Teaching 5G Networks Using the ONOS SDN Controller

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***Abstract*—Software Defined Networks (SDN) and Network Functions Virtualization (NFV) are two significant answers to the demands raised by the next generation of mobile networks. Teaching 5G, wireless and mobile networking is becoming an absolute necessity as virtualization and SDN generate a whole new approach for these types of networks and are candidate solutions for the fifth generation. We present several ideas for teaching the combination of SDN and NFV in future mobile networks using the Open Network Operating System (ONOS) and its use cases. The architectural scheme which is experimented is thoroughly explained. There are several network simulations using the use cases vRouter (Virtual Router), IPRAN (Internet Protocol Radio Access Network) and MCORD (Mobile Central Office Re-architected as a data center) of the ONOS controller, which show how important the ONOS is and how it contributes in explaining 5G and SDN in the teaching process. Finally, experiments indicate that ONOS is suitable for teaching SDN and NFV in 5G. Future activity in the field is suggested.**

Keywords*—SDN, NFV, 5G, ONOS, IPRAN, MCORD, mobile networks, teaching, experimentation

I. Introduction

Since 2020 is going to be marked by the standardization and the introduction of 5G in mobile networks, it is extremely important to find methods to provide almost unlimited network resources including capacity, speed and coverage. Future network infrastructure will be very diverse and will consist of different types of networks (adhoc, mobile, wired, wireless, etc.). Therefore, the need of orchestrating networks in an unified way is raising. The heterogeneity of the network devices and technologies from Long Term Evolution (LTE) and beyond rises the expectation of providing better handover and management policies and better resource allocation in different coexisting technologies.

Software Defined Networking (SDN) is a modern technology, that splits the control and the data plane into two different layers. It offers centralized control, a centralized view of the network and many fundamental benefits. The Network Function Virtualization (NFV) is a way of replacing hardware and most network functionalities with software. This technique offers energy efficient and low-cost architectures freed from all hardware problems.

There is substantial research concerning the Radio Access Network (RAN) [1], [6] and [13]. Most research activity in the field of mobile SDN focuses on explaining and describing the extension of the OpenFlow protocol for mobile cases, such as [8], [9], [10] and [11]. Theoretical background suggestions [8], [9], [10] and [11] present the main mobile SDN architectures. The most important advantages included are presented in the previous papers, such as:

- Directly programmable network without the hardware installation difficulties (capital, operational, personnel, etc).
- Central network management, due to SDN controllers.
- Abstraction levels for data, control and devices.
- Effective configurations (prototypes, standards, protocols, control and application interfaces, etc).
- Effective Radio Resource Management (RRM).
- Scalability provided by both SDN and NFV.

The Open Network Operating System (ONOS) is created by the Open Networking Lab (ON.LAB). Many of its cases are ongoing projects. ONOS is a tool for experimenting with SDN and testing different topologies. In [3], there is an analysis of the prototypes developed for SDN and also the most important challenges that are deterrent factors regarding its wide adoption. There is an evaluation of ONOS when it comes to scaling, fault tolerance and performance improvement. [7] presents a way of monitoring the OpenFlow messages between the ONOS controllers and the OpenFlow switches. There is an evaluation of the OFMon, namely the unique monitoring system of the OpenFlow protocol. Two different protocols concerning the updates of nodes are analyzed in [12].

Although, many practical and pure technological aspects of SDN have been thoroughly analyzed, there is not much research, when it comes to the experimentation and the teaching of mobile SDN. [5] focuses on teaching SDN and its benefits when it is adopted in an academic organization. Suggested technologies for 5G networks include several technical aspects usually abstruse by most students in networking tutorials. Authors have already presented an overview of mobile SDN & NFV solutions in 5G [4]. In this paper, authors introduce ONOS as an educative tool for experimenting with SDN & NFV technologies in 5G networks. This study consults network tutorials of SDN and virtualization teaching techniques to initiate students into the abstraction logic. Authors present possible exercising simulations and experiments, using ONOS use cases: vRouter (Virtual Router), IPRAN (Internet Protocol Radio Access Network) and Mobile Central Office Re-architected as a data center (MCORD), which are basic use cases provided by the ONOS. Most studies focus on a different aspect of the technology, while this paper focuses on the training capabilities provided by ONOS use cases.

