution Protocol, which is close to being the defining feature of MPLS. SR has been a subject of interest for quite some time, and even more so when talking about centralised network controlling and SDN [4]. Although some of the most commonly used hardware can face compatibility issues with SR, that lack is not really a major concern to the development of the thesis, as no implementation will not be dependant on a physical topology. Considerable research has been conducted into SR and a few tutorials have been made available (mostly by Cisco and Juniper) to help with its implementation, using both open source or copyrighted appliances.

2.1. Multi Protocol Label Switching

To better understand SR, we must first delve into one of its bootstrap technologies: MPLS encapsulation.

Traditionally, MPLS makes use of the Label Distribution Protocol (LDP) as its main mechanism

to encapsulate the routed packets by an Interior Gateway Protocol (IGP) such as "Open Shortest Path First" (OSPF) and "Intermediate System to Intermediate System" (IS-IS) , throughout the MPLS-enabled network. As the name suggests, the protocol enables the routing of packets based on assigned labels to the routing paths, providing some QoS (quality of service) that simple IGPs do not have. More so, it can escalate into both MPLS VPN (Virtual Private Network) and MPLS TE (Traffic Engineering).

When evaluating presently employed networks with traffic engineered MPLS, we conclude that although it is a clear improvement over the pure IP networks, there are still problems that come with the encapsulation protocol[1]. To start with, large networks can be very complex, and although MPLS hides the complexity, it does not make it go away, making them more expensive and harder to maintain. Secondly, the overall view of the network is hidden by the encapsulation protocol, limiting the manageability of the network regarding unexpected traffic situations. Lastly, the usage of heavy signaling protocols such as LDP and RSVP-TE lead to a sub-optimal performance of the network. As is the case, this heavily used protocol has started to be outperformed by a more recent solution.

2.2. Segment Routing over MPLS

With the evolution of the internet progressively shifting its focus towards cloud, virtual and application-centric platforms integration, the need for both flexible, scalable, and simpler to manage networks is ever increasing. MPLS can no longer sustain the mentioned needs of worldwide operators regarding application engineered routing, and since SR can be implemented over MPLS without changing the forwarding plane, it has become a rather attractive technology to ISPs. Not only that, the prospects of migrating from an IPv4 into an IPv6 data-plane give SR an extra boost in popularity, since the technologies benefits can be manifested without the need of MPLS.

Researchers have delved into the architecture of this new technique. Their findings conclude that SR removes the need for heavy protocols such as LDP and RSVP-TE, improving the scalability and flexibility of the networks [8]. Moreover, by decreasing the number of protocols inside the network, it becomes more scalable and displays performance gains.

All network devices are composed by 3 major architecture planes: Management, Control and Data planes. Here, the Control and Data planes will be focused on, as the difference of how SR deals with them in comparison to the traditional devices is pivotal to the improvements SR offers, along with the decoupling process of SDN which will be approached later on.

The **Data Plane** dictates the processing of packets in the network, based on the information in each packet's header - a list of segments. These segments represent subpaths that form a complete route with instructions on how the packet should be forwarded. In that segment list there is one active segment - the instruction being ran at the moment. Each segment has an identifier (SID), and these can be differentiated into 3 main types [9]:

- **Node SID -** Forward to a certain node with the referred SID using the shortest path.
- **Adjacency SID -** Forward through a certain path considered as an adjacency by the running IGP.
- **Service SID -** Forward a packet to a service with the established SID.

The **Control Plane** defines how the SID information is shared throughout the network. SR makes use of the running IGP to handle segment distribution inside a local network. The most commonly used IGPs are IS-IS and OSPF, and the extentions developed for both these protocols make it possible for any SR compatible router in the network to maintain an SID database, as well as providing end-to-end encapsulation without the need of the LDP protocol.

Another role of the Control Plane in SR is the selection of the forwarding path. Static configuration is possible, but except for specific cases such as troubleshooting it is obviously sub-optimal in regards to performance and scalability. Thus, the main methods for selecting a forwarding path are the **Distributed Constrained Shortest Path First (CSPF)** calculation, or the implementation of a SDN-based approach integrated with a controller centralized network.

