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Thesis Master: Testbed for SDN applications using OpenFlow. Create testbed that could be used for experimentation and research of software defined network applications.

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Abstract

Software-Defined Network (SDN) has become one of the most important architectures for the management of largescale complex networks, which may require re-policing or reconfigurations from time to time. SDN achieves easy re-policing by decoupling the control plane from data plane. Thus, the network routers/switches just simply forward packets by following the flow table rules set by the control plane. Currently, OpenFlow is the most popular SDN protocol/standard and has a set of design specifications. The *Intorduction* of this thesis will present the basic advantages to choose the SDN configuration instead of traditional network configuration. *Chapter 2* presents the SDN basic concepts and architectures. *Chapter* 3 introduces the SDN protocol OpenFlow protocol, its usage and components. *Chapter 4* presents one widely used SDN controller the OpenDaylight which is used in this testbed and it is meant to be the control plane of the SDN architecture. *Chapter 5* presents the SDN deployment on a virtual cloud infrastructure. *Chapter 6* presents the Mininet tool which is the data plane of the SDN architecture. *Chapter 7* presents the deployment of the SDN testbed with Mininet and OpenDaylight controller. *Chapter 8* presents how to isolate a network via OpenDaylight feature Virtual Tenant Network. And finally *Chapter 9 uses the AAA service of OpenDaylight* to configure a custom user for the network configuration.

1 Introduction

1.1 Traditional legacy network vs Software Defined Network

The last years in networking industry there is a tendency to have a centralized management system that allows the network programmability and automation in order to develop intent based network (IBN). Software-Defined Network (SDN) is a flourishing technology that approaches this type of management and more network providers are convinced to build confidence on how SDN works and what are the benefits of it. Demand for SDN solutions are rising rapidly due to existing problems in traditional legacy networks. The advantages of the SDN technology are presented and they explain why SDN wins against the traditional network.

Infrastructure: In order to deploy SDN solutions it does not require the existence of physical hardware (switches, routers, cables, etc). SDN is composed of software-based infrastructure. Devices of the network are software-based virtual entities both in control and data plane able to support any SDN deployed application.

Scalability: The drawn inference from previous statement is that SDN is more scalable in contrast with a traditional it is easier and faster to add and remove resources without generating side effects for the rest of the network resources and functions. Resources demands are solved from mouse clicks. In a traditional network however this means money cost and manual configuration that takes more time. Another advantage of SDN is the in integration with cloud applications. SND provides integration with cloud applications and network virtual functions (NFV) in data centers.

Traffic Management: Another main difference is that in a traditional network the decisions about traffic management are configured in data plane. The data plane and control plane are in same box. In others words, there is already build in software logic in switches that will handle the traffic. In SDN the traffic management is configured from control plane. The data plane is not responsible to program the forwarding logic of the traffic, it sends the packets as they are programmed from control plane.

Security: SDN provides customized security between the end user, the data center and the network traffic. Security policies that are easily defined in end-to-end network comparing to the legacy network [1]

2 SDN Fundamentals

Software Defined Network (SDN) was launched from collaboration of Stanford University and the University of California at Berkeley in 2008. SDN is a dynamic network that separates the control plane from data plane and its components consists of two main parts see **Figure 1**:

- The SDN controller or control system which is always located on the top layer in SDN architecture refers to control plane.
- The SDN switches or forwarding elements which are always located in a layer below from the control plane in the SDN architecture.
- Interface between the control plane and data plane, a common interface that is connects the SDN elements are the OpenFlow protocol.

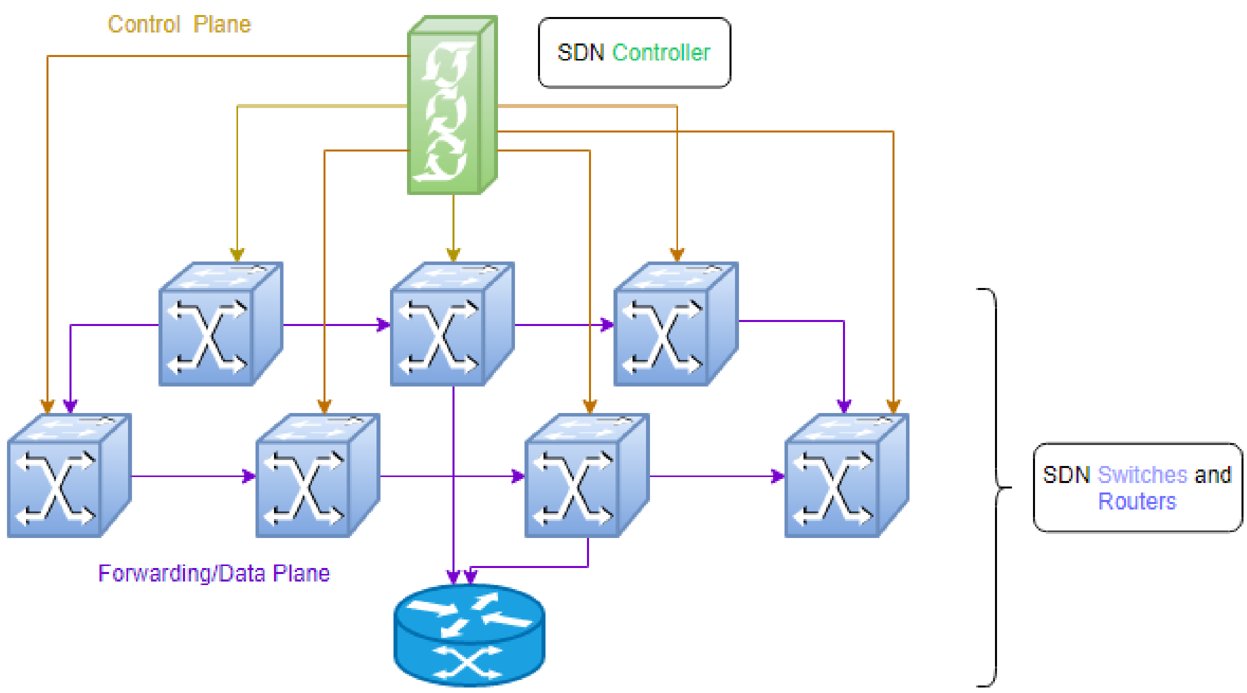


Figure 1: SDN architecture

The network **control plane** is composed of the SDN controller which is the "brain" of the network and is responsible to manage the functions of data plane components. SDN uses the OpenFlow protocol in order to manage configurations of switches and/or routers. Nowadays, there are plenty of open-source SDN controllers, but also many companies have privatized they own controllers for commercial purposes.

The **data plane** is a lower layer that is included the SDN switches. The management of the forwarding packets take place in the data plane, however how the packets will be forwarded is decision of the control plane using the OpenFlow protocol or any other SDN protocol.

2.1 SDN basic programming logic

Traditional network switches have already pre-installed programming logic in their software. Also, a traditional network switch contains fixed table entries that define the routing rules by switch software, consequently a switch has already a prior-knowledge on how to forward the received frame/packet. SDN has different programming logic comparing to traditional network, there is no built-in programmed traffic logic in switches and the controller decides what to do with the received packet from switch and then fills in the tables that are called in SDN world **flow tables** with **flow entries** of the switch. The controller programs the traffic logic of the switch based on SDN southbound protocols. There are plenty of southbound protocols, a widely-known southbound protocol is the **OpenFlow** protocol. OVSDB protocol along with the NETCONF are also familiar SDN southbound protocols. Next chapter analyzes the OpenFlow protocol, since it is used in this testbed. The rest of protocols will be presented in the section of the OpenDaylight features.

3 Understanding OpenFlow Protocol

OpenFlow protocol was the first protocol that was adopted from SDN, it was created by ONF (Open Networking Foundation) which is an organization that creates standards for SDN. OpenFlow protocol is a key component in SDN solutions and it stands between the data and control plane. Its initial intention was slightly different comparing to the current functionality. The first version 1.0 of the OpenFlow protocol specification was released in December 2009, the latest version is 1.6. In aspect of this research the used version is 1.3. OpenFlow is software running on each switch in SDN and communicates with the SDN controller.

The main purpose of the OpenFlow is to update the flow tables of the switch or router through SDN controller involvement, since the control plane is the one that configures how the flow tables will be updated.

3.1 OpenFlow Components

OpenFlow defines flow tables, groups tables, and meter tables, **Figure 2** presents how they distributed in an SDN switch [2].

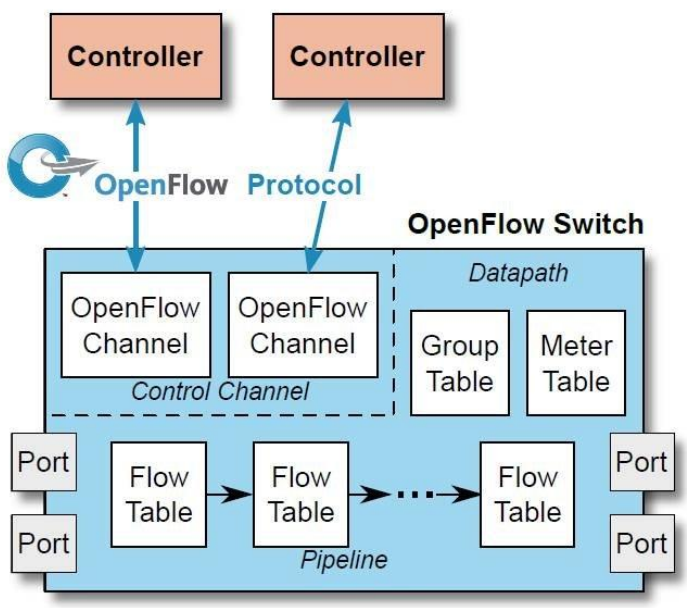


Figure 2: OpenFlow protocol components

3.1.1 OpenFlow Flow Tables

OpenFlow tables define a pipeline to process a packet header. A pipeline may contain one or many flow tables. Every table in the pipeline handles the input received from the previous flow table.

Each flow table consist of table flow entries, flow entry has data such as see **Figure 3**:

- **Matching rules:** When a packet is reached the port the packer header is matched regarding the fields it has in its header e.g port number, destination port, source port etc.
- **Instructions:** Another important field in a flow table entry is the instruction, which is a decision taken on what to do with the packet obeying the matching fields. The instructions field is a set of actions. An action can be anything among apply_actions, clear_actions, write_actions, write_metadata, goto_table.
- **Statistics:** Keeps track of the number of times the flow has been matched.

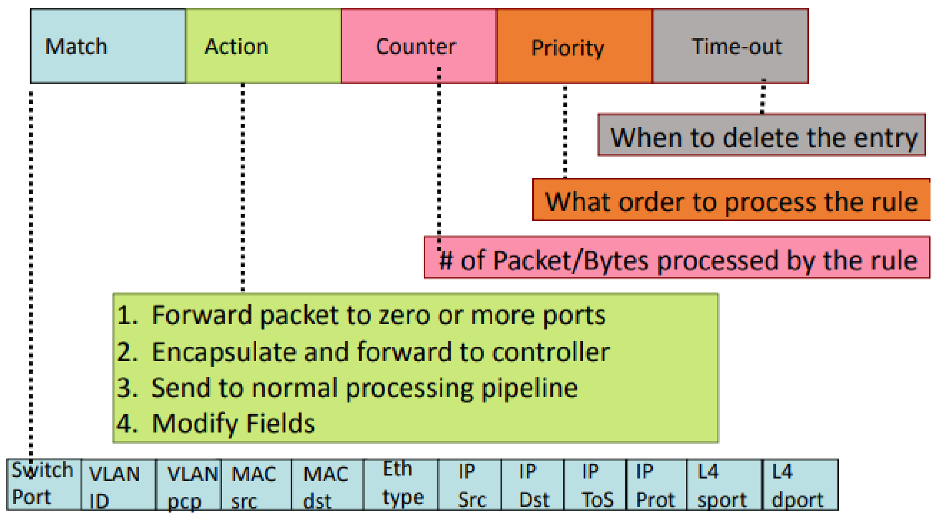


Figure 3: OpenFlow flow entry

The next figures present the taken action based on the matching rule.

Figure 4 is relevant to L2 switching the matching rule is the destination MAC address (00:1f) and the action is to forward the packet to port 6 of the switch. In other words, this means that when the packet header contains 00:1f... for a destination MAC address then this packet must be forwarded to port 6 of switch.

Switching

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	00:1f:..	*	*	*	*	*	*	*	port6

Figure 4: L2 Switching

Figure 5 presents flow switching with the complex combination of matching rules in order for the packet to be forwarded to port 6.

Flow Switching

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
port3	00:20..	00:1f..	0800	vlan1	1.2.3.4	5.6.7.8	4	17264	80	port6

Figure 5: Flow with complex maching rules

Figure 6 presents packet filtering, flow entry is a firewall that will drop the packet.

Firewall

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	*	*	*	*	*	*	*	22	drop

Figure 6: Firewall

Figure 7 defines a L3 routing flow where the matching rule is the destination IP address (5.6.7.8) and the action is to forward the packet to port 6 of the switch.

Routing

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	*	*	*	*	5.6.7.8	*	*	*	port6

Figure 7: L3 Routing

When the packet header contains the VLAN it isolates the network. **Figure 8** presentas a flow entry with VLAN in header and destination MAC address will be outcast this packet to ports 6,7,9.

VLAN Switching

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	00:1f..	*	vlan1	*	*	*	*	*	port6, port7, port9

Figure 8: VLAN Switching

3.1.2 OpenFlow Meters

OpenFlow meters are another component of the OpenFlow protocol. It was first introduced in OpenFlow version 1.3.0 as an optional feature. A meter is a switch element which measures and controls the ingress rate of traffic of packets. Ingress rate is the rate of packets prior to the output. Similar to flows meters are generated in the meter table and consist of meter entries which define the meters. The meters are attached directly to the flow entries. Each flow entry can specify a meter in its instructions set. The meter measures and controls the rate of the aggregate of all flow entries to which it is attached. Flows direct packets to the specified meter using the goto-meter instruction, thus the meter can perform operation based on the rate it receives. Per-flow meters enable OpenFlow to implement various **Quality of Service** operations, such as rate-liming which is the main application of the meters. However, meters can be combined with other features like queues to provide more advanced services.

A meter entry in the meter table is composed of the following elements:

- **meter identifie**r: a 32 bit unsigned integer uniquely identifying the meter
- **meter bands**: an unordered list of meter bands, where each meter band specifies the rate of the band and the way to process the packet
- **counters**: updated when packets are processed by a meter

The main element of the meter entry is the meter band which specifies the rate at which meter is applied and the way packets should be processed. A meter can have one or more-meter bands but only a single band is applied for a flow at a time based on the measured packets rate. The meter applies the meter band with the highest configured rate that is lower than the current measured rate. If the current rate is lower than any specified meter band rate, no meter band is applied. The meter triggers a meter band if the packet rate or byte rate passing through the meter exceeds a predefined threshold. If the meter band drops the packet, it is called a rate limiter.

Each meter band is identified by its rate and contains:

- **band type**: defines how packets are processed
- **rate:** used by the meter to select the meter band, defines the lowest rate at which the band can apply
- **counters:** updated when packets are processed by a meter band
- **type specific arguments:** some band type has optional arguments

A meter is for example a simple token bucket policer that can be instantiated and configured to a certain rate and burst. Whenever a flow exceeds the bucket's rate, the packet is dropped. In this case the meter is identified as late limiter and this is the main application of the meters. If the packet complies with its traffic definition and the burst is not exceeded, the remaining actions in the action set will be executed. Another functionality of the meters is to achieve a specific (Quality of Service) [4] [5].

3.1.3 OpenFlow Groups

An OpenFlow group was first introduced in version 1.1. Similar to a Flow and Meter, a group also consists of entries, as result the group entries make the Group table. OpenFlow groups are also elements defined from the OpenFlow specification and they created to support functions that flows are unable to execute. OpenFlow groups provide advanced services in order to solve real-time networking issues. Groups are forwarding the packets when the flows are unable to perform any actions to them. Unlike flows OpenFlow groups do not define matching rules nor instructions. OpenFlow specification supports different group types and each group type is dedicated to apply specific actions to the packet.

When the packet enters the group table, it receives actions, however the group is not allowed to forward the packet to any flow table, neither meter tables. Each group contains a list of actions lists that are known as **list of bucket**s and they are applied to the ingress packets. Each group may define zero to many buckets. When a group does not contain any bucket, this means the packet remains untouched. Also, there are cases that the bucket contains a list of actions that order the packets to be sent to the next groups.

The group types are classified in four categories [5] [6]

- **ALL**: This is the simplest group type. Takes as an input the ingress packets and reproduces it in order to handle it in each bucket. As a result, for each replica of the original packet different set of actions are performed.
- **SELECT: T**his group is using for load balancing. Every bucket that contains a list of actions has a specified weight. An ingress packet is forwarded to a single bucket, target bucket is selected based on the bucket weight.
- **INDIRECT:** This group contains only one bucket and all packets are transferred to this bucket. This group consolidates a common set of actions, as a result memory consumption is significantly reduced.
- **FAST-FAILOVER:** This is the most significant group of all group types dedicated to handle the cases of network failures. This group has many buckets and each bucket is defined from watch port and an optional watch group. The watch port and/or group detects the active status of the indicated port and/or group. Only in case the port is active the bucket is usable. When a specific bucket is used other buckets cannot be used. Bucket will be replaced with other when the watch port or group will be deactivated. The bucket selection of the FAST-FAILOVER will be the nearest bucket in the bucket list with a watch port or group that is up.