The remaining part of this paper is structured as follows: In Section II there is an analysis of the theoretical background alongside with the motivation of experimentation regarding the ONOS controller. In Section III the main architectural models implemented are presented. In Section IV the opted parameters for the suggested network topologies are summarized. In Section V the results of the conducted experiments are described and commented. In Section VI the results are evaluated. In Section VII the paper is concluded and several ideas for future research activity in the field are listed.

II. Motivation

In this section, there is a theoretical background analysis of the ONOS controller and its main components. The SDN and NFV are fundamental technologies that should be examined by tutors and be taught to students, as they will consist essential ideas in the formation and management of future networks. What is more, the OpenFlow protocol, alongside with its mobile extension will be studied and explained in universities and colleges. ONOS is a simple controller with a unix-like interface which could be combined with mininet emulator and provide a full teaching framework.

Fig. 1 describes the main cellular architecture in the fifth generation of mobile networks based on SDN solutions. It analyzes how SDN nodes co-ordinate with the core network and how the total infrastructure connects to the Internet.

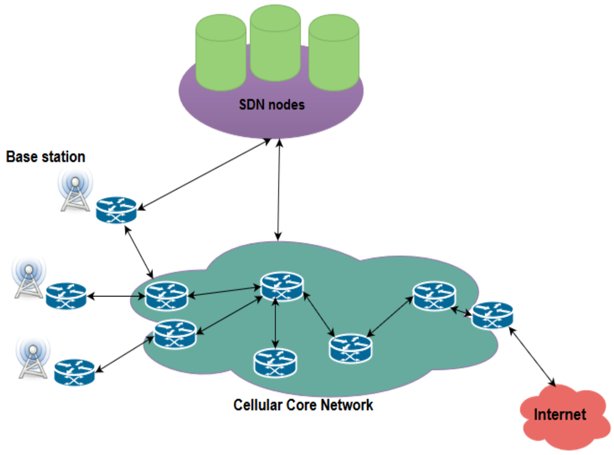

Fig. 1: The overall mobile architecture based on SDN networks, such as ONOS.

Fig. 2 describes basic RAN architectures in combination with SDN, all included components and their interconnections and all RAN components. It also summarizes the parts, that are virtualized and are integrated in the RAN. ONOS is the SDN service controller and supports a RAN SDN controller and a Wide Area Network (WAN) SDN controller.

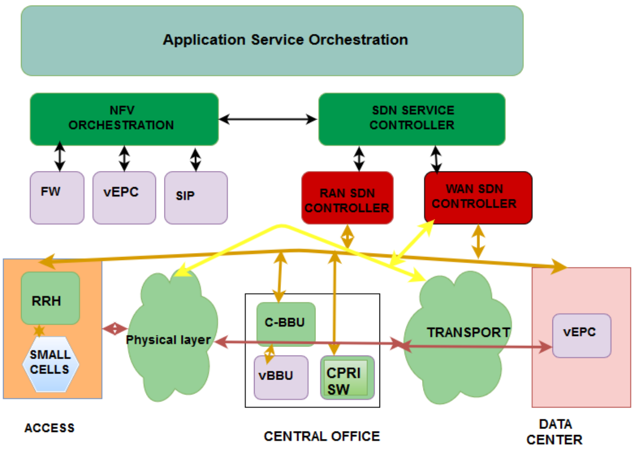

Fig. 2: The RAN architecture as described in mobile networks based on SDN controllers, such as ONOS.

ONOS offers an easy way to experiment with SDN architectures. It simulates the abstraction layers, namely the Southbound and the Northbound as described in [2]. Fig. 3 describes the ONOS general concept architecture as described by the ON.LAB. The most important benefits of the ONOS architecture, such as: distributed core, integral coherence, northbound and southbound abstraction, software modularity, easy addition and maintenance of servers could easily be explained to network students. ONOS controller includes many important use cases for experimentation.