With CSPF, an ingress router (router placed at the edge of the SR network that first receives the packet and forwards it throughout said network) calculates the shortest path to a destination, and matches said path with a SID sequence referring to it. The shortest path may or may not be subjected to extra decision-making parameters with traffic engineering purposes.

With an SDN-based approach however, broader options beyond shortest path calculation are avail-

able. With the centralized controller, a network manager can better analyze traffic inside the network, and can directly act on it by providing traffic engineering commands specifically design to deal with the current situation in real time.

2.3. SDN Overview

Software Defined Networking is a paradigm that has emerged with the desire to reduce the impact of the limitations present on current networks. The current vertically integrated networks mostly rely on a rigid network infrastructure, possessing several nodes that take it upon themselves to individually deal with both the control and data planes. Although this offered resilience to the network, any change could turn out to be a daunting task, as modifications regarding the control plane would have to be made individually on each of the managed routers, switches and other specialized infrastructure hardware [11], SDN decouples the network's control plane from the underlying hardware, and attributes it to a controller that can manage it in a collective manner. This defining behaviour provides a broader viewpoint of the entire network that results in the possibility to manage the control of the network's hardware in its entirety, improving the network's manageability and flexibility [10]. The separation of data and control planes also allows for generic middleboxes to be used in place of the traditional specialized hardware, as the SDN controller takes charge of forwarding and logical decisions in the network. This would directly result in a lower cost of network maintenance.

In summary, SDN is defined by 4 fundamental pillars:

1. The functionality of the control plane is removed from network devices' responsibility (i.e. routers, switches, etc.), simplifying them into packet forwarding nodes.
2. That same functionality is given to an entity (SDN controller) possessing of an abstract network view, allowing for broader management options that are easier to implement.
3. Contrary to traditional IP networks, forwarding decisions are no longer destination-based. They are instead flow-based - a packet stream between a source and a destination with identical forwarding services, managed by the SDN controller.
4. Through an API (Application Program Interface) running on top of the controller, the network becomes programmable, interacting directly with the network's infrastructure devices.

The SDN architecture can be broken down into 3 distinct layers. Along with the Control and Data layers, there is also the Application layer [10]. The approach to this architecture will be bottom-up, that is, starting with the infrastructure layer (equivalent to the Data plane) ([1][11]).

- **Infrastructure Layer -** The bottom-most layer of the architecture. It is composed of all the hardware found in traditional networks. It is responsible for executing packet forwarding and communication between nodes in the topology, receiving the instructions to do so from the Control plane, since the devices do not possess autonomous decision making.
- **Control Layer -** Considered by some as the most relevant layer of the three, it is the mastermind behind most benefits brought to the table by the SDN paradigm[1]. The control layer manages the forwarding tables and the logical decisions that would traditionally be made by each device. It communicates with the Infrastructure layer through the Southbound Application Program Interfaces (APIs). These interfaces enable the dynamic changes in real-time events of all network devices in the first layer.
  This layer also has possesses Northbound APIs, which link it to the third and topmost layer, the Application layer. These APIs differ from the Southbound ones as they focus on receiving information on the running applications' needs such as, but not limited to, bandwidth and storage. The exchange of this information allows the automation of network applications (for example, firewalls and other security services) in the SDN network.
- **Application Layer -** Responsible for the network applications that take action in the network. It provides the controller with all the needed information for it to coordinate the forwarding logic needed for the data plane to transmit packets throughout the network.

With the segregation of the Control and Application layers and the information exchanged between the applications running on top of the network and the network itself through the Northbound APIs, SDN can provide the network with an application-based network management. This means that each application is aware of the network state, resulting in a network capable of operating in accordance with each of the applications needs [23].

2.4. Network Function Virtualization

The motivation behind the enforcement of NFV revolves around the desire to horizontally segregate

Virtual Network Functions (VNFs), and replace the traditional dedicated hardware with virtualized software, providing improved manageability while reducing capital expenditures and operation expenses. These VNFs are software implementations of traditional network functions, decoupled from the hardware. The isolation of said functions facilitates the identification of points of failure in the network. This allows the network to evolve to one where failure of a function (for example, a firewall) can quickly be identified and resolved.
Network Function Virtualization (NFV), is the overall concept of running software defined network functions along with the virtualization of the network.