3.2 OpenFlow Architecture

Based on ONF OpenFlow protocol is an interface that communicates the control plane with the data plane of SDN architecture. The OpenFlow architecture is a composition of three elements sees following **Figure 9** [7]:

- The OpenFlow controller
- The OpenFlow switch
- The OpenFlow channel

The OpenFlow channel is the interface that connects each OpenFlow Logical Switch to an OpenFlow controller. Through this interface, the controller configures and manages the switch, receives events from the switch, and sends packets out the switch. The Control Channel of the switch may support a single OpenFlow channel with a single controller, or multiple OpenFlow channels enabling multiple controllers to share management of the switch. Between the datapath and the OpenFlow channel, the interface is implementation-specific, however all OpenFlow channel messages must be formatted according to the OpenFlow switch protocol. The OpenFlow channel is usually encrypted using TLS, but may be run directly over TCP [5].

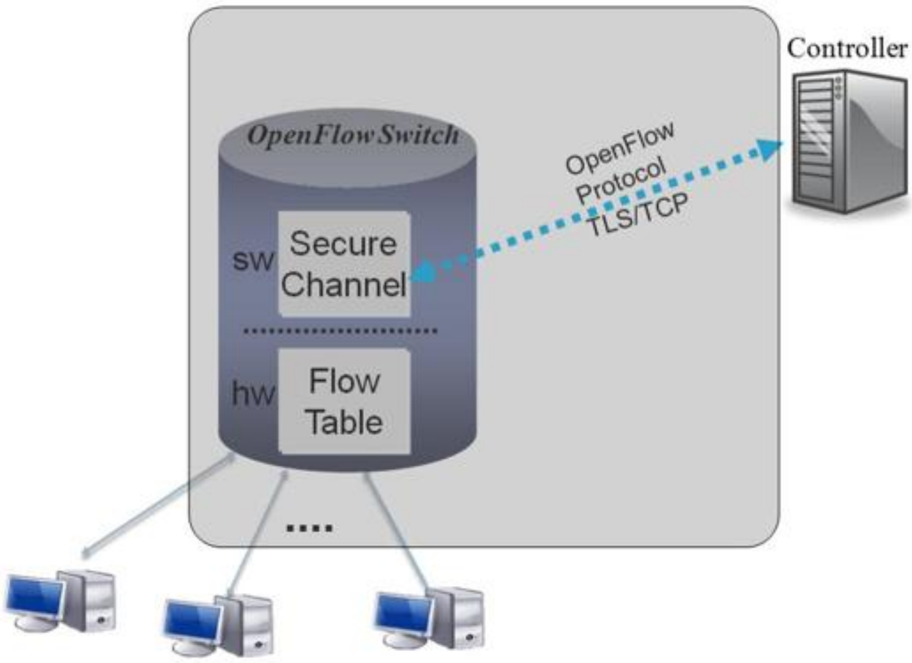


Figure 9: Connection between SDN Elements

4 OpenDaylight Fundamentals

This chapter provides general information about the OpenDaylight (ODL) which is an open-source SDN project implemented in Java language. It was created by the Linux Foundation and its first release (Hydrogen) was announced in February 2014. The purpose of the ODL project is to decouple the networking hardware from the software and allow the end users to build networking applications with the concept of plug-n-play architecture. The ODL controller platform is considered as a modular SDN controller due to many modules that are embraced in one single platform. It can be installed on Linux, Windows, Macintosh Operating Systems and any other that supports Java. Up to this time, there are ten releases Hydrogen, Helium, Lithium, Beryllium, Boron, Carbon, Nitrogen, **Oxygen**, Fluorine and Neon. Each release name of the ODL is based on the periodic table elements. ODL community announces at least two releases every year. The Oxygen SR4 (Stable Release 4) will be used as an SDN controller.

OpenDaylight supports [8]:

- **OSGi container**: OSGi (Open Services Gateway Initiative) is a framework, also known as the Dynamic System for Java defines a specification for deploying modular applications. Allows to break the applications into many modules that can be dynamically loaded and managed as bundles in the container. OSGi bundles are .JAR files with a MANIFEST.MF file with the last containing configuration for the OSGi. When a bundle is dependent from other bundles OSGi will start first these dependencies and next the bundle itself, otherwise the bundle will not start. As a result, a user can start, stop, install and uninstall modules without affecting the container. Currently, there are many open-source OSGi containers. Apache Karaf is a bundle used by the ODL in order to create the OSGI container where all OSGi bundles can be loaded and started [9] [10] [11].
- **Maven**: Maven is a tool for build automation usually for Java applications. Maven uses **pom.xml** (Project Object Model) to define the dependencies which are nothing that already implemented libraries to be used between the modules. It also can download libraries from a remote repository. Currently the most used remote repository for the ODL dependencies is the Nexus https://nexus.opendaylight.org/. Maven contains many phases which are the build lifecycles like install, test, clean, deploy, generate-sources etc. The next examples show how to define a dependency in a pom.xml and how to execute maven goal phase.

```
<dependency>
  <groupId>org.opendaylight.mdsal.binding.model.ietf</groupId>
  <artifactId>rfc8345-ietf-network-topology</artifactId>
  <version>1.2.6</version>
</dependency>
```

A maven dependency containes a **groupId**, an **artifactId** and **version** all fields included in tag <dependency> defined in XML language.

The next command shows how to build a maven project “testbed”.

~/testbed$ mvn clean install

- **Java Interfaces**: Java interfaces are used for event listening, specifications, and forming patterns. This is the main way in which specific bundles implement call-back functions for events and also to indicate awarenessoof specific state.
- **Rest APIs**: These are part northbound interface. These RESTful APIs are implemented in order to be integrated custom applications. They also support GUI (Graphical User Interface) for ODL.
- **YANG**: ODL platform supports the YANG (Yet Another Next Generation) language, used for data modeling and generated payload for NETCONF protocol.

ODL supports the southbound OpenFlow protocol as well as other protocols. ODL allows to develop new applications and also use the already build applications to make an enhancement of any feature.

4.1 OpenDaylight Architecture

ODL supports a layered architecture with clear integration points and APIs that allow end users and networking vendors to participate in the power SDN capabilities of ODL. ODL supports a layered architecture with clear integration points and APIs that allow end users and networking vendors to participate in the power SDN capabilities of ODL. In general, ODL architecture consists of next four layers, each layer will be described separately [12] see **Figure 10** :

- **Northbound Layer**: is meant for communication with upper, Application layer and would be in general realized through REST APIs of SDN controllers.
- **Controller Platform Layer**: Is meant for communication with lower layers, Infrastructure layer of network elements and would be in general realized through southbound protocols
- **Service Abstraction Layer:** Service abstraction layer is a component that is introduced only from ODL controller and it is located between the southbound protocols and the northbound protocols where third-party applications are supported. The first release of the ODL launched the API-driven Service Abstraction Layer (AD-SAL) which in next releases was enhanced and renamed to Model-driven service abstraction layer (MD-SAL).
- **Data plane Layer**: Is composed of various networking equipment which forms underlying network to forward network traffic. It could be a set of network switches and routers in the data center. This layer would be the physical one over which network virtualization would be laid down through the control layer (where SDN controllers would sit and manage underlying physical network

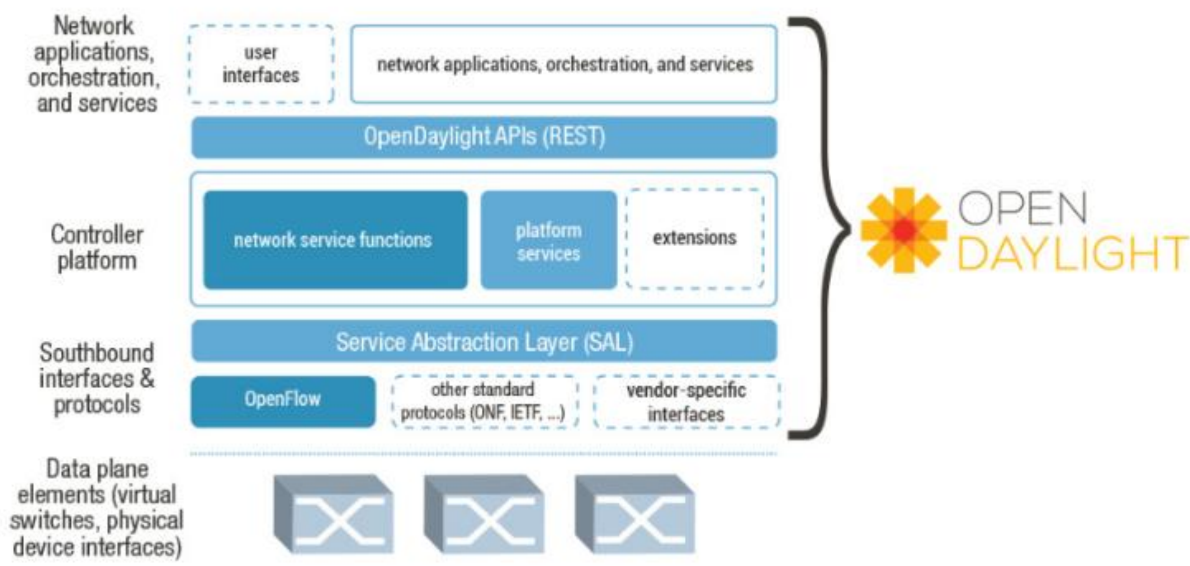


Figure 10: ODL architecture

4.2 OpenDaylight Features/Applications

This section will sum up all ODL existing features and their functions see **Figure 11**. The features used in testbed will be analyzed in detail:

- **Networking**: ALTO, BGPLS PCEP, BIER, CAPWAP, DIDM, FaaS, **L2-Switch**, LACP, LISP, NATApp Plugin, NETCONF, OF-CONFIG, **OpenFlow**, OpFlex, OVSDB, NetVirt, NIC, Neutron Northbound, P4, Packet Cable, SFC,TTP, **VTN**, VPN Service, Unimrg.
- **Security**: **AAA**, Controller Shield, USC.
- **Management**: Cardinal, **DluxApps**, EMAN, Federation, GBR, IoTDM, NEMO, NetIDE, OCP, SNMP, SNMP4SDN, SXP.
- **Core**: MD-SAL, OpenDaylight Controller, ODL-SDNi, YANG Tools.
- **Data Collectors:** Centinel, TSDR

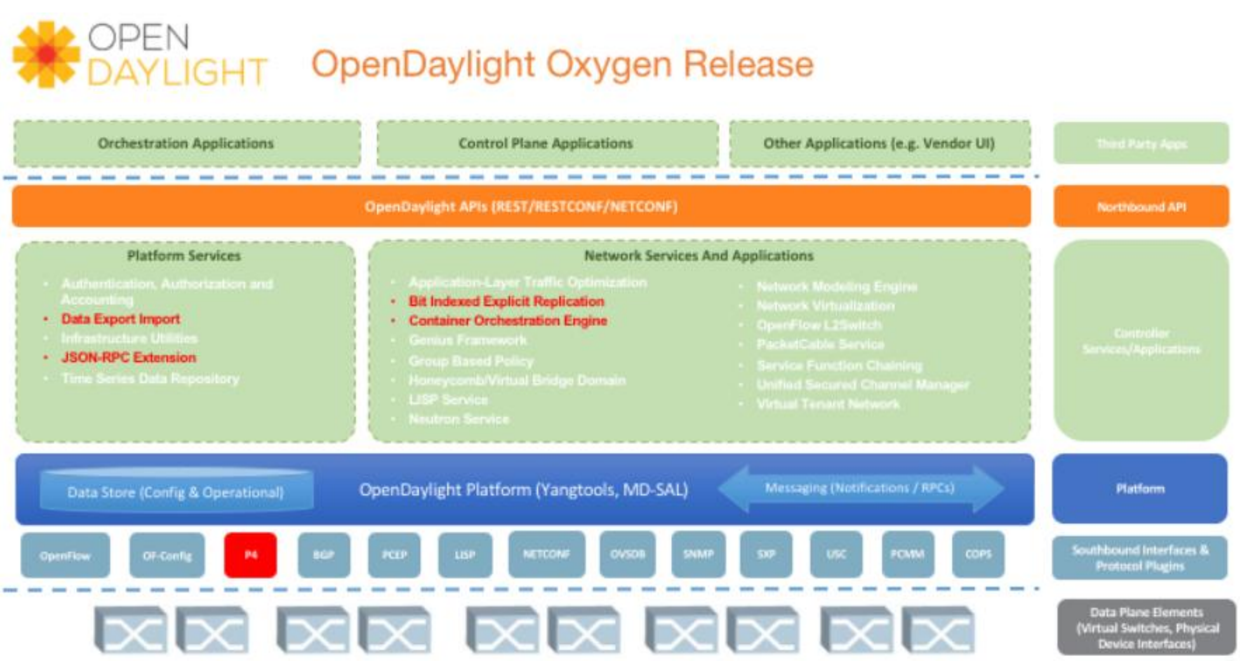


Figure 11: OpenDaylight features

4.2.1 DLUX

This module is the web user interface of the ODL implemented in Angular JS. It is an OpenFlow management application for the ODL [13]. It provides authentication, navigation and lists the following features:

- Topology: Shows the OpenFlow topology components.
- **Nodes**: This is a very simple inventory node manager.

- **YANG visualizer:** This provides visualization of YANG models in graphical form.
- **YANGMAN:** This is an advanced and more user-friendly YANG UI replacement.
- **YANG GUI:** This is a simple UI for interaction with the controller. It is based on Yang models, and it renders a form so that users can read or write data even if they have no knowledge of the models.

For accessing the DLUX any web browser will work by entering the URL http://localhost:8181/index.html/ providing the credentials "admin" for both fields access to this feature is offered.

4.2.2 L2 Switch

L2 switch is an ODL module that provides Layer 2 switch functionality specifying how the packets should be forwarded [14]. L2 Switch comes along with other useful features:

- **Packet Handler:** This feature processes and decodes the incoming packets and forwards them appropriately.
- **Loop Remover:** Removes loops from the network.
- **Arp Handler**: Manages the decoded ARP packets
- **Address Tracker:** Retrieves the MAC Addresses and IP addresses of the elements existing in the network.
- **Host Tracker:** Tracks the host locations in the network
- **L2 Switch Main:** Installs flows on switches based on specific rules that must follow the network traffic.

When l2 switch receives a packet that does not match any entry in flow table it encapsulates the packet in an OpenFlow PACKET_IN message and sends this packet to the controller. Then L2 switch feature finds where it should be sent. The MAC address must be identified through OpenFlow PACKET_IN message. The next table summarizes how the L2 switch module identifies the MAC address see **Table 1**.

Source MAC	Destination MAC	Action
Unknown	Unknown	Broadcast the packet to all external ports except the ingress port
Unknown	Known	L2 module sends the packet to the node where the target is attached. The attachment point refers to the target that is physically attached.
Know	Unknown	Broadcast packets to all external ports. L2 switch module knows the source MAC.
Known	Known	Packet forwarded from source MAC to target MAC and installed flows in the flow tables of switches.

Table 1: L2 MAC Learning

4.2.3 OpenFlow Plugin

The OpenFlow plugin is belongs to a southbound plugin of the ODL and defines is a communication Interface that allows interaction between the control and forwarding plane of an SDN. This plugin implements the OpenFlow standard [15]. The current versions of OpenFlow 1.0. and 1.3.x are supported, however it gives the opportunity to adopt the other version too. Similar to other modules of the ODL this plugin also is based on the Model Driven Service Abstraction Layer (MD-SAL). It allows TLS secure connection on port 6633 and non-secure connection on port 6653 to listen for OpenFlow messages coming from OpenFlow devices.

The following features are supported from the ODL plugin [15] see **Figure 12**:

- Connection Handling
- Session Management
- State Management.
- Error Handling.
- Mapping function (Infrastructure to OF structures).
- Connection establishment will be handled by the OpenFlow library using opensource netty.io library.
- Message handling for example Packet in.
- Event handling and propagation to upper layers.
- Plugin will support both MD-SAL and Hard SAL.
- Will be backward compatible with OF 1.0.

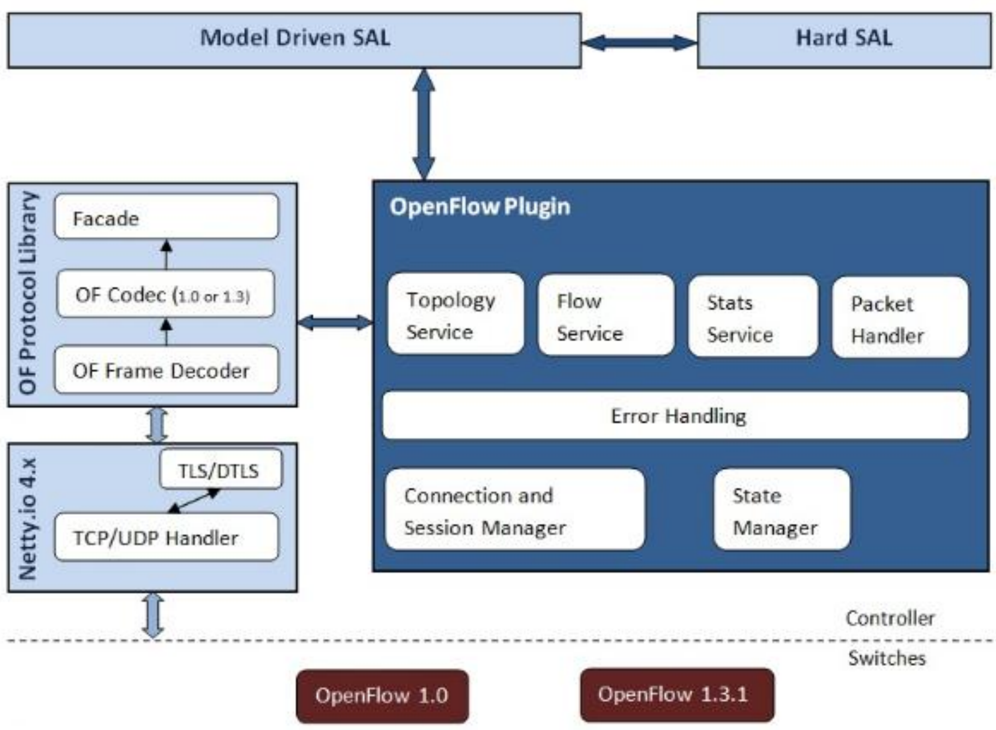


Figure 12: OpenFlow protocol implementation in ODL controller

5 OpeDaylight Deployment in VirtualBox

Nowadays, plenty amount of virtualization software exists free to download. The chosen virtualization program for this testbed is the **VirtualBox** that will host the ODL controller and next the Mininet tool. It can be installed easily without many manual configurations. Similar to other virtualization solutions, it provides specific network card, hard disk, graphics and RAM for every virtual machine.