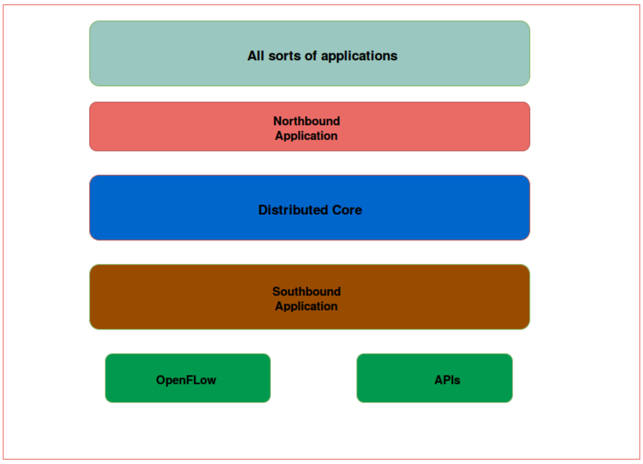

Fig. 3: The presentation of the high-level concept of the ONOS architecture.

CORD and its mobile case are technologies that are rather difficult to understand. Nowadays, Emu and beyond releases of the ONOS project are enabling CORD. Its combination with the NFV is going to play an important role. This integration is going to happen in the next release of the Open NFV's next generation, that is called Brahmaputra. This integration will create a prototype model of SDN-NFV system and will provide scientists and engineers with the concept of the future SDN systems, which will include more opportunities for experimentation. ONOS also includes several important mechanisms and capabilities that should be examined and included in exercises.

III. Architectural Models

In this section, there is a description of the topologies in the experimental procedure in this paper. All topologies were created and built in mininet for the vRouter and in mininet-wifi for the mobile network cases respectively. Mininet-wifi is useful, because of the need to introduce base stations, access points and other components of the mobile networking. Mininet-wifi is a simulation tool that helps experimenting with the wireless, mobile and adhoc networks.

The first topology creates a virtual router including a switch, which performs the routing and communicates with the SDN controller using the Border Gateway Protocol (BGP). ONOS plays the role of the remote controller and among other advantages it enables the communication with the Internet. The vRouter is included in Fig. 4. It includes only simple devices, such as hosts and switches. The switch functions as a router. The main benefit is that although it is a device with no routing capabilities or network intelligence, it performs demanding tasks (e.g. routing) thanks to integrated programmable logic. For simplicity reasons a switch connected to the controller alongside with two hosts are included in the created topology. VRouter enables explaining about programmable logic and virtualization.

The IPRAN topology is depicted in Fig. 5. The IPRAN use case allows the SDN network to exchange traffic with neighboring networks using the BGP routing protocol. The importance of the IPRAN topology is that it examines wireless network cases using the ONOS controller. It tests one access point and two base stations. What is more, it is easy to include hosts and test mobility and handovers between these stations. This topology includes 2 base stations and 1 access point.

An heterogeneous topology is depicted in Fig. 6. The heterogeneous topology is introduced based on the IPRAN use case and allows the SDN network to exchange traffic with

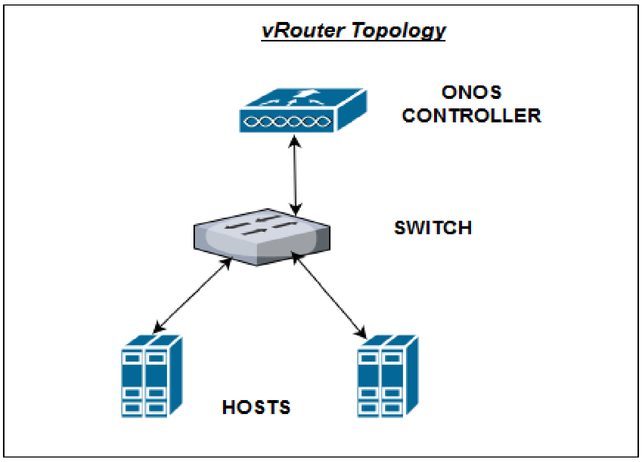

Fig. 4: The vRouter architecture built in mininet to interact with the ONOS controller.

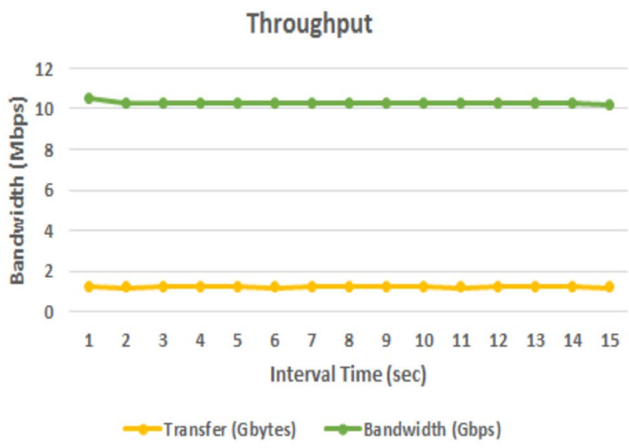

Fig. 6: The heterogeneous architecture built in mininet to interact with ONOS controller.