Research regarding the efficiency of such virtualization techniques demonstrate though that the performance, flexibility, and other important metrics have unexpected and sometimes undesired values, depending on the type of functions and services being implemented. It was noted that for the same functions, performance varied depending on the order of the execution, as well as the type of service being provided (for example, network infrastructure compared to cloud services) [14] [15] [16]. Eventually, it was established that depending on the service set to be implemented, one had to manage VNFs specifically with the services to be provided in mind. But through this thought process another problematic scenario arose: VNFs requiring managing increased, and consequently, the complexity of the overall NFV management. As such, Management Orchestration (MANO) started being developed, to provide a platform to simplify handling the increasing complexity of NFV.

MANO systems are normally tasked with the management of virtualized infrastructures and VNFs (often implemented as virtual machines or software container images). Being able to provide better automation, high-availability and flexibility to those components are some of the factors that highlight the usefulness of MANO systems.

There are different MANO projects being developed. The purpose differs from each project: some are more academic-centered, others aim at business environments. Most MANO project adhere to the ETSI MANO framework model. Most Mano frameworks are supported by the **European Telecommunications Standards Institute (ETSI)**, commonly referred to as **ETSI MANO**. The framework used is viewed as one of the most relevant NVF MANO frameworks available, if not the most relevant. The platform focused on this thesis is the OSM platform.

For this project, open source MANO (OSM) will be used to provide a dedicated framework to view and manage the entirety of virtual functions being ran in the network. As such, Management Orchestration (MANO) started being developed, to provide a platform to simplify handling the increasing complexity of NFV.

The MANO framework in question is composed of three essential function modules [14]:

- **Virtualized Infrastructure Manager (VIM) -** Responsible for management of virtual machines and containers (VNFs), handling the virtual links between them. In this project, that will be achieved through usage of SDN.
- **Virtual Network Function Manager (VNFM) -** Its focus lies on dealing with network services, that is, controlling the VNFs' life-cycles, separately. The manager is charged with more than just the automation of the VNFs, delving into the configuration, the start of a function, and it's death.
- **Network Function Virtualization Orchestrator (NFVO) -** Ensures the integrity of the overall service provided by the interaction of all the VNFs in the system. It is in charge of all the data required to ensure the end-to-end integrity of the service. External applications communicate directly with the orchestrator when in need of critical information regarding the entities involved in the service (for example, VNFs, network services, and available resources).

2.5. ONOS Controller Platform

The Open Network Operation System (ONOS) is an open source project that leverages a network controller that can be used alongside SDN networks. It provides the control plane of the SDN network, and it is this platform that will be used in the development of this project.

ONOS is seperated into several subsystems. Although every subsystem is essential in some manner towards the functioning of ONOS and the overall network being managed, they are fairly independent from one another in terms of each of their functions, as some of them work within the northbound scope, while others are related to the devices and southbound API.

When referencing the Southbound API managing the connection between the ONOS Controller and the devices in the Infrastructure Layer, it

is worth noting that ONOS Southbound API is not limited by any specific protocol, and supports several different implementations, namely OpenFlow, NETCONF/YANG, and SNMP. As mentioned in the SDN section, ONOS makes use of its Southbound API to communicate with the devices in the infrastructure layer. Subsystems like **Flow Rule**, which are responsible for managing and enforcing the rules for network forwarding on devices, are directly involved with the information sent to the devices by the controller through it's southbound interfaces[12].

Regarding the Northbound API connecting to the application layer, ONOS takes advantage of its own **"Intent Framework"**. This subsystem allows for the applications to declare their management needs to the controller, based on a pre-existing policies of the applications in question. This "intent-based" networking is a way for the applications to simply state their needs to the controller and letting it handle all the work, believing that these needs will be met. This is the foundation for the automation offered by ONOS' SDN approach, resulting in a much more scalable network [13] than a traditional non-SDN network.