This section prepares the VM that will host the ODL controller. Presents step-by-step guide to start and deploy features of SDN ODL controller.

Host operating system is Windows 10 Pro and hypervisor software is VirtualBox for hosting a virtual machine (Ubuntu 16.04) for ODL controller. The environment settings of VM are as follows:

Host Operating System Settings:

- Operating System Windows 10 Pro Version 1903
- Installed Memory RAM: 16GB
- Processor: Inter(R) Core(TM) i5-9600K CPU @ 3.70 GHz
- Operating System type: 64-bit x64-based processor
- Disk: 400GB

Software Settings:

- Operating System: Windows 10 Professional
- Hypervisor: Oracle VM VirtualBox Manager version 6.1
    - Operating System: Ubuntu Desktop Image 16.04.1 LTS
    - ODL Version: Oxygen SR4 having:
        - 40GB hard disk, 2048 MB RAM, 2 CPUs

There are two options to deploy the ODL controller:

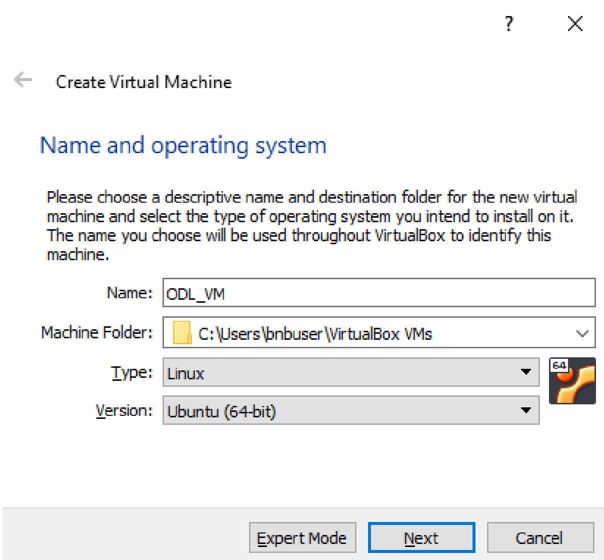
- ***Standalone*** deployment: The ODL controller will run as one server. Used for simple use cases. Karaf container will be used in order to install any ODL feature.
- ***Distributed*** deployment [16]: In distributed deployment there is a cluster where exist many ODL server instances that are working together as one entity and sharing a common configuration. Deploying ODL servers in a cluster assures there will be at least one ODL instance running in case of any other ODL server failure occurs. This is very important for real enterprise network systems that cannot accept failure. Consequently, when multiple ODL instances are running there are some advantages such as:
    - *Scaling*: Data can be shared among smaller chunks (known as shards) and either distribute that data across the cluster or perform certain operations on certain members of the cluster.
    - *High-Availability*: From multiple controllers running if one of them crashes, other instances working and available.
    - *Data Persistence*: Data will not erased gathered by controller after a manual restart or a crash.

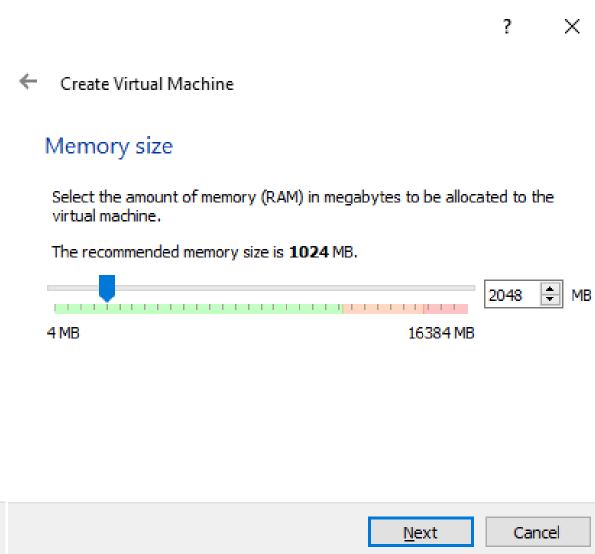
5.1 OpenDaylight Deployment Karaf Distribution

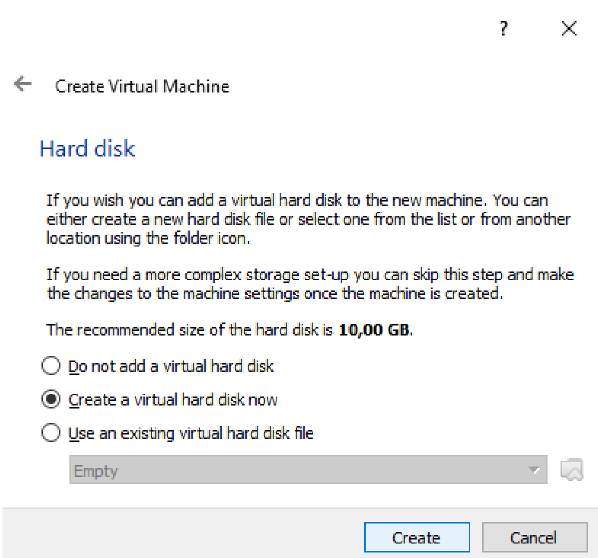
This section will present how to start the ODL controller as karaf distribution. The ODL as karaf distribution is an OSGI container that provides all features available to install, but none of them will start automatically, only after user command. The ODL karaf distribution version that is used in the scope of this investigation is Oxygen SR4 karaf-0.8.4.zip or karaf-0.8.4.tar.gz file format downloaded from [17]

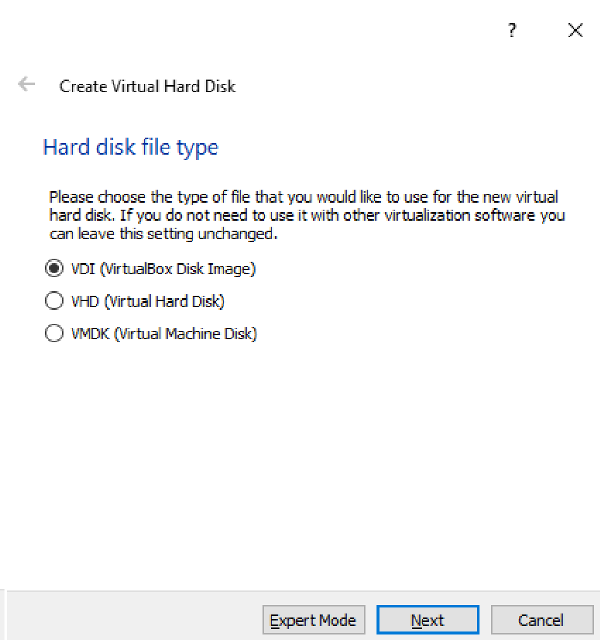
5.1.1 Preparing the VM machine to host the ODL controller

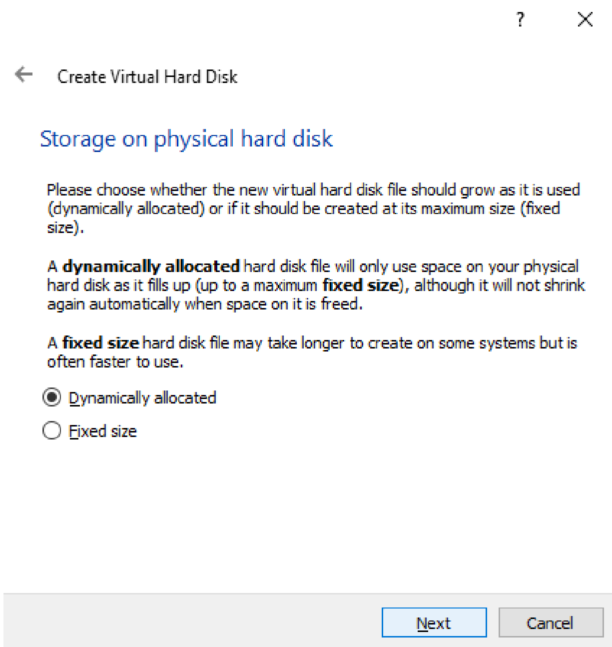
The next images show step-by –step ODL deployment in virtual host.

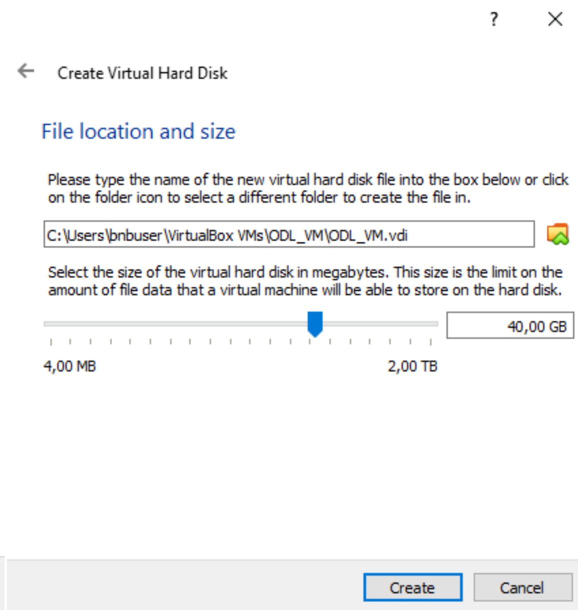


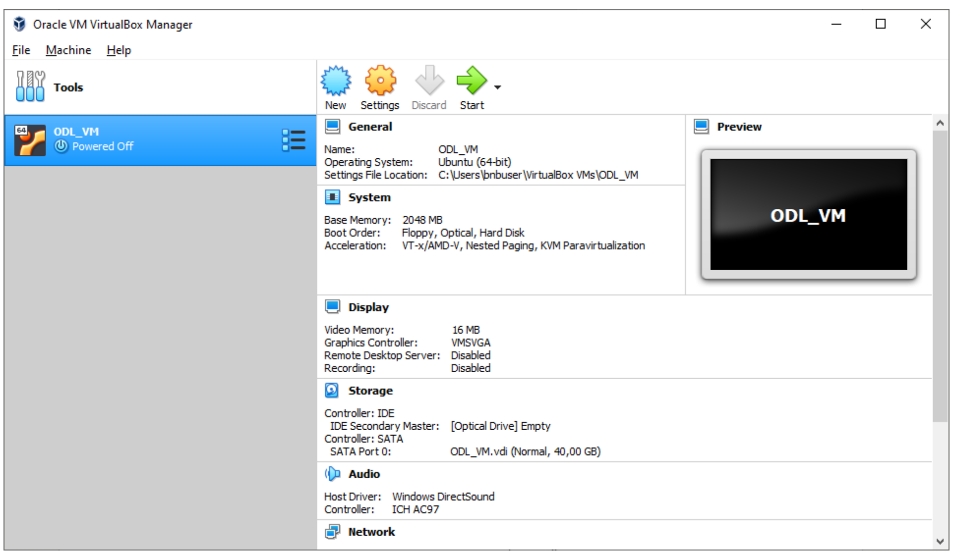


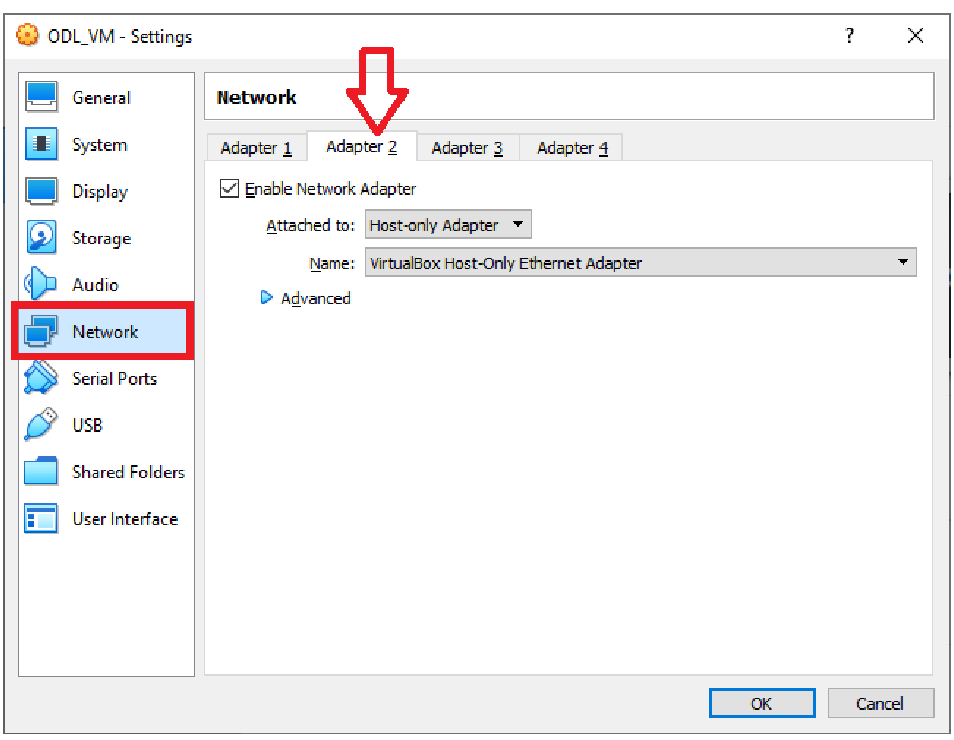


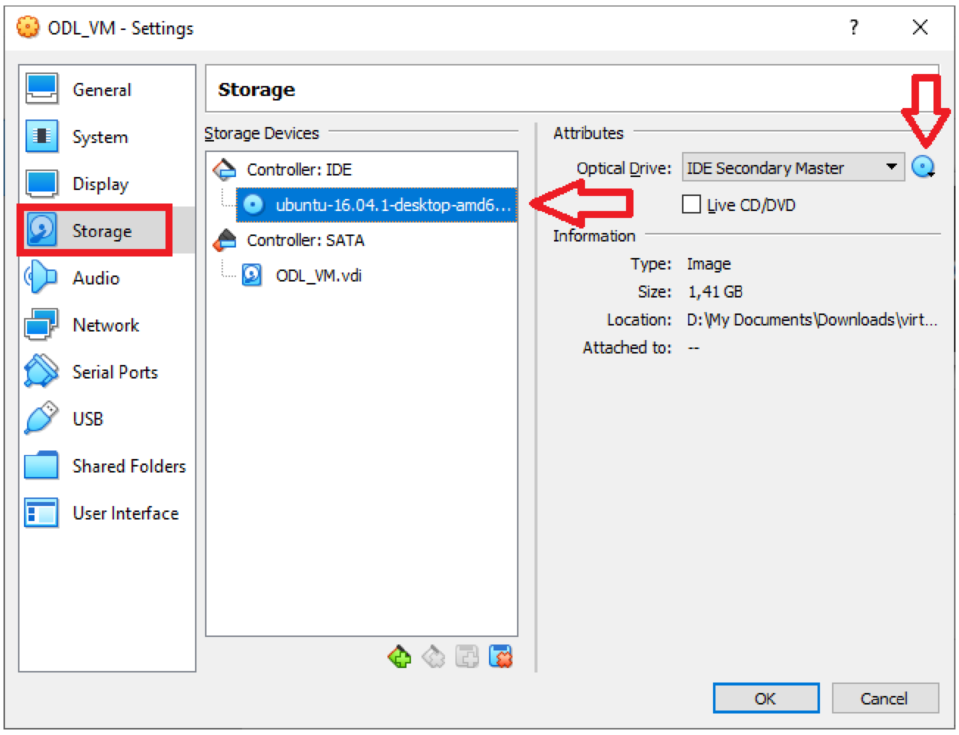


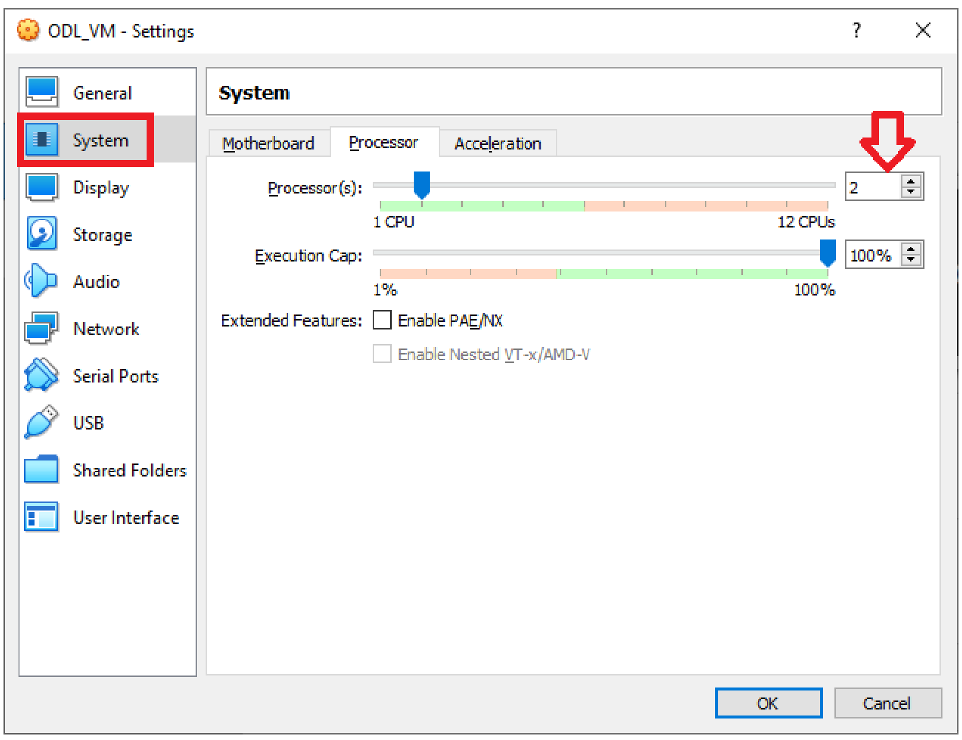

?
Create Virtual Hard Disk
Storage on physical hard disk
Please choose whether the new virtual hard disk file should grow as it is used (dynamically allocated) or if it should be created at its maximum size (fixed size).
A dynamically allocated hard disk file will only use space on your physical hard disk as it fills up (up to a maximum fixed size), although it will not shrink again automatically when space on it is freed.
A fixed size hard disk file may take longer to create on some systems but is often faster to use.
Dynamically allocated
Fixed size
Next
Cancel