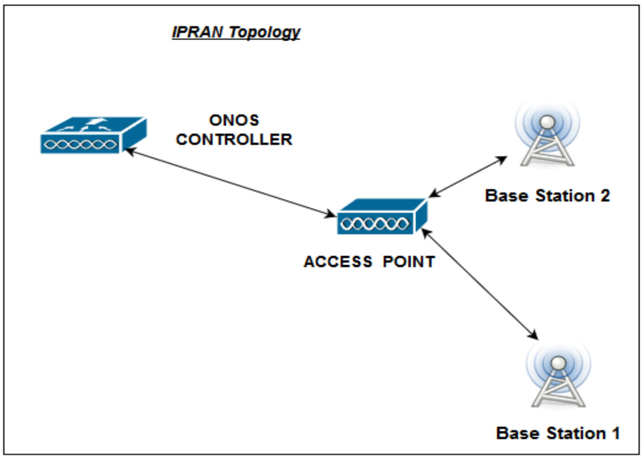

Fig. 5: The IPRAN architecture built in mininet, which interacts with the ONOS controller.

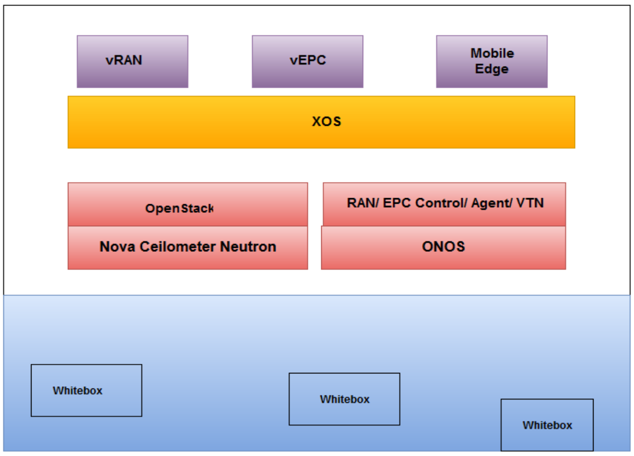

Fig. 7: The MCORD architecture as it is described in the ONOS documentation.

external neighboring nodes using the BGP routing protocol. The importance of this topology is that it introduces the modern heterogeneous networks onto the ONOS controller. It tests one access point, two base stations, one switch and four hosts connected to it. The configuration of the switch is held on the controller. What is more, it is easy to include more hosts and test mobility and handovers between these stations.

CORD is a use case of ONOS. It offers important benefits, among which are: Access as a Service (AaaS), Subscriber as a Service (SaaS), Internet as a Service (IaaS), Content Delivery Network (CDN), Monitoring as a Service (MaaS). These are complicated notions that confuse students and ONOS could be an easy way to enable experimentation with them, deep knowledge and understanding. CORD is fundamental, because it is very cheap compared to the conventional data centers, as it consists of commodity building blocks and open source software white-boxes.

Its mobile version is called MCORD, which exists as one of the use cases of ONOS. MCORD is an ongoing project. The scientists deploying it promise that it will help meeting several important challenges in the next few years, that will lead to the 5G formation and architecture. MCORD is going to be the main answer in the increased data traffic, resulting in the augmentation of the demands for alternative access points. There is also a huge investment when it comes to spectrum, alongside with LTE (Long Term Evolution) infrastructures, that has to ensure benefits and augment revenue growth for the operators. The diversity and the management of devices are also very important matters as the IoT (Internet of Things) is forthcoming.

MCORD could enable teaching the enhancement of the spectrum utilization. It is enabling Quality of Experience (QoE) for users as it reduces latencies and round-trip delays. It consists a tool for developing more personal provider services, such as billing, which will be much easier with the usage of MCORD. Agility and cost-efficiency are also very important for the evolution of the networks and are offered by MCORD.