2.6. OSM - Open Source MANO

After the specification of NFV MANO frameworks, specific projects started to emerge from each framework. This paper makes use of OSM, an expansion project based on the ETSI MANO architecture previously mentioned.

OSM aims to deliver the automation and modelling of enterprise-grade services. By implementing a virtualized network supervised by OSM, the integration of NFV infrastructures and VNFs is meant to be simplified, providing a stable approach to the emergence of virtualized networks. The OSM project delivers a VIM-independent product, compatible with multiple SDN technologies and capable of managing all types of VNFs [17].

The first factor contributing to the automation of Network Functions and Services is the **Information Model (IM)**. This model generates tree representations of the various Network Functions (not limited to virtual ones) managed by the system and automates their lifecycles at instantiation and proceeds to do so throughout their daily operation. Any given element can be instantiated independently of the VIM module, as well as any SDN software, in use. During the implementation phase of this project, it is planned that OSM will make use of ONOS' SDN software in its Virtualized Infrastructure Manager module. Another factor that is offered by OSM is its feasibility of integration in brownfield environments: by providing one single **Northbound Interface (NBI)** integration point, which allows for the handling of both physical and virtual assets/functions simultaneously, guaranteeing the proper handling without the need to make any distinction between said assets.

2.7. Service Function Chaining

The future for networks seems to aim towards virtualization, and the escalation of NFV environments employing multiple VNFs comes as no surprise. To support this escalation, the Service Function Chaining (SFC) paradigm was proposed to deal with the sequential traffic routing between VNF instances. Automation and improved performance are two of the giveaway benefits of SFC, but while there are well documented benefits to this approach, there are also some concerns regarding its deployment[18]. One of such concerns is a recurrent performance uncertainty, originating from the usage of VNFs as opposed to hardware dedicated functions. This issue is commonly looked at as a question of improving performance, leading to the research and development of faster and more powerful NFV tools. Still, there are different perspectives on this matter that approach the problem not as a lack of performance, but regarding the reasons behind the performance variations for multiple cases in the same system.

Studies have comprised possible triggers such as uneven CPU usage by VNFs, bad handling of said resources by the managing tools, and the routing of SFC of throughout a network with multiple VNFs and VNF instances where the specific sequence of running instances matter [15] [18]. One conclusion of such research revolves around the need to implement a mechanism to be able to spot bottlenecks and irregularities in various sequences of instances and different environments, that can identify and act on said instabilities locally, regardless of the network implementation. One such tool is Probius[15] that aims to provide an abnormal behaviour detector based on several performance features according to the VNF's architecture, matching said abnormalities with possible performance variation triggers.

3. Segment Routing Applications

In this chapter it will be explained how our solutions can help to reach the goals proposed in section 1.2, as well as the reason behind the choice of said solutions.

With Segment Routing gaining popularity, and SDN along with NFV looking to be the future of programmable networks, it seemed a good idea to expand on the idea of integrating the 3. The plan was to use an already existing tool,by the name

SREXT (found in [19]), as an extension to the mininet capabilities, by conferring its virtual hardware the capability to route VNFs with Segment Routing.
The following use case is related to datacenters. The reason for that choice is based on the biggest challenges and needs that datacenters have not been able to overcome. They have faced and still face a problem regarding the usage of non-commodity hardware, and the reliance on in-site installation of dedicated hardware, which are direct causes of its high OPEX and CAPEX. Thus, the lack of agility and programmability is an issue that many enterprises wish to tackle and overcome, as it will drastically reduce costs. With this in mind, the first use case elaborated in this thesis is a Spine-Leaf network, much like a Datacenter network, where Segment Routing is enabled and a demonstration of its functioning is achieved.
One open source community that is in the forefront of SDN development is ONOS. They have many projects ongoing regarding different advantages and use cases for software defined networks. One of such projects is SPRING-OPEN. This project aims to demonstrate maturity, readiness and scaling capabilities of Segment routing and SDN usage in already available hardware in professional environments and enterprises. This seemed like a noble pursuit, and this thesis aimed to replicate the functioning of SPRING-OPEN.

4. Results

The focus of this section is on the implementation of the Segment Routing Solutions found. It will describe each solution including the achieved results, implementation variations, and faced challenges throughout the development of each.