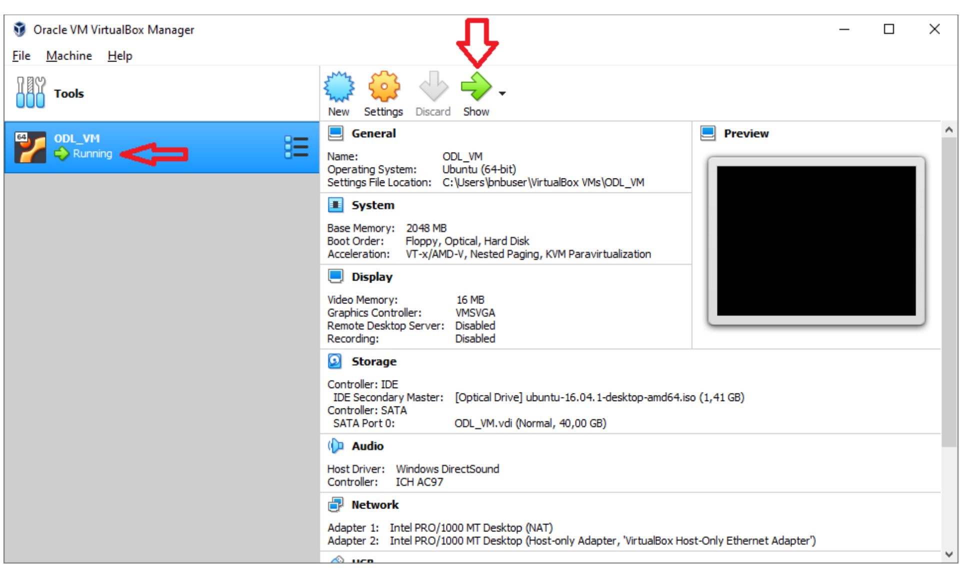

?
Create Virtual Hard Disk
File location and size
Please type the name of the new virtual hard disk file into the box below or click on the folder icon to select a different folder to create the file in.
C:\Users\pnbuser\VirtualBox VMs\ODL_VM\ODL_VM.vdi
Select the size of the virtual hard disk in megabytes. This size is the limit on the amount of file data that a virtual machine will be able to store on the hard disk.
40,00 GB
4,00 MB
2,00 TB
Create
Cancel


Oracle VM VirtualBox Manager
File Machine Help
Tools
ODL_VM
Powered Off
New Settings Discard Start
General
Name: ODL_VM
Operating System: Ubuntu (64-bit)
Settings File Location: C:\Users\pnbuser\VirtualBox VMs\ODL_VM
System
Base Memory: 2048 MB
Boot Order: Floppy, Optical, Hard Disk
Acceleration: VT-x/AMD-V, Nested Paging, KVM Paravirtualization
Preview
ODL_VM
Display
Video Memory: 16 MB
Graphics Controller: VMSVGA
Remote Desktop Server: Disabled
Recording: Disabled
Storage
Controller: IDE
IDE Secondary Master: [Optical Drive] Empty
Controller: SATA
SATA Port 0: ODL_VM.vdi (Normal, 40,00 GB)
Audio
Host Driver: Windows DirectSound
Controller: ICH AC97
Network


ODL_VM - Settings
?
General
System
Display
Storage
Audio
Network
Serial Ports
USB
Shared Folders
User Interface
Network
Adapter 1 Adapter 2 Adapter 3 Adapter 4
Enable Network Adapter
Attached to: Host-only Adapter
Name: VirtualBox Host-Only Ethernet Adapter
Advanced
OK
Cancel


ODL_VM - Settings
General
System
Display
Storage
Audio
Network
Serial Ports
USB
Shared Folders
User Interface
Storage
Storage Devices
Controller: IDE
ubuntu-16.04.1-desktop-amd6...
Controller: SATA
ODL_VM.vdi
Attributes
Optical Drive: IDE Secondary Master
Live CD/DVD
Information
Type: Image
Size: 1,41 GB
Location: D:\My Documents\Downloads\virt...
Attached to: --
OK
Cancel


ODL_VM - Settings
General
System
Display
Storage
Audio
Network
Serial Ports
USB
Shared Folders
User Interface
System
Motherboard
Processor
Acceleration
Processor(s):
2
1 CPU
12 CPUs
Execution Cap:
100%
1%
100%
Extended Features:
Enable PAE/NX
Enable Nested VT-x/AMD-V
OK
Cancel


Oracle VM VirtualBox Manager
File
Machine
Help
Tools
New
Settings
Discard
Show
ODL_VM
Running
General
Name: ODL_VM
Operating System: Ubuntu (64-bit)
System
Base Memory: 2048 MB
Boot Order: Floppy, Optical, Hard Disk
Acceleration: VT-x/AMD-V, Nested Paging, KVM Paravirtualization
Display
Video Memory: 16 MB
Graphics Controller: VMSVGA
Remote Desktop Server: Disabled
Recording: Disabled
Preview
Storage
Controller: IDE
IDE Secondary Master: [Optical Drive] ubuntu-16.04.1-desktop-amd64.iso (1,41 GB)
Controller: SATA
SATA Port 0: ODL_VM.vdi (Normal, 40,00 GB)
Audio
Host Driver: Windows DirectSound
Controller: ICH AC97
Network
Adapter 1: Intel PRO/1000 MT Desktop (NAT)
Adapter 2: Intel PRO/1000 MT Desktop (Host-only Adapter, 'VirtualBox Host-Only Ethernet Adapter')

```
sdn@sdn-opendaylight:~$ ifconfig
enp0s3    Link encap:Ethernet  HWaddr 08:00:27:67:9f:12
          inet addr:10.0.2.15  Bcast:10.0.2.255  Mask:255.255.255.0
          inet6 addr: fe80::2cda:5256:ef60:62c1/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:526351 errors:0 dropped:0 overruns:0 frame:0
          TX packets:204735 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:492862787 (492.8 MB)  TX bytes:12449398 (12.4 MB)

enp0s8    Link encap:Ethernet  HWaddr 08:00:27:57:f2:a4
          inet addr:192.168.56.101  Bcast:192.168.56.255  Mask:255.255.255.0
          inet6 addr: fe80::512b:b930:f993:b03b/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:910 errors:0 dropped:0 overruns:0 frame:0
          TX packets:67 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:274746 (274.7 KB)  TX bytes:8260 (8.2 KB)
```

The main requirement for the deployment is the proper JDK version.

5.1.2 Java Installation

The latest releases of the ODL controller features require Java Development Kit (JDK) version 1.8. or later. The OpenJDK 1.8 will be installed, to resolve this requirement with the next command:

```
sdn@sdn-opendaylight:~$ sudo apt-get install openjdk-8-jdk
```

Verification of the JDK installed version.

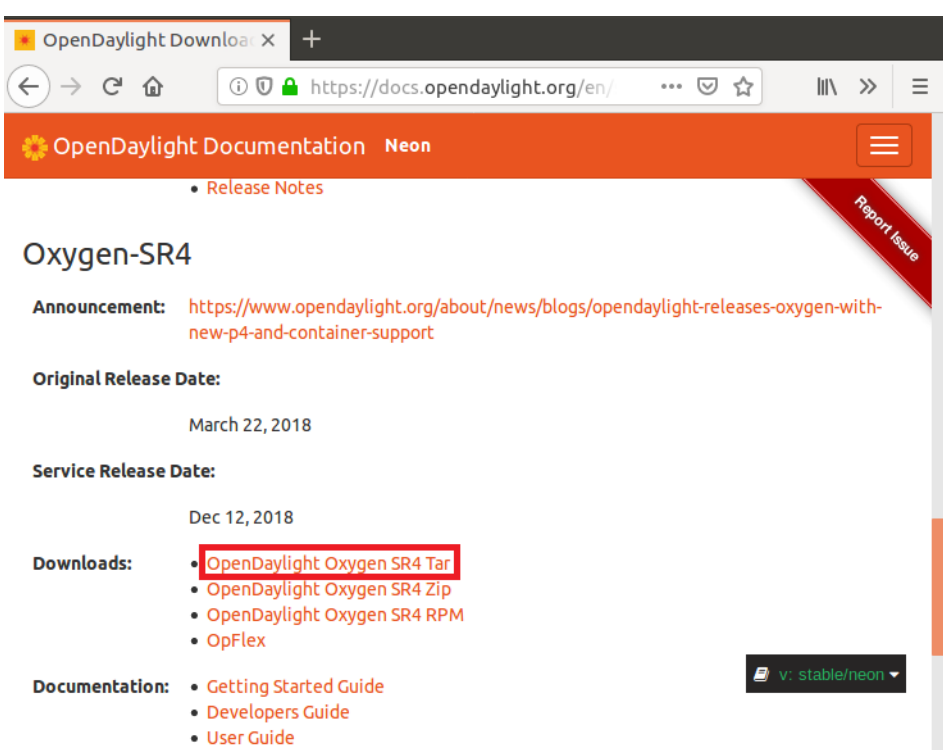
```
sdn@sdn-opendaylight:~$ java -version
openjdk version "1.8.0_222"
OpenJDK Runtime Environment (build 1.8.0_222-8u222-b10-1ubuntu1~16.04.1-b10)
OpenJDK 64-Bit Server VM (build 25.222-b10, mixed mode)
sdn@sdn-opendaylight:~$
```

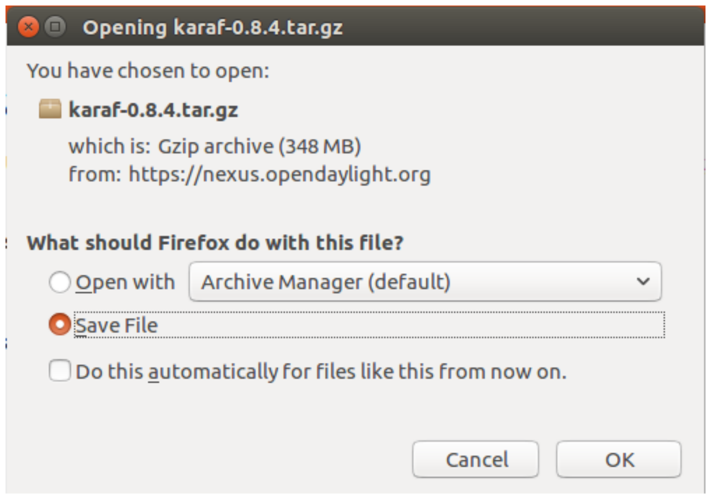
Settings for the environment variables JAVA_HOME to JAVA installed location and PATH.

```
sdn@sdn-opendaylight:/usr/lib/jvm/java-8-openjdk-amd64$ cd
sdn@sdn-opendaylight:~$ export JAVA_HOME=/usr/lib/jvm/java-8-openjdk-amd64
sdn@sdn-opendaylight:~$ export PATH=$JAVA_HOME/bin:$PATH
sdn@sdn-opendaylight:~$ echo $JAVA_HOME
/usr/lib/jvm/java-8-openjdk-amd64
sdn@sdn-opendaylight:~$
```

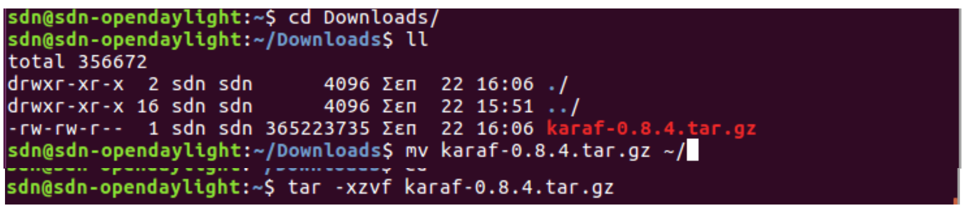
5.1.3 Downloading and running of the karaf container

The next images show how to downlaod the distributed karaf Oxygen version [17].



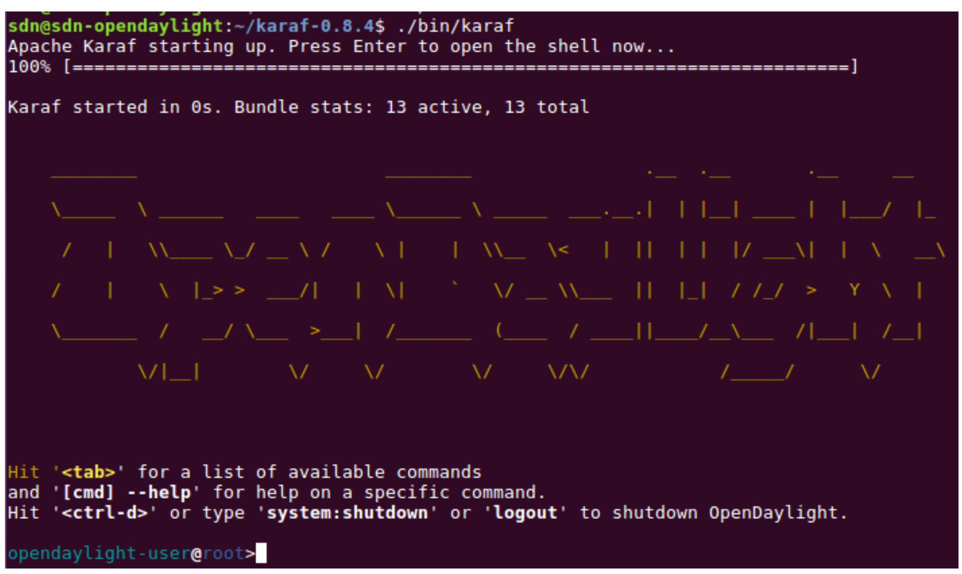


Moving the **karaf-0.8.4.tar.kar** file to VM home directory.



Once the downloaded file is unziped. Starting the ODL karaf can take place next. The following command shows how to start the ODL container.

$ sdn@sdn-opendaylight:~/karaf-0.8.4$ ./bin/karaf

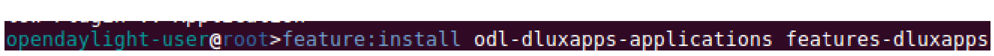


5.1.4 Installing karaf features

Once the OD is in running state any feature can be installed and used as an SDN application. Any ODL feature can be activated by the following command in ODL CLI, where feature1 is the feature name.

opendaylight-user@root>feature:install <feature1>

There is an option to install many features simultaneously, by separating the features names with space, the next command shows how to install all DLUX modules.



Another useful ODL commands are:

opendaylight-user@root>feature:uninstall <feature1> : uninstalls the feature1 from ODL karaf.

opendaylight-user@root>feature:list: shows all active features to be installed in ODL karaf.

opendaylight-user@root>feature:list -i: shows all installed features of ODL karaf.

5.2 ODL Deployment Clustering

5.2.1 Clustering Specifications

ODL clustering is using the AKKA technology which is compatible with the design of the MD-SAL. In order to deploy distributed environment, at least three nodes of ODL must be configured. ODL require at least three nodes in order to verify high-availability, however if in a 4-node cluster two of nodes crash, again this cluster is not functional. The clustering mechanism switches between nodes when the minimum number of nodes in a cluster is valid. The next table shows how many nodes must exist in a cluster [16] [18].

Node number	Minimum number of servers must exist
2	2
3	2
4	3
5	3
6	3
7	4

Table 2: High –Availability requirements

Before setting the cluster, a brief description of ODL clustering mechanism will be described.

Shards: The MD-SAL datastore uses chunks to store data, in ODL word they are known as shards. Shard is a partition of data that can be stored either on one server or many servers. For example, one shard can contain all the inventory data while another shard contains all of the topology data. Thus, the data are stored in default shard unless, a specific shard configuration is done then, the data will be stored in a datastore regarding the shard configuration too. Shards configuration takes place in a ***modules-shards.conf*** file. This file allows configuring shards replicas for the clustering mechanism. A X-node cluster to be able to tolerate any single node crashing, a replica of every defined data shard must be running on all three cluster nodes.

Roles: Another detail that must be clarified is the ***role*.** Assuming that, a cluster consists of three nodes there must be a way to identify each node. Every node in a cluster must have unique identifier. ODL has introduced the concept of node ***role.*** In particular, the roles of nodes are defined as member-X depending on X number of nodes exist in a cluster. This configuration takes place in an ***akka.conf*** file. For example, if the nodes-1 role is defined as member-1, ODL recognizes the node-1 by the member-1.

To make a cluster operational multiple seed node must be configured. When a cluster member is started, it sends a message to all its seed nodes. Once the seed node (any of them) responds, the cluster member sends a join command to the first seed node that initiated the response. If none of the seed nodes respond, the cluster member repeats the process until it successfully establishes a connection with one of the seed nodes else, it remains shutdown. In case a any node fails for any reason, it needs to be restarted to be able active and take part in a cluster. When a node is restarted after any failure first it searches for lead node and then joins the cluster.