The architecture of MCORD is based on the fact that it is possible everything to be ”viewed” as a service (XaaS). Analytically, it consists of a virtual Base Band Unit (vBBU), a virtual Mobility Management Entity (vMME), a virtual Serving Gateway (vS-GW), a virtual Packet data network Gateway (vP-GW), the OpenStack, the ONOS, monitoring and a virtual CDN (vCDN). Fig. 7 indicates the basic MCORD architecture as presented by the ON.LAB and the way it interacts with the other components, which could be another educational goal.

IV. Experimentation

In this section, the use cases of the ONOS for the experimentation procedure are: the vRouter, IPRAN and MCORD. Firstly, it is important to install the ONOS controller based on the ON.LAB documentation. Then, the ONOS controller is configured according to the suggested configurations for the used cases. Apart from installing the ONOS version, creating the mininet topology files, we introduce and test topologies in the ONOS controller.

The vRouter case includes an ONOS controller, one switch connected to the controller and with two different hosts. This is a wired case scenario, so there are not any access points or base stations. The internal BGP speaker and quagga are configured by accesing the zebra and the quagga configuration files and storing values for the controller and the network.

The IPRAN use case scenario is a mobile one. It includes two different base stations and one access point, which communicate using the BGP protocol for communicating via the SDN controller. The controller communicates with the access point. The access point communicates with both base stations and the base stations communicate with one another. There are links between all the components and there are several configurations within the zebra and quagga configuration files.

The heterogeneous topology includes the ONOS controller, one access point connected with two base stations. There is also a switch connected to the ONOS controller and 4 hosts connected to the switch, that communicate via the controller. The controller communicates with the access point. The access point communicates with both base stations and base stations communicate with one another. There are links between all the components and there are several configurations with the zebra and quagga configuration files.

V. Simulation

In this section, the experimental procedure is analyzed and the results that arise from the analysis are presented. The total simulation procedure shows that ONOS is a very valuable, useful and reliable controller. ONOS is open source, so is the mininet and the mininet-wifi that are used for the network emulation. This fact is extremely useful for experimental and educational purposes.

In the following subsections, there are analyses of the experiments conduced for each one of the different topologies. Analytically, there are analysis on the commands executed in the simulation procedure and the results provided. The xterm is also used for the record of the throughput in function to the seconds elapsing since the topology starts. Using these data several graphs are formed considering the experimented use cases.

A. vRouter

In this section, there is a presentation of the experiments conduced concerning the vRouter case. There is an explanation of the steps followed in the experimentation, which are described below:

- Starting the ONOS and executing the ”summary” before introducing the topology, the only device existing in the controller interface is the controller.
- After introducing the topology inside the network and executing ”summary” there is another device in the controller interface that is the switch.
- After ping tests for the connectivity of the hosts, in the ONOS interface are introduced 2 different hosts and several flows exchanging packets. Analytically, tests are h1 ping h2 and h2 ping h1. All hosts are connected.
- The execution of ”devices” apart from the controller are introduced by the switch and are visible in the ONOS interface.
- The packets are exchanged with 0% packet loss in little time, that are depicted in the ”flows”.
- Executing the ”net” command the switch is the router.

Fig. 8 describes the Transmission Control Protocol (TCP) traffic after the ”iperf” test. It presents the TCP flows as throughput per time. The network is very efficient and the throughput is very high. In the time interval 0-15 sec 42.2 GBytes are transfered and the bandwidth is 24.1 Gbps.

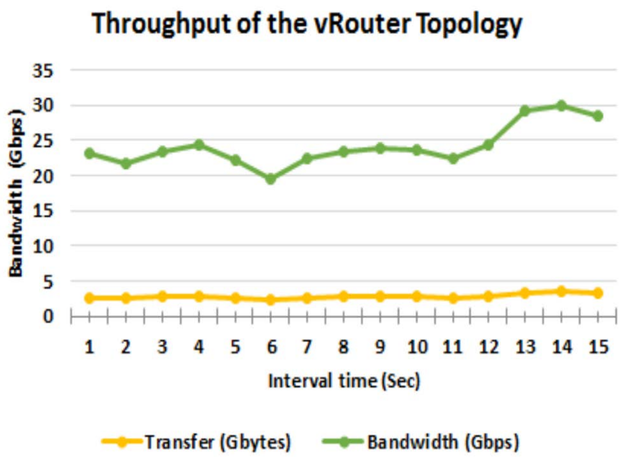

Fig. 8: The performance of the vRouter use case is depicted presenting throughput as a function of time.