4.1. Implementing VNF Chaining in a Linux-based NFV Infrastructure

The initial plan of this project was to utilize the already developed Linux-based NFV Infrastructure from the research paper "Implementation of Virtual Network Function Chaining through Segment Routing in a Linux-based NFV Infrastructure" [19]. The developers behind this tool called "SREXT" had programmed the default networking appliances offered by the Linux environment, conferring extra configuration options. With these improved appliances, it would be possible to implement not only IPv6 Segment Routing, but also NFV function chaining. Another benefit offered by the tool was the possibility of chaining SR-unaware VNFs. This means that it would be possible for VNFs that are not designed specifically to be used with Segment Routing would still function in this environment, making it so that generic VNFs could still be used in an SR network. A tutorial version was developed and made available by the authors, where a basic version of the utilities of the tool were demonstrated.
Although SREXT was functional at the time, after the Ubuntu kernel 5.2 update, the installation of the tool was no longer possible. This problem was raised by multiple users and was indeed acknowledged by the developers, but not fixed. According to the authors of SREXT, there will be no update to the tool, making it so that whoever wants to use the tool cannot do so if the Ubuntu version of their machine uses the kernel version 5.2 or higher.
Another problem arose out of this situation, related to the use-case tutorial provided by the authors. The tutotial was a testbed provided in a VirtualBox using Vagrant, a tool for managing virtual machine environments. This testbed broke due to the same reason, and this problem was documented as an issue on December 9, 2019, by the community. Both issues are still unresolved at this time.

4.2. ONOS Implementation - Spine-Leaf Solution and Results

After the SREXT implementation setback, the project suffered some changes, and the development was centered around the ONOS platform. ONOS allowed for the development of the Segment routing network on top of the mininet network emulator in which the standard Linux network software is ran. The implementation of Segment Routing using the ONOS in this project platform can be divided into 2 solutions: Spine-Leaf and SPRING-OPEN.
Spine-Leaf is the name given to a popular type of network architecture that is used in datacenters. Its is composed of 2 layers of switches, the leafs, connected to servers and spines, and the spines, connected only to leafs. A leaf connects to all spines, the same way as a spine connects to every leaf. This architecture is specially popular in datacenters with heavy server-to-server communication, as it minimizes latency and bottlenecks.
The objectives of this solution are twofold: to look into the functioning of SR in the Spine-Leaf architecture, and to see how it is possible to apply traffic engineering measures with the usage of the ONOS controller.
The implementation of Segment Routing in the Spine-Leaf topology was successful, and the objectives achieved. Connectivity verification was done to see if Segment Routing was working properly. Hosts from different Leafs were able to communicate, no matter which Leaf or host. Afterwards, the packets were analyzed in order to see if the labels used by the SR protocol were being handled as expected, which was proven the case. Another feature implemented with the Spine-Leaf solution was a simple firewall appliance, in the form of an

Access List rule. This appliance worked as intended by blocking the specified traffic.

4.3. ONOS implementation - SPRING-OPEN solution

The objective of using this solution was to implement a more comprehensive test-case of the Segment Routing capabilities, capable of incorporating VNF chain routing. ONOS SPRING-OPEN is a use-case developed by the ONF, relying on the ONOS controller, that can demonstrate the possibility of using SDN and Segment Routing along with already existing hardware, in a professional environment. The ONOS website provides a Virtual Machine build regarding the SPRING configuration for the ONOS controller. Along with the Virtual Machine and an installation guide, there are also some tutorials that explain the capabilities of the tool specifically for Segment Routing. This solution would be used to demonstrate other advantages beyond the ones demonstrated in the Spine-Leaf solution. Instead of just demonstrating the functioning of the protocol, more specific use-cases can be demonstrated, such as Fine Grain Traffic Steering, Load-Balancing without the use of ECMP, and Segment stitching. These functionalities are not native to the ONOS controller by its own, meaning that such use-cases would not be able to function without extra configurations for ONOS.
Sadly, the SPRING-OPEN project was archived and deprecated, despite its usefulness. The Virtual Machine containing the ready for use project was made unavailable, and the documented procedure to build the project from source is no longer functional. The main reason for the decommission of the project was the lack of integration offered by the SPRING-OPEN project regarding new complementary technologies and ideas. As mentioned, SPRING-OPEN relied on the heavy configuration of a specific ONOS version, which limited the configuration capabilities of the ONOS controller CLI, which in turn could only handle tunneling and other routing policies. All needed startup-configuration needed to be arranged via a configuration file loaded at startup. This means that [26]. The network would have limited potential to adapt "on the fly" to other changes beyond tunneling and routing policies. With a combination of SR and SDN, both which brag about flexibility and ability to adapt, this kind of limitation is counter productive.
In its stead, ONOS adapted a different project, less reliant in the startup configuration of the controller. the Next Generation SDN Platform (NG-SDN) leverages 3 technologies at its core: μONOS Stratum, and Trellis.