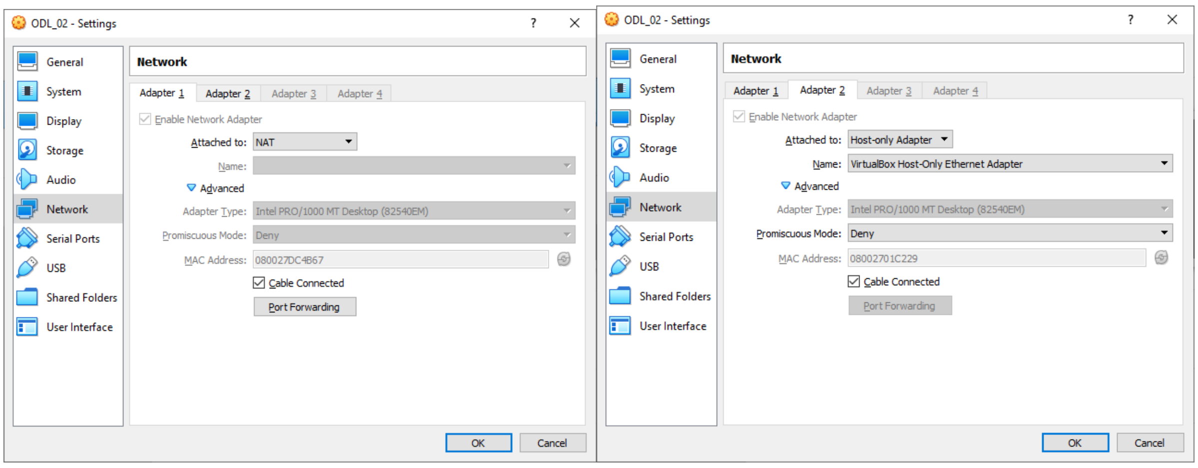
This means that for a particular shard you need to verify that member-1 is hosting (lead node) and the replica of this shard is stored on both member-2 and member-3 servers (seed node).

5.2.2 Clustering in Practice

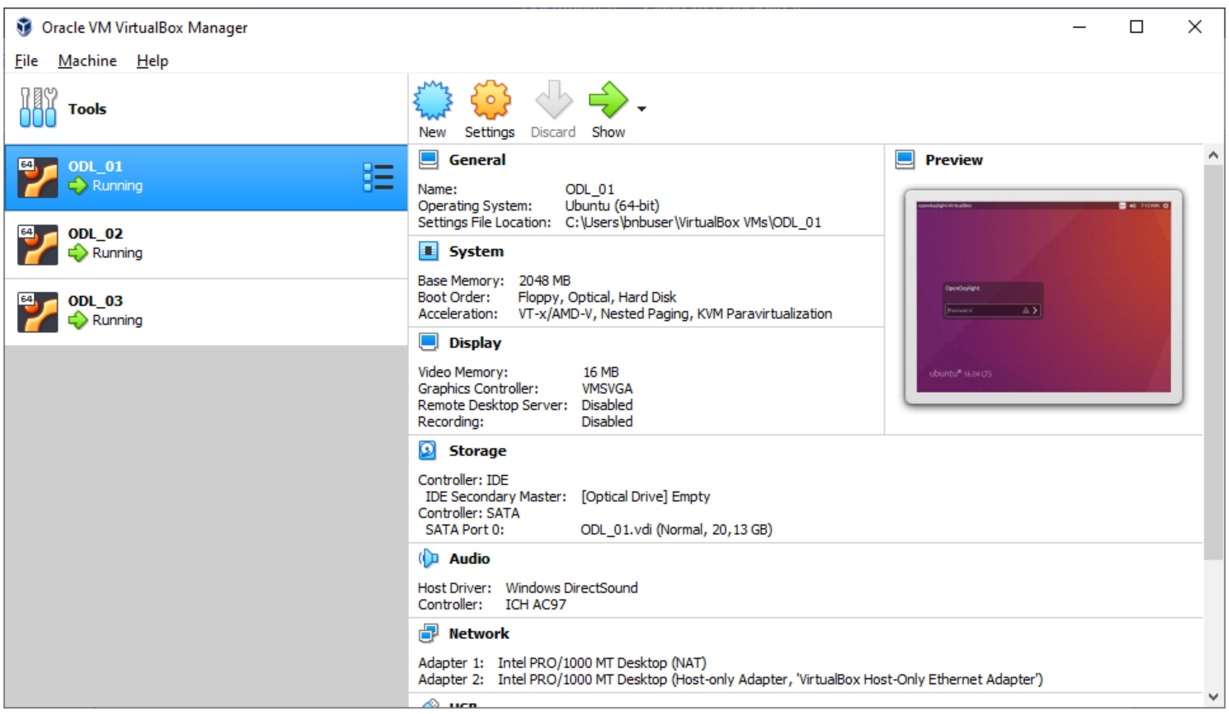
The clustering environment that will be demonstrated will contain three ODL nodes running in the same hypervisor as depicted in table.

Cluster Nodes	Virtual Machine Name	IP-Address	RAM (MB)	Hard Disk (GB)
ODL Server 1	ODL_01	192.168.56.101	2048	20
ODL Server 2	ODL_02	192.168.56.102	2048	20
ODL Server 3	ODL_03	192.168.56.103	2048	20

Network configurations adding the host only adapter to ODL_VMs



The following figure shows the configured ODL VMs for the clustering environment:



All ODL VMs are in a running state and each node has the ODL Oxygen SR4 release hosted on it.

There are several steps in order to manage an ODL cluster. For this purpose, ODL allows to configure a clustering with build-in scripts.

Step 1: This step defines which are the seed nodes and which are the lead node. As has been mentioned before on seed nodes replicas of data shards will be stored. In this step ***akka.conf*** and ***module-shards.conf*** files will be configured. In ***/home/opendaylight/karaf-0.8.4/bin*** directory exist an executable file with a name ***configure_cluster.sh.*** This file allows to define the clustering parameters. ***The command must be executed as following:***

```
./configure_cluster.sh <index> <seed_nodes_list>
```

Where

<index>: is the number that defines the seed nodes number. This indicates which controller node is configured by the script and

<seed_nodes_list>: defines the sed nodes IP addresses separated by comma.

The IP address at the provided index should belong to the member executing the script. When running this script on multiple seed nodes, keep the seed_node_list the same, and vary the index from 1 through N.

The next command shows an example of the aforementioned command

opendaylight@opendaylight-VirtualBox:~/karaf-0.8.4/bin$ ./configure_cluster.sh 1 192.168.56.101 192.168.56.102 192.168.56.103

The above command will configure the member 1 (IP address 192.168.56.102) of a cluster made of 192.168.56.101 192.168.56.12 192.168.56.103.

```
opendaylight@opendaylight-VirtualBox:~/karaf-0.8.4/bin$ ./configure_cluster.sh 1 192.168.5
6.101 192.168.56.102 192.168.56.103
################################################
##              Configure Cluster             ##
################################################
Configuring unique name in akka.conf
Configuring hostname in akka.conf
Configuring data and rpc seed nodes in akka.conf
modules = [

        {
                name = "inventory"
                namespace = "urn:opendaylight:inventory"
                shard-strategy = "module"
        },
        {
                name = "topology"
                namespace = "urn:TBD:params:xml:ns:yang:network-topology"
                shard-strategy = "module"
        },
        {
                name = "toaster"
                namespace = "http://netconfcentral.org/ns/toaster"
                shard-strategy = "module"
        }
]
Configuring replication type in module-shards.conf
################################################
##   NOTE: Manually restart controller to     ##
##         apply configuration.               ##
################################################
opendaylight@opendaylight-VirtualBox:~/karaf-0.8.4/bin$ 
```

Navigating the directories of the **/configuration/initial/** all configuration files for this ODL controller have been created.

```
opendaylight@opendaylight-VirtualBox:~/karaf-0.8.4/configuration/initial$ ll
total 20
drwxrwxr-x 2 opendaylight opendaylight 4096 Σεπ  12 21:49 ./
drwxr-xr-x 3 opendaylight opendaylight 4096 Σεπ  12 21:48 ../
-rw-r--r-- 1 opendaylight opendaylight 1438 Σεπ  12 21:49 akka.conf
-rw-r--r-- 1 opendaylight opendaylight  336 Σεπ  12 21:49 modules.conf
-rw-r--r-- 1 opendaylight opendaylight  555 Σεπ  12 21:49 module-shards.conf
opendaylight@opendaylight-VirtualBox:~/karaf-0.8.4/configuration/initial$ 
```

The **akka.conf** file verifies that the applied configuration by the script has been set. The next figure shows that the IP address of ODL node is 192.168.56.101 (**netty.tcp** field). The ***seed-nodes*** field indicates that ODL controllers join the cluster are these that defined running the script file. Finally, the ODL _01 is assigned to “member-1" role.

```
-rw-r--r-- 1 opendaylight opendaylight  336 Σεπ  12 23:23 modules.conf
-rw-r--r-- 1 opendaylight opendaylight  555 Σεπ  12 23:23 module-shards.conf
opendaylight@opendaylight-VirtualBox:~/karaf-0.8.4/configuration/initial$ cat akka.conf

odl-cluster-data {
  akka {
    remote {
      artery {
        enabled = off
        canonical.hostname = "192.168.56.101"
        canonical.port = 2550
      }
      netty.tcp {
        hostname = "192.168.56.101"
        port = 2550
      }
      # when under load we might trip a false positive on the failure detector
      # transport-failure-detector {
        # heartbeat-interval = 4 s
        # acceptable-heartbeat-pause = 16s
      # }
    }

    cluster {
      # Remove ".tcp" when using artery.
      seed-nodes = ["akka.tcp://opendaylight-cluster-data@192.168.56.101:2550",
                    "akka.tcp://opendaylight-cluster-data@192.168.56.102:2550"
,
                    "akka.tcp://opendaylight-cluster-data@192.168.56.103:2550"
]

      roles = ["member-1"]

    }

    persistence {
      # By default the snapshots/journal directories live in KARAF_HOME. You can choose to
 put it somewhere else by
```

Checking the next file **modules-shards.conf** assignment for the replicas has been set.

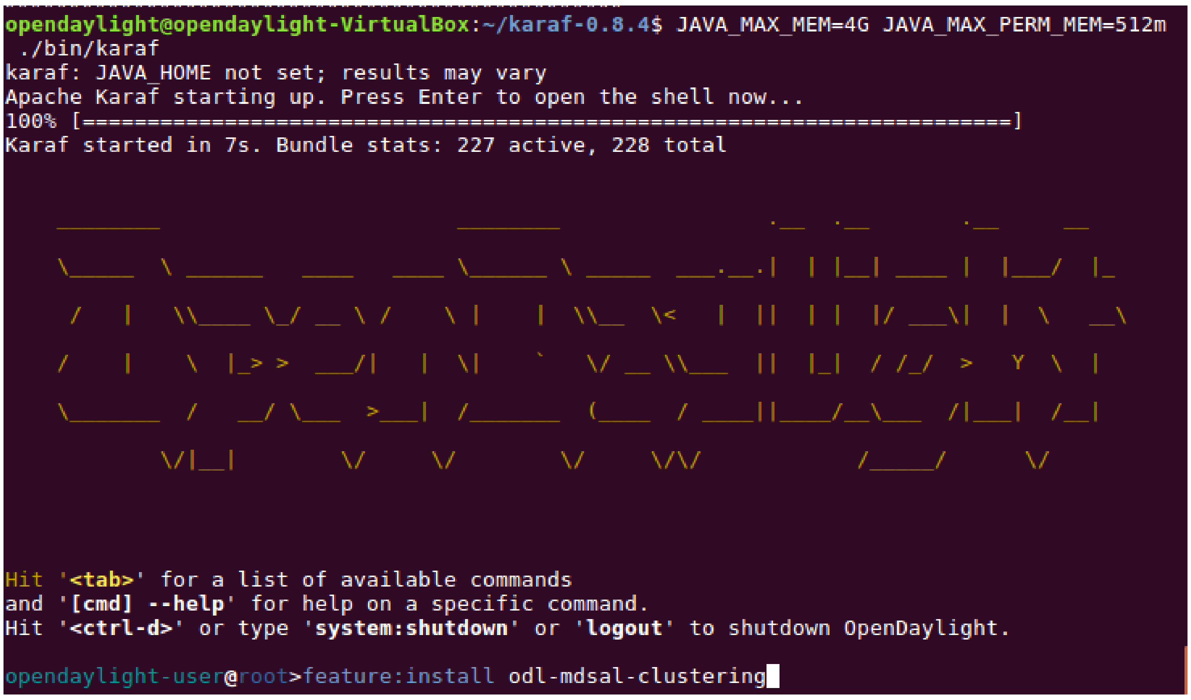
```
opendaylight@opendaylight-VirtualBox:~/karaf-0.8.4/configuration/initial$ cat module-shards.conf
module-shards = [
        {
                name = "default"
                shards = [
                        {
                                name = "default"
                                replicas = ["member-1",
                                "member-2",
                                "member-3"]
                        }
                ]
        },
        {
                name = "inventory"
                shards = [
                        {
                                name="inventory"
                                replicas = ["member-1",
                                "member-2",
                                "member-3"]
                        }
                ]
        },
        {
                name = "topology"
                shards = [
                        {
                                name="topology"
                                replicas = ["member-1",
                                "member-2",
                                "member-3"]
                        }
                ]
        },
        {
                name = "toaster"
                shards = [
                        {
                                name="toaster"
                                replicas = ["member-1",
                                "member-2",
                                "member-3"]
```

The next configuration is to run the ODL instances on every VM with the following command:

opendaylight@opendaylight-VirtualBox:~/karaf-0.8.4**$ JAVA_MAX_MEM=4G JAVA_MAX_PERM_MEM=512m ./bin/karaf**

And the final command is to install odl-mdsal-clustering.

opendaylight-user@root>feature:install odl-mdsal-clustering



```
opendaylight@opendaylight-VirtualBox:~/karaf-0.8.4$ JAVA_MAX_MEM=4G JAVA_MAX_PERM_MEM=512m ./bin/karaf
karaf: JAVA_HOME not set; results may vary
Apache Karaf starting up. Press Enter to open the shell now...
100% [========================================================================]
Karaf started in 7s. Bundle stats: 227 active, 228 total

Hit '<tab>' for a list of available commands
and '[cmd] --help' for help on a specific command.
Hit '<ctrl-d>' or type 'system:shutdown' or 'logout' to shutdown OpenDaylight.

opendaylight-user@root>feature:install odl-mdsal-clustering
```

Same configuration must be applied for the rest of ODL _01 and ODL_02 servers changing just the index parameter.

Using the ODL CLI command opendaylight-user@root>log:tail the logging messages verify that a candidate node can be a lead node and backward.

Finally, if an ODL_01 node will be crashed in the cluster, the logs of any of the rest ODL nodes will notify that the ODL_01 node is not running. However, when this node will be recovered it immediately became again a candidate node.

```
 - com.typesafe.akka.slf4j - 2.5.11 | Association with remote system [akka.tcp://opendaylight-cluster-data@192.168.56.101:2550] has failed, address is now gated for [5000] ms. Reason: [Association failed with [akka.tcp://opendaylight-cluster-data@192.168.56.101:2550]] Caused by: [Connection refused: /192.168.56.101:2550]
2019-09-12 23:56:08,264 | INFO  | lt-dispatcher-18 | kka://opendaylight-cluster-data) | 68
 - com.typesafe.akka.slf4j - 2.5.11 | Cluster Node [akka.tcp://opendaylight-cluster-data@192.168.56.102:2550] - Leader can currently not perform its duties, reachability status: [akka.tcp://opendaylight-cluster-data@192.168.56.102:2550 -> akka.tcp://opendaylight-cluster-data@192.168.56.101:2550: Unreachable [Unreachable] (1), akka.tcp://opendaylight-cluster-data@192.168.56.103:2550 -> akka.tcp://opendaylight-cluster-data@192.168.56.101:2550: Unreachable [Unreachable] (1)], member status: [akka.tcp://opendaylight-cluster-data@192.168.56.101:2550 Up seen=false, akka.tcp://opendaylight-cluster-data@192.168.56.102:2550 Up seen=true, akka.tcp://opendaylight-cluster-data@192.168.56.103:2550 Up seen=true]
2019-09-12 23:56:10,459 | WARN  | lt-dispatcher-30 | NettyTransport                   | 68
 - com.typesafe.akka.slf4j - 2.5.11 | Remote connection to [null] failed with java.net.ConnectException: Connection refused: /192.168.56.101:2550
2019-09-12 23:56:10,460 | WARN  | lt-dispatcher-30 | ReliableDeliverySupervisor       | 68
 - com.typesafe.akka.slf4j - 2.5.11 | Association with remote system [akka.tcp://opendaylight-cluster-data@192.168.56.101:2550] has failed, address is now gated for [5000] ms. Reason: [Association failed with [akka.tcp://opendaylight-cluster-data@192.168.56.101:2550]] Caused by: [Connection refused: /192.168.56.101:2550]
2019-09-12 23:56:15,661 | WARN  | lt-dispatcher-18 | NettyTransport                   | 68
 - com.typesafe.akka.slf4j - 2.5.11 | Remote connection to [null] failed with java.net.ConnectException: Connection refused: /192.168.56.101:2550
2019-09-12 23:56:15,663 | WARN  | lt-dispatcher-18 | ReliableDeliverySupervisor       | 68
 - com.typesafe.akka.slf4j - 2.5.11 | Association with remote system [akka.tcp://opendaylight-cluster-data@192.168.56.101:2550] has failed, address is now gated for [5000] ms. Reason: [Association failed with [akka.tcp://opendaylight-cluster-data@192.168.56.101:2550]] Caused by: [Connection refused: /192.168.56.101:2550]
2019-09-12 23:56:20,794 | WARN  | ult-dispatcher-3 | NettyTransport                   | 68
 - com.typesafe.akka.slf4j - 2.5.11 | Remote connection to [null] failed with java.net.ConnectException: Connection refused: /192.168.56.101:2550
2019-09-12 23:56:20,797 | WARN  | ult-dispatcher-3 | ReliableDeliverySupervisor       | 68
 - com.typesafe.akka.slf4j - 2.5.11 | Association with remote system [akka.tcp://opendaylight-cluster-data@192.168.56.101:2550] has failed, address is now gated for [5000] ms. Reason: [Association failed with [akka.tcp://opendaylight-cluster-data@192.168.56.101:2550]] Caused by: [Connection refused: /192.168.56.101:2550]
```

6 Mininet

Mininet is an open source tool that creates virtual network environment with one single command. In particular it is used for creating the data plane elements (switches) for the SDN environment. Mininet networks usually are a composition of hosts, switches, routes, controllers and links with the last being represented as virtual Ethernet connections. Mininet not only creates a network but it also allows to configure it and test it. Using Mininet it is possible to develop a network based on a single GNU/Linux kernel [19].