The experimentation procedure indicates that the implementation of the vRouter is successful. Firstly, it functions as virtual router. Secondly, hosts are added in the topology, they interact, they are connected, because it is possible to exchange messages. The packet loss is very low and the data sending ratio is very high. Every change made on the network or the topology including several command executions in mininet is also depicted in the ONOS controller. The previous experiment could contribute in teaching about:

- How simple network devices such as switches or bridges could become more complex (routers) with the usage of programmable logic or network virtualization
- Introduction into virtualization techniques
- SDN networking, abstraction layers in SDN, SDN controllers, OpenFlow protocol
- Understanding of the BGP protocol and how it functions in SDN networks or in general
- Network configurations and network management
- Familiarization with unix systems and running scripts
- Usage of the xterm, usage of terminal
- TCP or UDP protocols and their differences
- Ping and Iperf tests

B. IPRAN

In this section, there is a presentation of the experiments conduced regarding the IPRAN case. There is an explanation of the steps followed in the experimentation procedure, which are described below:

- Starting the ONOS and executing ”summary” before introducing the topology, the only device existing in the controller interface is the controller.
- After introducing the topology and executing ”summary”, inside the network there is another device in the controller interface that is the access point.
- After ping tests for the connectivity of the base stations, several flows exchanging packets are introduced in the ONOS interface. Analytically, there are tests: bs1 ping bs2, bs2 ping bs1. There is also a test executing the ”flows” command, that shows that the necessary components are integrated in the ONOS controller.

TABLE I: The testbed of the topologies, that were tested in mininet.

Network component	HetNet	vRouter	IPRAN
Controller	ONOS	ONOS	ONOS
Switches	1	1	-
Router	✓	Virtual (Switch)	✓
Hosts	4 hosts	2 hosts	-
BS	2	-	2
AP	1	-	1
BGP communication	✓	✓	✓

- Executing the command ”devices” the controller and the switch are visible in the ONOS interface.
- The packets are exchanged with 0% packet loss in little time which is indicated by executing the ”flows” commands.
- Executing the ”net” there are the sta1, the sta2 and the ap, namely the two base stations and the access point.

The experimentation procedure indicated that the implementation of the IPRAN was successful. Firstly, it is a wireless network and it is possible to introduce mobility into it. Secondly, the base stations that are added in the topology, interact, are connected and exchange messages. The packet loss is very low and the data sending ratio is very high. Every change made on the network topology including several command executions in mininet-wifi is also depicted in the ONOS controller. The previous experiment could contribute in teaching about:

- How wireless network components communicate with the SDN controllers
- Introduction into mobile network architectures and its basic problems
- Network interfacing, controller interfacing
- Understanding of the BGP protocol and how it functions in SDN networks or in general
- Mobile network configurations and management, management of network resources, such as bandwidth, etc.
- Configuration of mobile network components, which differs from the wired ones, because position, mobility, etc. play a special role

C. Heterogeneous

In this section, there is a presentation of the experiments conduced in the IPRAN use case for an heterogeneous network. An analysis of the steps followed in the experimentation is described below:

- Starting the ONOS and executing ”summary” before introducing the topology, the only device existing in the controller interface is the controller.
- After introducing the topology inside the network and executing the ”devices” there is another device in the controller interface, namely the access point.
- After ”ping” tests for the connectivity of the base stations, in the ONOS interface are introduced several flows that exchange packets. Analytically, several ping tests are conducted for every host and every base station.
- Executing the command ”devices” apart from the controller are introduced by the switch and are visible in the ONOS interface.
- The packets are exchanged with 0% packet loss in little time executing the ”flow” command.
- Executing the ”net” command there are the sta1, the sta2 and the ap, namely the two base stations and the access point and the switches and the hosts.

The experimentation procedure indicated that the implementation of an heterogeneous wireless network was successful and it is possible to introduce mobility into it. Several hosts are added in the topology, they interact, they are connected and exchange messages. The base stations that are added in the topology, interact connected and exchange messages. The packet loss is very low and the data sending ratio is very high. Every change made on the network or the topology including several command executions in mininet is also reflected in the ONOS controller. The previous experiment could contribute in teaching about:

- How heterogeneous network components communicate with the SDN controllers.
- Introduction into mobile network architectures and their basic problems.
- Network interfacing, controller interfacing.
- Understanding of the BGP protocol and how it functions in SDN networks or in general.
- Mobile network configurations and management, management of network resources, such as bandwidth, etc.
- Configuration of mobile network components, which differs from the wired ones, because position, mobility, etc. play a special role.
- Introducing and explaining heterogeneous issues raised by novel 5G technologies, such as IoT, adhoc networks etc.