4.4. NG-SDN outline

The successor to the SPRING-OPEN project is called the new generation SDN project, or NG-SDN for short. Like its predecessor, it is an open source platform that focuses on the development of SDN networks, but unlike the previous project, it manages to integrate multiple technologies otherwise incompatible with the ONOS controller. For example, NG-SDN makes use of the P4 language and P4 Runtime protocol, which is growing in popularity among the tools utilized in the development and controlling of Software Defined Networks. [27]

One of the main components of NG-SDN that differentiates it from SPRING-OPEN is the new upgraded controller, μONOS. This upgrade focuses on the ONOS controller, conferring zero-touch provisioning, extending its capabilities in configuration, control, and monitoring, and also opening up the possibility to configure the network in real time and "on the fly" in ways not previously possible. The performance of the controller is also upgraded, as the improved μONOS is also aimed at 5G networks [28].
The second core technology used by NG-SDN is Stratum. This technology is one of the two core additions that differentiate NG-SDN from SPRING-ONOS. Stratum is essential in conferring hardware independence and top down progammability in the network, along with Fine-grained control and measurement, by providing an intelligent and cooperative data plane [29].
The third core component of this new project is Trellis. Trellis cannot be considered an upgrade on the old ONOS' SPRING-OPEN project, as its utilities go beyond the scope of the previous project. Trellis is a platform to create open-source multipurpose L2/L3 switching fabrics, such as Spine-Leaf and NFV switching fabrics, specifically developed for integration with μONOS and Stratum [30].
There are other platforms currently being developed to be used with the upgraded μONOS, for different uses and objectives. With the use of the 3 mentioned, the integration of NFVs with a Segment Routing capable network would be much less troublesome. For one, there would be no need to develop from scratch software to integrate NFVs into the network like the case with SREXT, in section 4.2. The fact that this project is still expanding but already possesses functional cases is also a plus.

5. Conclusions

SDN threatens to become a core feature of networks in the futures. It leverages many benefits and even more so when paired with other technologies such as SR and NFV. This thesis demonstrates a successful use case where these technologies can be im-

plemented, as well as bright prospects for future development and possible adoption by enterprises in professional environments.

Segment Routing presents benefits for networks that are tailored for today's needs, and show promise to secure its position alongside SDNs in the future. From datacenters to broad international networks, several solutions are in development and many strive to be mature enough to be adapted into professional environments. It is the case that, as shown, some use cases are already capable to hold its own in the networks of today, with others following the same footsteps.

Network Virtualization is a fairly recent technology that has taken off and is expected to grow into a major player in the networking field. Relevant technologies such as 5G make use of virtualization techniques, and it is desirable that these technologies operate to the best of their abilities. Unfortunately, its development is still in the early stages, and the integration with other relevant technologies is still problematic, although projects have been manifesting themselves during the last year.

The integration of Segment Routing and Service Function Chaining as a VNF dissemination tool is a scarcely explored improvement to the already existing software in charge of VNF control and transmission. In this thesis, it was not possible to demonstrate the supposed synergy that the integration of NFV, NFV and SR could accomplish, but the project leaves a challenge for the future regarding the usage of the μONOS, Stratum and Trellis to achieve exactly what was not possible this time.

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