6.1 Why to use Mininet

Mininet is the best choice to simulate virtual networks because it is compatible with many SDN controllers and switches. Also, it comes with built-in SDN switch Open vSwitch that supports the OpenFlow protocol and many other utilities that will be presented afterwards. Also, it allows easy to create custom topologies based on Python language. Furthermore, the command line interface (CLI) allows to test and configure the network topologies with real conditions, such as setting up link bandwidth, link delay, and loss characteristics. Finally, it supports the ***miniedit*** GUI (Graphical User Interface) to create a network topology [19].

6.2 Mininet-Deployment

In order to set up a Mininet tool that will be used to create virtual network topology, a virtualization platform is required. However, the Mininet tool can be used without being hosted in any hypervisor. There are three options to install the Mininet tool [19]:

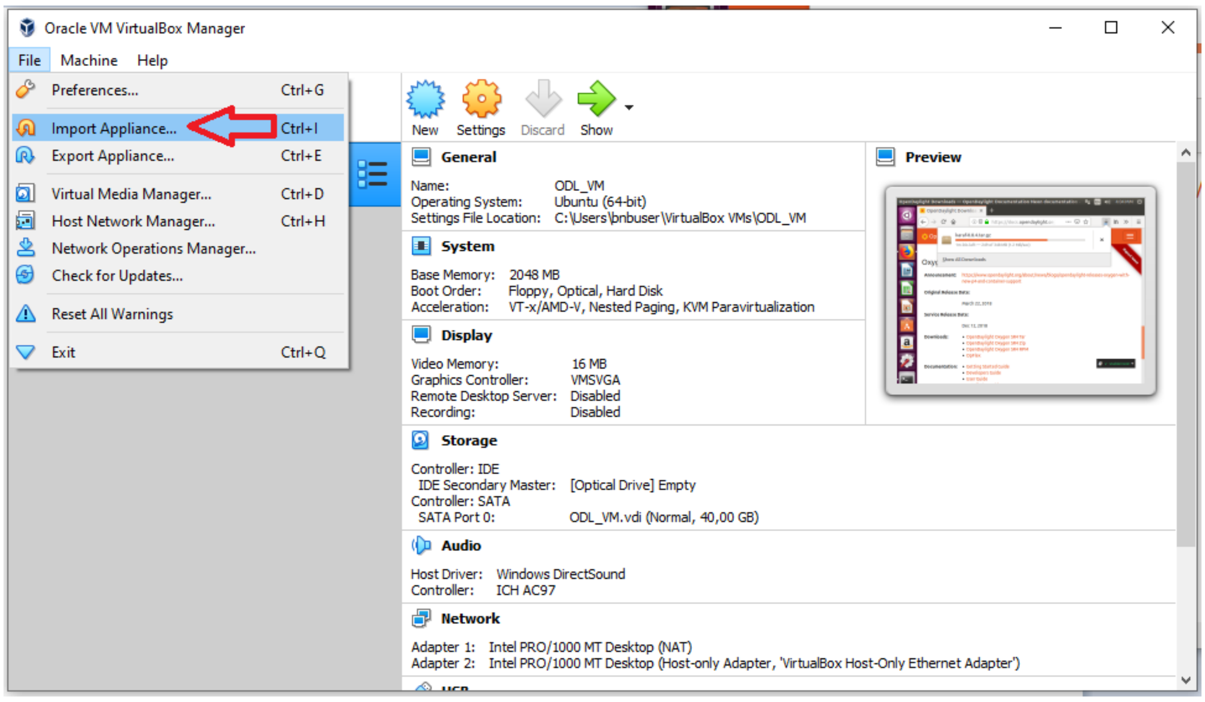
- Installing Mininet VM in hypervisor which is the recommended
- Native Installation from Source
- Installing Mininet from packages

6.2.1 Installing Mininet VM

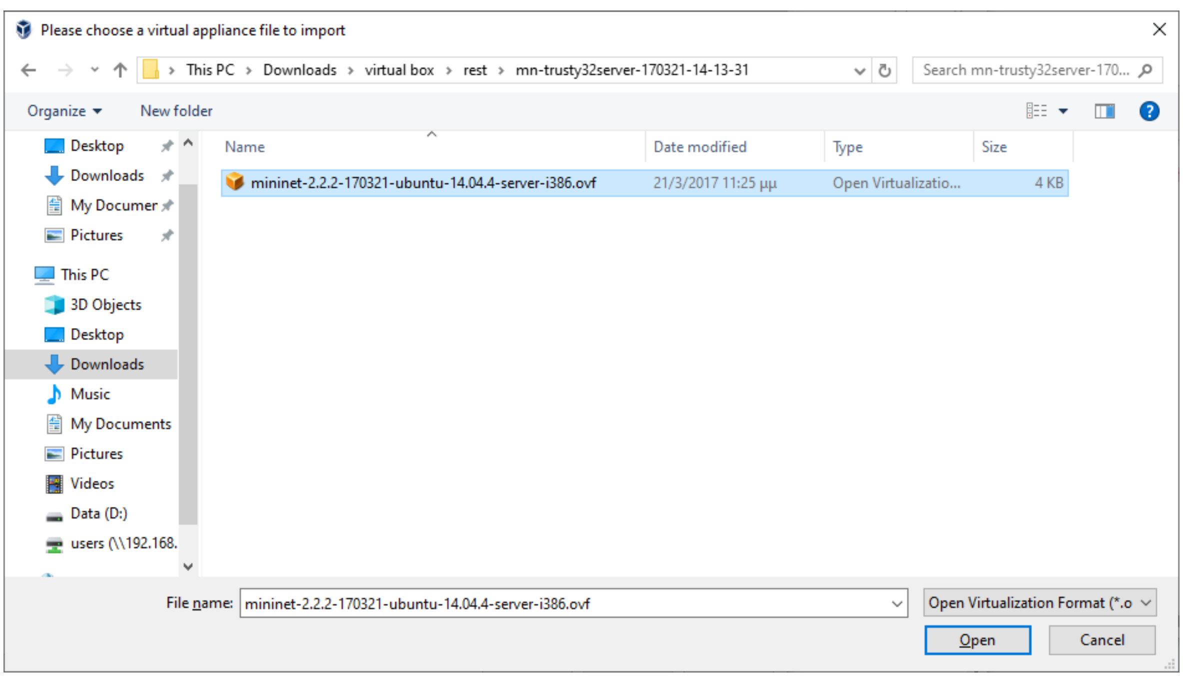
The required VM images are downloaded from [19] in order to set up the Mininet VM. The retrieved zip file contains two files as demonstrated in following figure.

Next step-by-step Mininet Deployment in VirtualBox hypervisor will be presented.

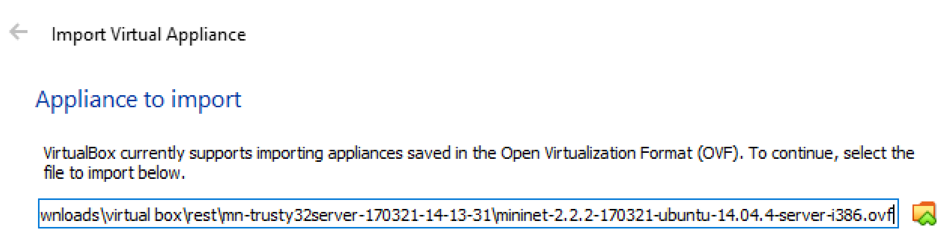
Step 1: Since the VirtualBox is in running state selecting from File-> Import Appliance a new wizard pops-up to browse an appliance.



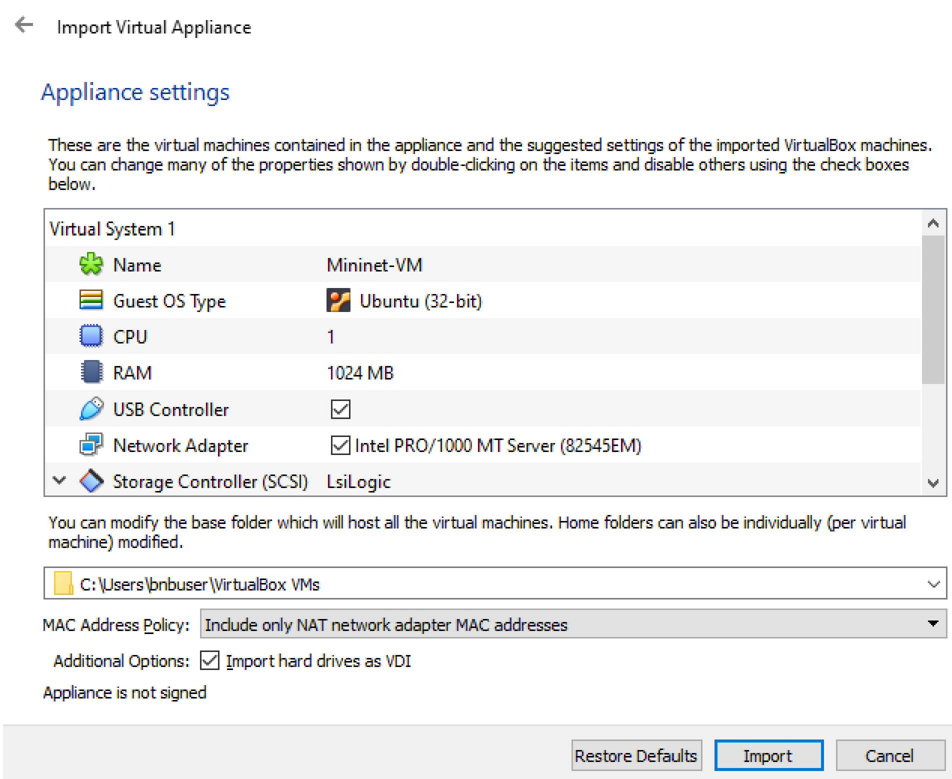
Step 2: The next wizard browses the .ovf (Open Virtualization Format) image.



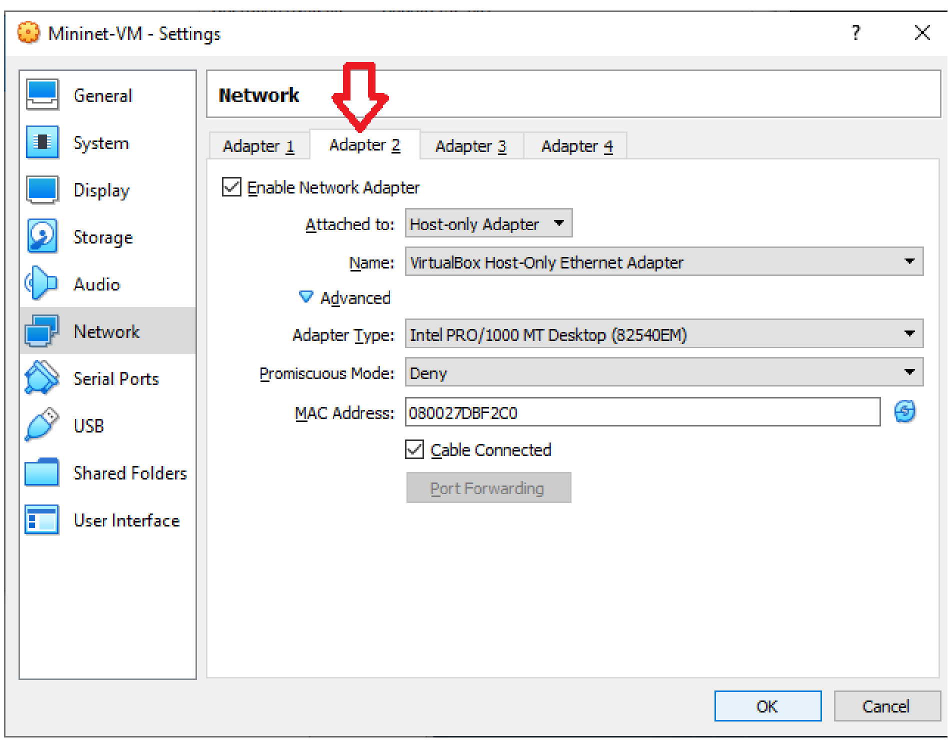
This will unpack and import the VM in your local machine. It will take a while, as the unpacked image is about 3 GB. Once the Mininet VM is completed, Mininet version 2.2.2 is installed along with Wireshark, Openflow13, Open vSwitch, a POX and NOX SDN controllers and other useful utilities on Ubuntu 14.04.4 LTS (GNU/Linux 4.2.0-27-generic x86_64) operating system.



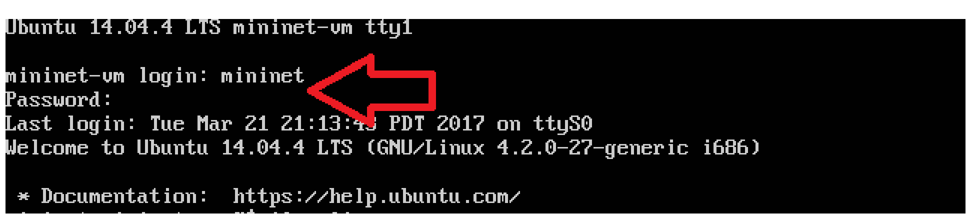
Step 3: This step shows the assigned memory to 1GB RAM, 1 CPU and OS type Ubuntu for the VM. The provided values are sufficient to assure that the Mininet tool will work effectively.



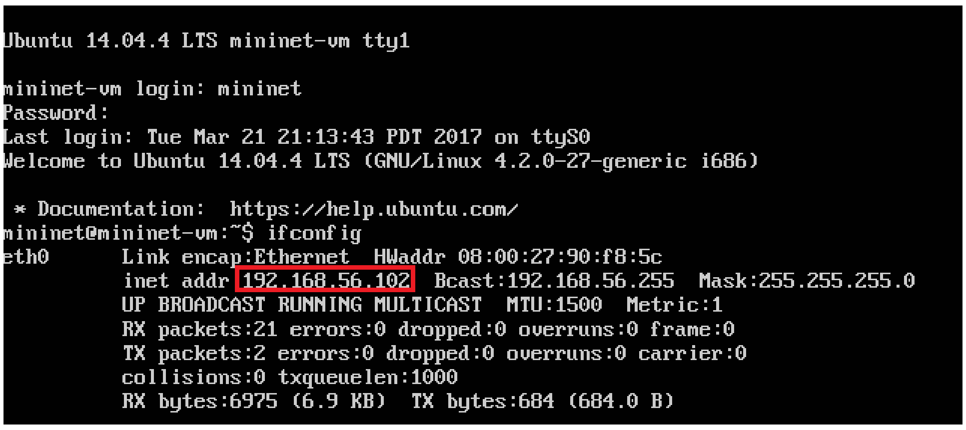
Step 4: Similar to ODL configuration Host-only Adapter is configured.

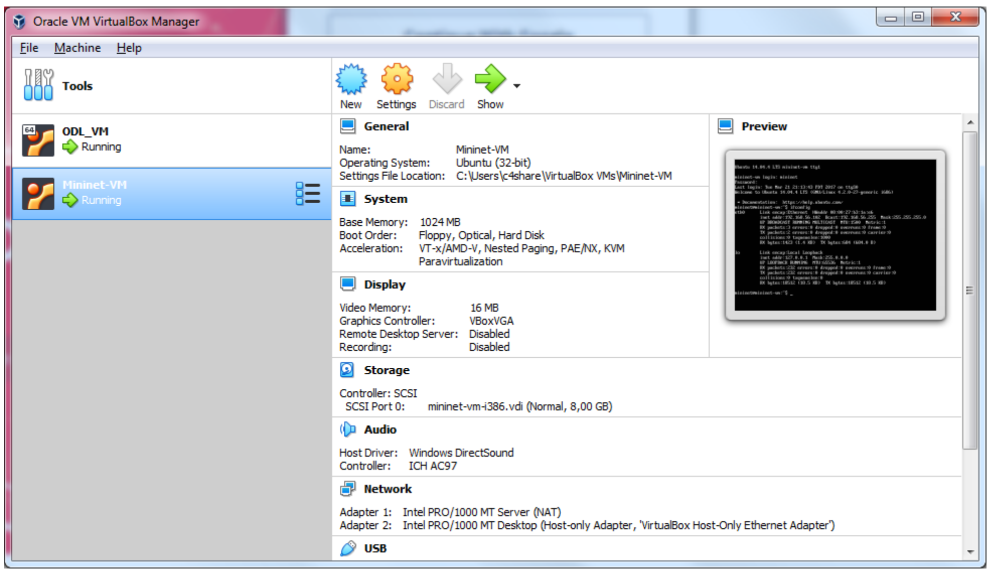


When the Mininet VM is running it starts booting and throws a login prompt, providing the default credentials for username and password "***mininet***" allows access to It. This user is a sudoer, as a result, root permissions are available for any command. It is worth to mention, that this VM does not include Graphical User Interface, so the built–in X server of the host machine will be used to solve this problem.