D. MCORD

In this section, there is a presentation of the experiments conduced in the MCORD use case. The parameters used are those of the ONLab use case. In this use case, the MCORD includes several services: RAN, Edge and virtual Evolved Packet Core (vEPC). Each one of the services includes several other components.

- RAN includes virtual Business Connection Network (vBCN), vBBU and the BBU.
- EDGE includes Firewall, Cache and Video Optimization.
- vEPC includes vP-GW and MME.

These services are included inside a service provider platform. There are many categories of services. The virtual BBU runs on a virtual machine (VM). Several new instances of VMs could be easily added using the platform. What is more, several other important network actions are easily monitored. The cache and firewall included in the EDGE services could be enabled or disabled for some users. Moreover, a very important capability offered by the MCORD is the video optimization. Video streaming demands high network resources, while in some other network applications the most important is the real-time responsiveness.

Another important ability of MCORD is the providing of a cell optimization environment. This environment could help ameliorate the state of the transimission of data between cells. What is more, it is obvious, that there are many scenarios that include RAN slicing and core network slicing. There is also immediate access to the uplink and downlink schedulers. Another important profit is that everything runs as a NFV. For example, the MCORD runs in a VM using the OpenStack. The Home Subscriber Server (HSS), the MME, the P-GW also run in virtualized network functions and several instances of user equipment. The previous experiment could contribute in teaching about:

- How CORD and MCORD function
- What are the main components, such as: HSS, MME, P-GW etc.
- RAN, EDGE, vEPC
- Network slices and their roles in networks, slices in 5G networks
- Mobile network configurations and management, management of network resources, such as bandwidth, etc.
- Configuration of CORD and MCORD
- Re-architecture of the central office to act as a data center
- Familiarization using examples and experiments with the notions: AaaS, IaaS, MaaS, CDN, IoT, QoS, QoE

VI. Evaluation

The topologies created and tested are simple topologies that were inserted into the ONOS controller. The experimentation procedure showed that it is easy to insert the topologies into the controller, to insert several components, such as base stations and access points to a mobile topology, insert traffic, add mobility and monitor everything via the ONOS controller. Several instances of the controller could be created, which means that if the controller is disabled, another controller could easily take its place and function on its behalf instead. This fact is fundamental, because it shows the centralized character of the network, the abstraction in the control layer and the SDN controllers' survivability. The topologies may seem simplistic, however, they are indicative cases, that could be tested in networking laboratories.

When it comes to CORD and as a result to MCORD, slices could be based on: Service, User/Devices/Data type, Application, Quality of Service (QoS) & QoE, Enterprise, Location. Anyone could create several scenarios on how to teach and explain MCORD in 5G networks using SDN-based architectures.

A special reference to Service Level Agreements (SLAs) and their principles in 5G could be raised with the opportunity of services and slices in MCORD. Usage and management of network resources could be investigated using iperf tests.

The fact that it is an open source controller contributes to education, because there is no need for commercial license, it is easy to be used and enables familiarize with unix-like systems. There is much documentation for its use cases and there is a big active community, that supports ONOS.

VII. Conclusions & Future Work

To sum up, in this paper the ONOS controller was proved to be essential for educational purposes. It could easily contribute to the understanding of the routing and the RRM. It could also resolve to the conduct of experiments regarding the CORD or MCORD use cases. Incomprehensible notions such as IaaS, SDN, abstraction levels, programmable logic, network virtualization, cloud computing, CORD, MCORD, network heterogeneity, etc. could be analyzed thoroughly and easily using network tutorials and experimental examples for better knowledge and understanding.

In the future, SDN and NFV are going to play a very important role regarding the next generation of mobile networks. Several methods could focus on how to explain students about 5G important capabilities, enable experimentation procedures using controllers such as ONOS, or comparing known controllers such as POX, NOX, ONOS with one another concluding which one is better for education, checking as documentation, utility, applications, simplicity, complexity, adaptation to "real-world" experiments etc.

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