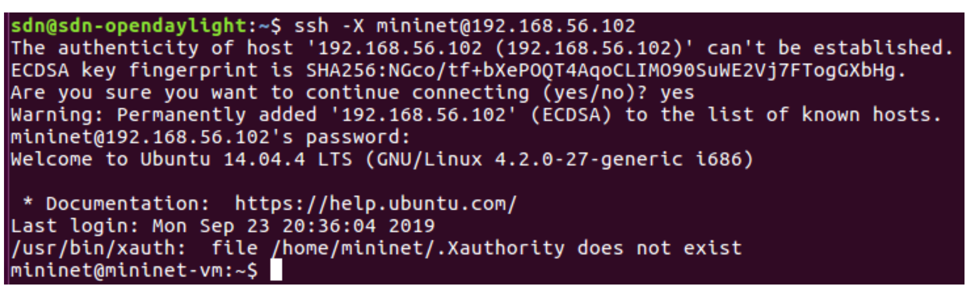


Next, the IP address is retrieved in order to set up the X forwarding. The next figure shows the eth0 interface with IP address 192.168.56.102, which means this is the Mininet VM IP address is 192.168.56.102 and there is access to it via SSH (Secure Shell).





From now on, all actions that will take place in this VM will be accomplished after SSH (Secure Shell) connection and forwarding the X server from the host machine terminal as shown from figure bellow.



6.3 Mininet build-in Tools

Mininet VM has already pre-installed many tools networking presented next:

- **Mininet:** command line tool, creates a virtual network that is composed of controller, virtual switches, hosts, and links.
- **Open vSwitch (OVS)[22]:** Is a virtual OpenFlow-enabled switch and it is used in many open source and commercial networks and virtualization platforms. It was implemented by Nicira company. OVS in based on Linux Kernel Module. It supports different technologies and protocols, such as 802.1Q, BFD, NetFlow, sFlow, port mirroring, VLANs, LACP, VXLAN, GENEVE GRE Overlays, STP, and IPv6. Virtual Ethernet ports pair are used in order to connect hosts by OVS. Virtual Ethernet ports are equivalent to a pair of physical Ethernet interfaces interconnected by a cable however, they are implemented using software. The virtual port connection is implemented at a link layer. OVS works like a regular MAC learning and forwarding switch when no controller is configured and OpenFlow rules are not programmed (standalone). It programs the OpenFlow flow tables when it receives inputs from the SDN OpenFlow-enabled controller. It also supports the OVSDB southbound protocol. OVS is always layered below the

OpenFlow interface. The release of the switch that is hosted in Mininet -VM is 2.0.2 The next figure verifies this version.

```
mininet@mininet-vm:~$ ovs-dpctl -V
ovs-dpctl (Open vSwitch) 2.0.2
Compiled Dec  9 2015 14:08:08
mininet@mininet-vm:~$
```

Figure 13 illustrates the structure of the OVS:

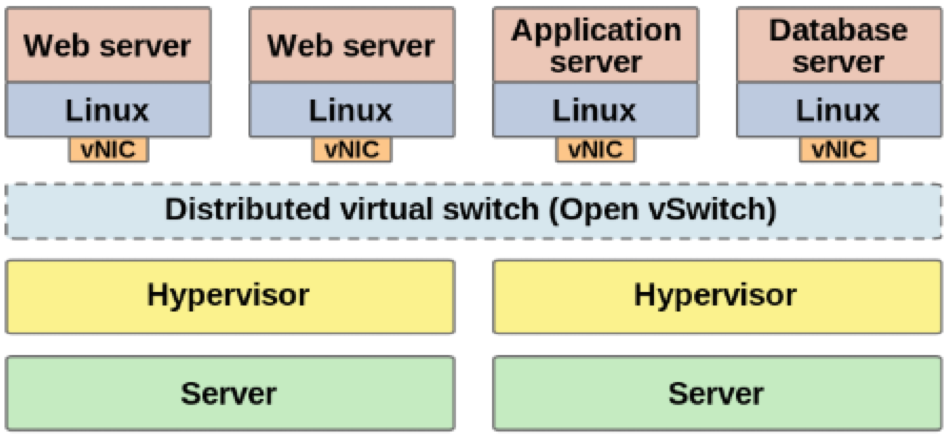


Figure 13: OVS atchitecture

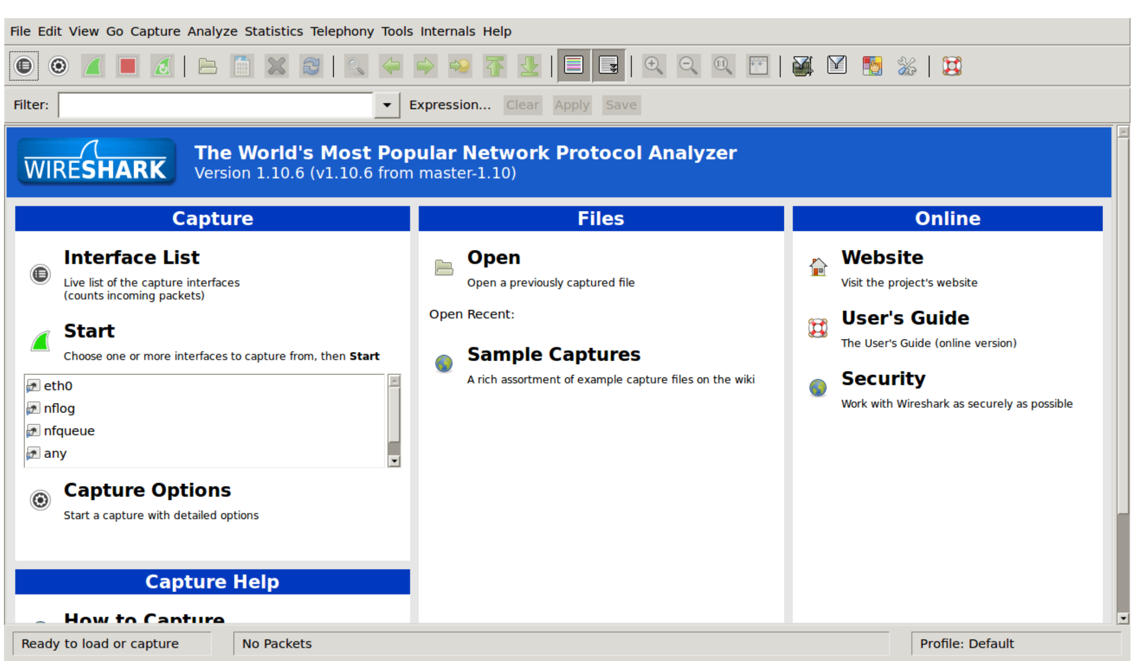
- **POX Controller:** Is a built-in OpenFlow controller, but can also function as an OpenFlow switch that resides in Mininet VM. In terms of this research the ODL controller will be used. Every OpenFlow controller is located above of the OpenFlow interface. The controller communicated with the switch with the OpenFlow protocol.
- **dpctl:** Is a command line tool that configures flow tables in OpenFlow switch. It allows to adds flows, modifies the flows, queries for switch features and status [20][21].
- **ovs-ofctl:** command line utility that sends quick OpenFlow messages, useful for viewing switch port and flow stats or manually inserting flow entries [20][21].
- **ovs-vsctl:** command line utility that allows queries and configuration on ovs-vswitchd which is an OVS deamon [20][21].
- **Wireshark:** Tool with GUI for analyzing the packets. In particular it will dissect OpenFlow packets [19].

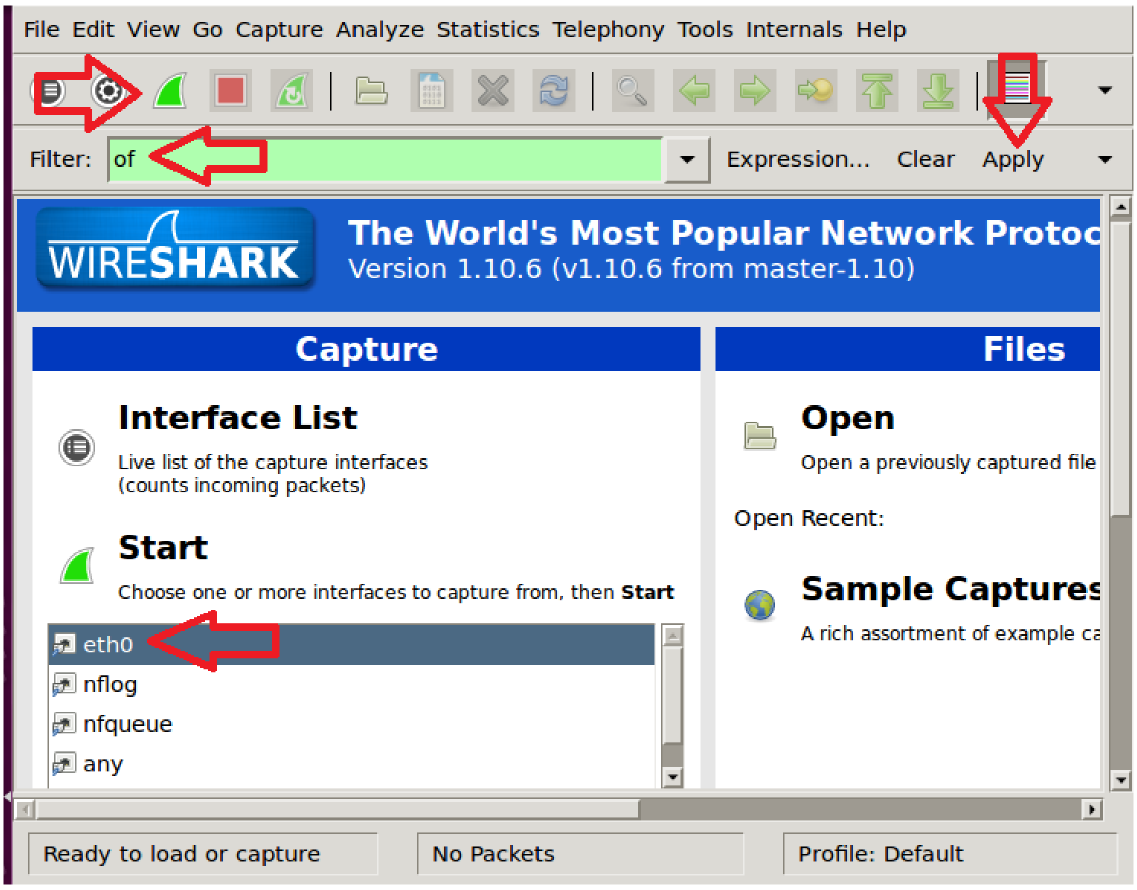
Before starting the Wireshark, capture privileges and permissions to specific files /urs/bin/dumpcap directory must be set by following commands

```
mininet@mininet-vm:~$ sudo chgrp mininet /usr/bin/dumpcap
mininet@mininet-vm:~$ sudo chmod 754 /usr/bin/dumpcap
mininet@mininet-vm:~$ sudo setcap 'CAP_NET_RAW+eip CAP_NET_ADMIN+eip' /usr/bin/dumpcap
```

The bellow command starts the Wireshark and filtering OpeFlow packets:

```
mininet@mininet-vm:~$ wireshark
```





- **iperf:** Tool for testing the speed of hosts.
- **cbench:** Cbench is a software for testing OpenFlow controllers by generating packet-in events for new flows. Cbench emulates a bunch of switches, which connect to a controller, sends packet-in messages, and waits for flow-mods to get pushed down.

7 Integration of Mininet with OpenDaylight Controller

In this chapter, will present how to build a virtual SDN lab using ODL and Mininet. Mininet is a tool for virtualizing OVS-based virtual switches and Linux container hosts. ODL and Mininet communicate with each other and how hosts in a virtual lab can ping each other by leveraging the SDN controller to program the flows inside the switches. In order to create the virtual network, the Mininet VM and the Opendaylight controller must be in running state. Connect to Mininet VM with default username:mininet and password:mininet

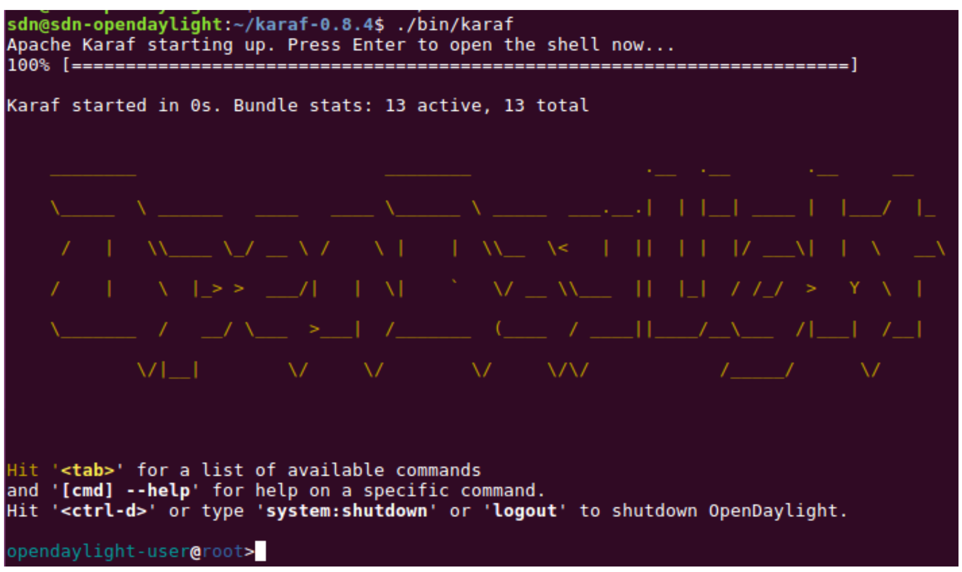
The ODL controller must be in running state. In addition, L2Switch feature must be installed, along with DLUX Web Interface and restconf API.

The next steps verify that required ODL modules are installed and are accessible. Also verify that Mininet VM is connected to ODL via OpenFlow.

- *Running ODL*

The following command starts the ODL container.

sdn@sdn-opendaylight:~/Downloads/karaf-0.8.4$ ./bin/karaf

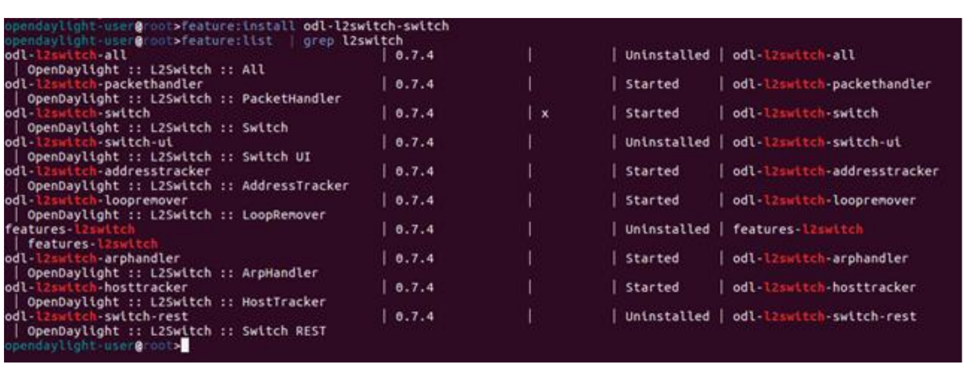


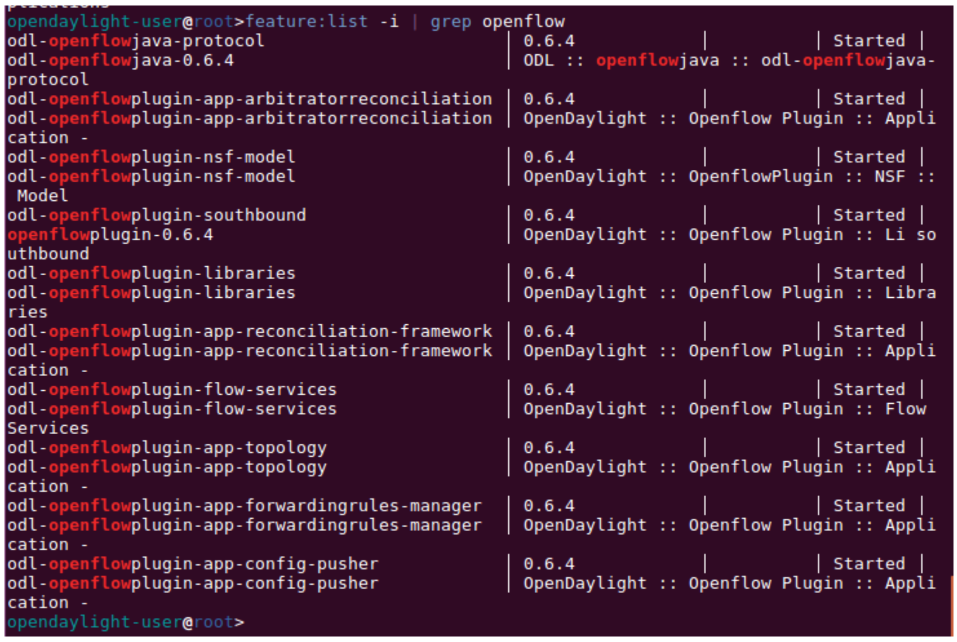
Since the controller is in running state, it allows installing any ODL module.

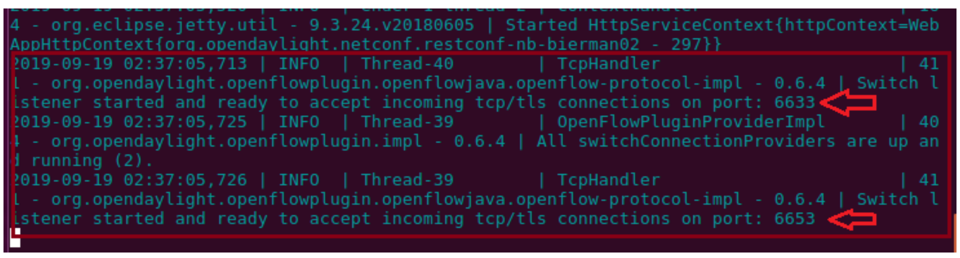
- *Enabling L2Switch*

In order to make Mininet to connect with the Opendaylight we need to install the l2switch feature.

After installing the l2switch in OpenDaylight karaf, the port 6633 will be activated to accept incoming TPC/TLS connections with mininet. Also, there is another TCP/TLS port which is 6653 and establishes a secure channel connection with the Opendayligh and Mininet.

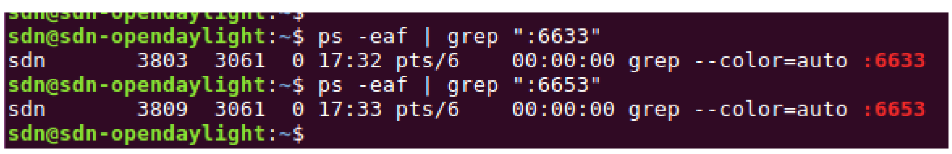






After installing the odl-l2switch-switch, verify that the ports 6653 and 6633 are activated in order to receive calls from Mininet.

sdn@sdn-opendaylight:~$ ps -eaf| grep ":6633"

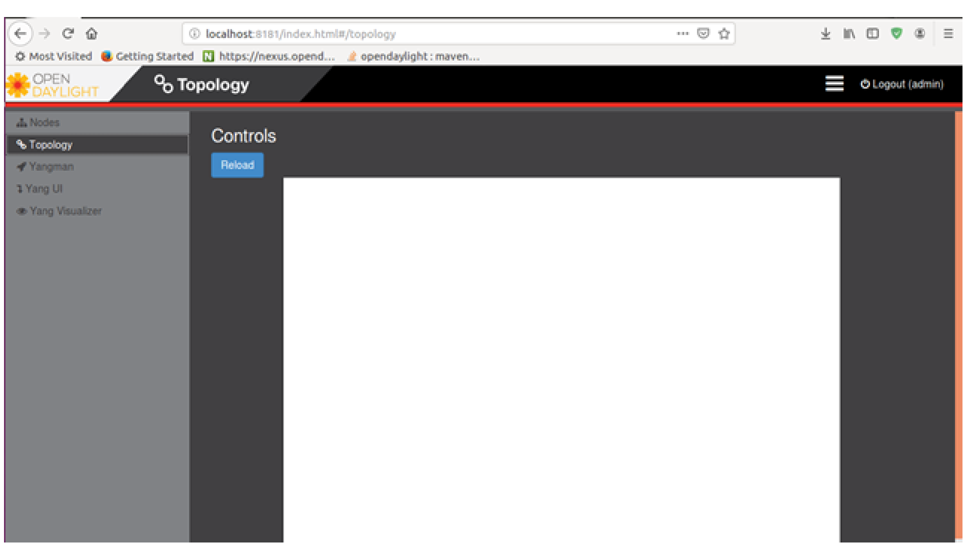


- *Enabling DLUX web interface*

Enable the DLUX web interface through command.

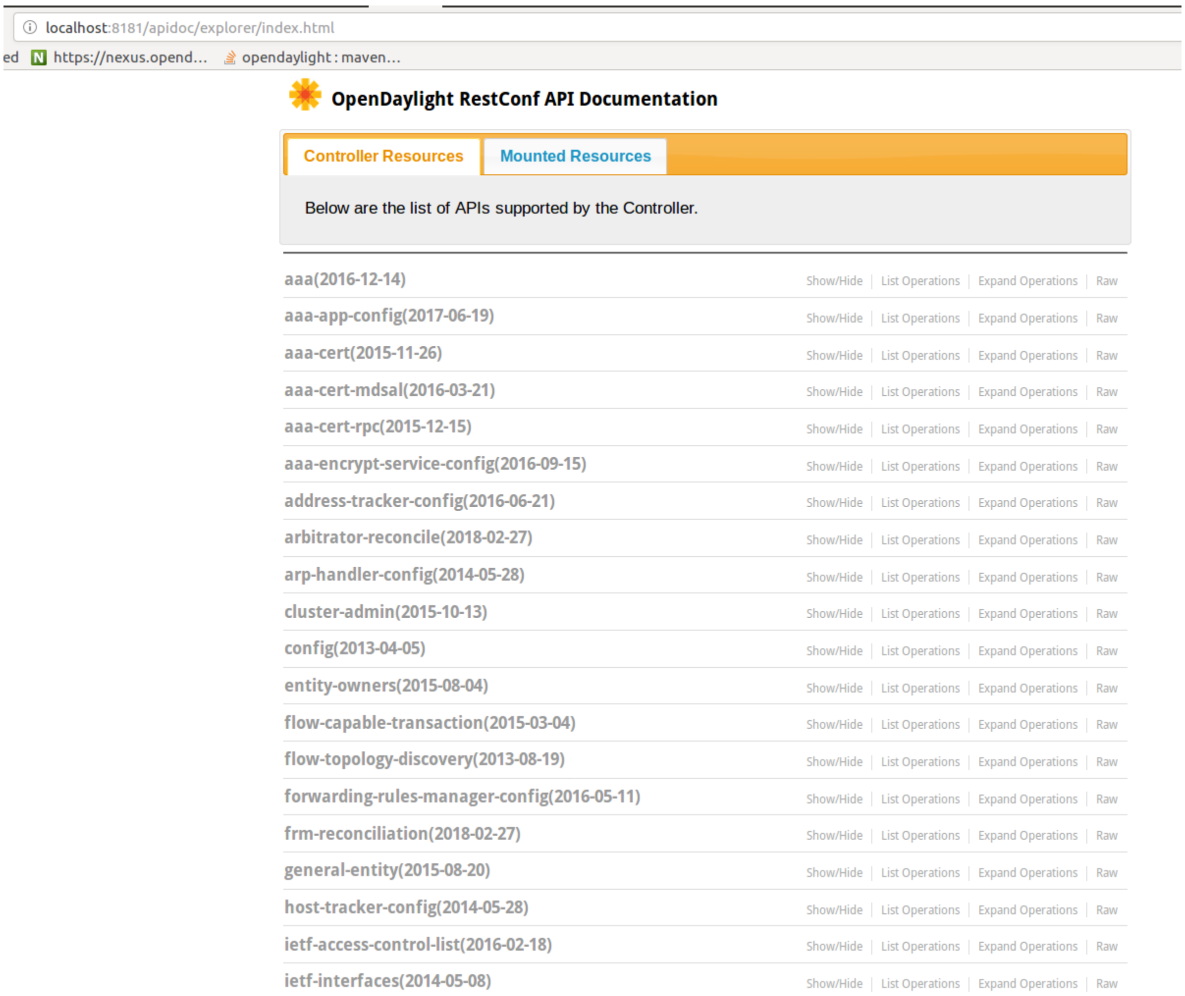
opendaylight-user@root>feature:install features-dlux

The “Started” annotation indicates that dlux modules have been started successfully. The next figure verifies that the DLUX Web interface is accessible.



- *Enabling restconf A PI*

To access the REST ODL apply navifate to http://localhost:8181/apidoc/explorer/index.html



From here on, a virtual network topology can be created and every switch will be defined as l2-learning-enabled switch. The controller is responsible to handle the forwarding rules of tables.

In order to create a virtual network in the VM, the following command.

mininet@mininet-vm:~$ sudo mn --topo=linear,3 --mac --controller=remote,ip=192.168.56.102 --switch ovsk,protocols=OpenFlow13

where

mac: will assign MAC address for every host equal to its IP address e.g. 00:00:00:00:00:01

ip: defines the IP address of the remote controller.

controller: is the IP address of the ODL controller where the virtual switches are connected,

topo: linear defines a network topology with three switches and three hosts, switches and hosts are connected with a virtual ethernet cable.

switch: is a parameter to identify the switch type in this case is an OpenFlow-enabled Open vSwitch.

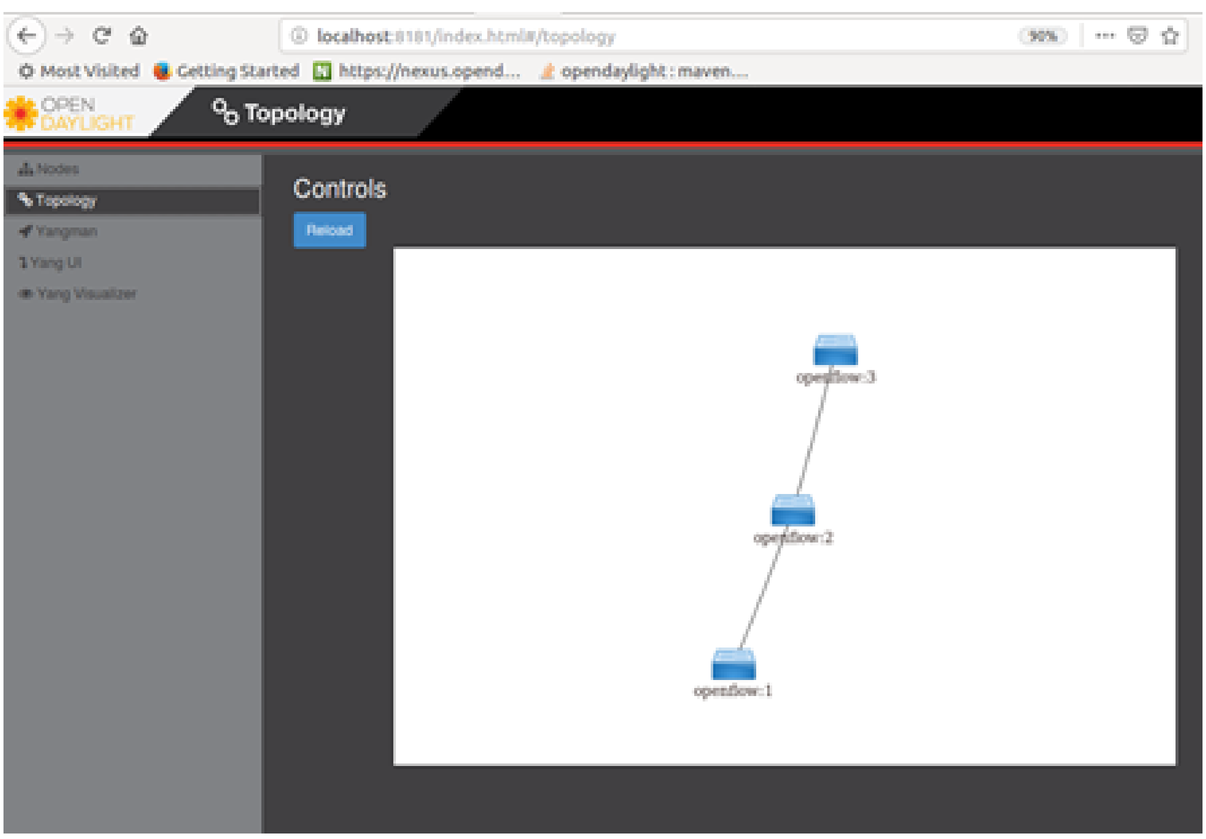
protocols: which is set to OpenFlow13 means that this switch is compatible with this protocol. The next figure shows the result of this command.

```
mininet@mininet-vm:~$ sudo mn --topo=linear,3 --mac --controller=remote,ip=192.168.56.101
--switch ovsk,protocols=OpenFlow13
*** Creating network
*** Adding controller
Connecting to remote controller at 192.168.56.101:6653
*** Adding hosts:
h1 h2 h3
*** Adding switches:
s1 s2 s3
*** Adding links:
(h1, s1) (h2, s2) (h3, s3) (s2, s1) (s3, s2)
*** Configuring hosts
h1 h2 h3
*** Starting controller
c0
*** Starting 3 switches
s1 s2 s3 ...
*** Starting CLI:
```

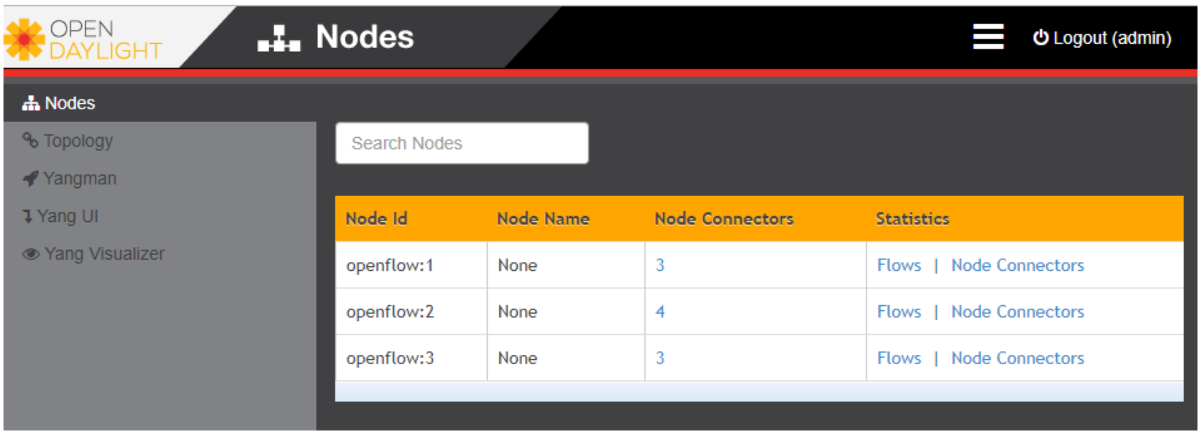
Using the mininet “**net”** command information about swich nodes aand links are provided.

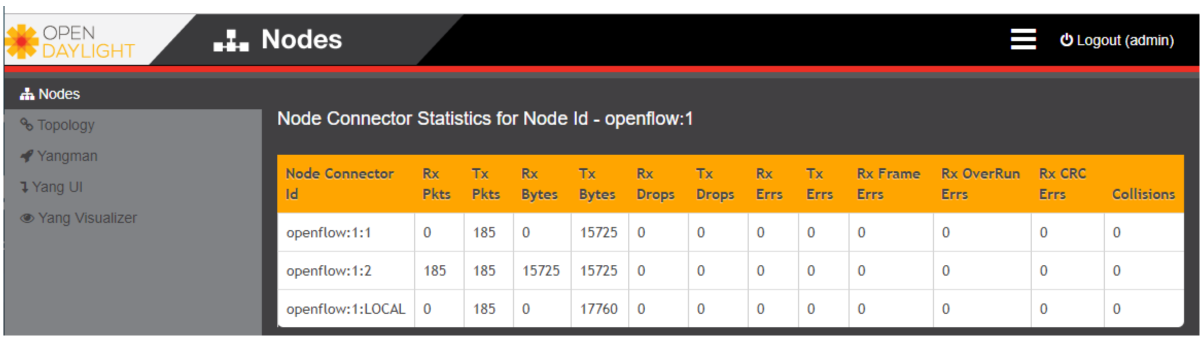
```
mininet> net
h1 h1-eth0:s1-eth1
h2 h2-eth0:s2-eth1
h3 h3-eth0:s3-eth1
s1 lo:  s1-eth1:h1-eth0 s1-eth2:s2-eth2
s2 lo:  s2-eth1:h2-eth0 s2-eth2:s1-eth2 s2-eth3:s3-eth2
s3 lo:  s3-eth1:h3-eth0 s3-eth2:s2-eth3
c0
mininet> links
h1-eth0<->s1-eth1 (OK OK)
h2-eth0<->s2-eth1 (OK OK)
h3-eth0<->s3-eth1 (OK OK)
s2-eth2<->s1-eth2 (OK OK)
s3-eth2<->s2-eth3 (OK OK)
mininet> nodes
available nodes are:
c0 h1 h2 h3 s1 s2 s3
mininet>
```

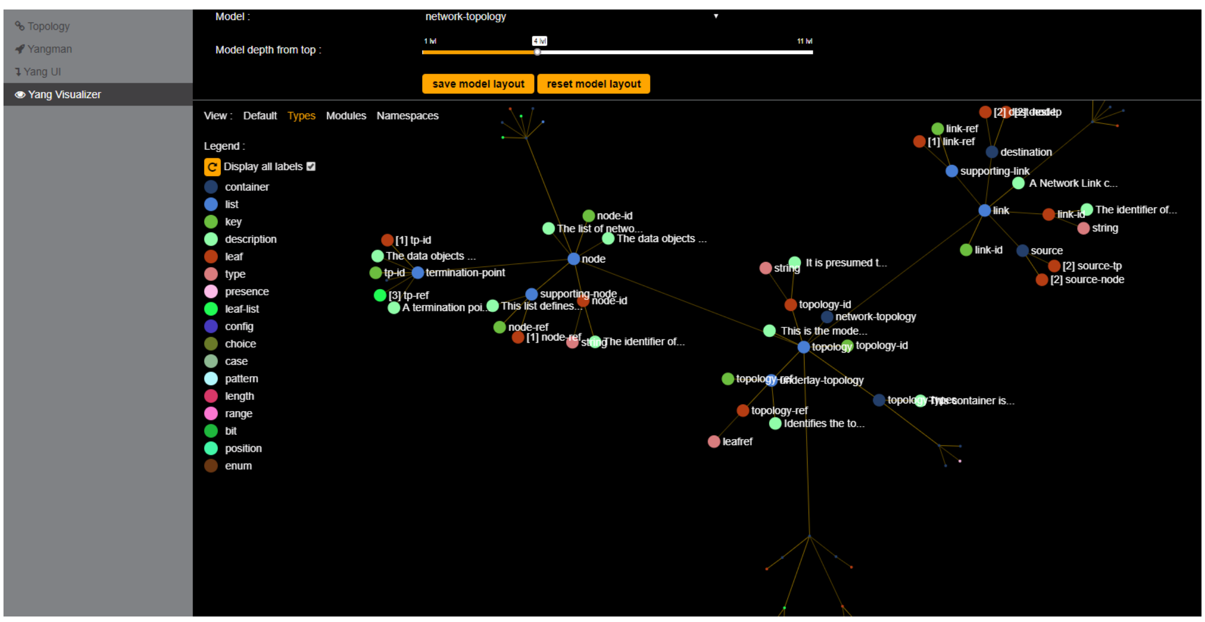
Using the web interface of the controller created network topology is depicted in topology tab.



Navigating through the GUI various data about nodes, flows, etc. are provide for the user.

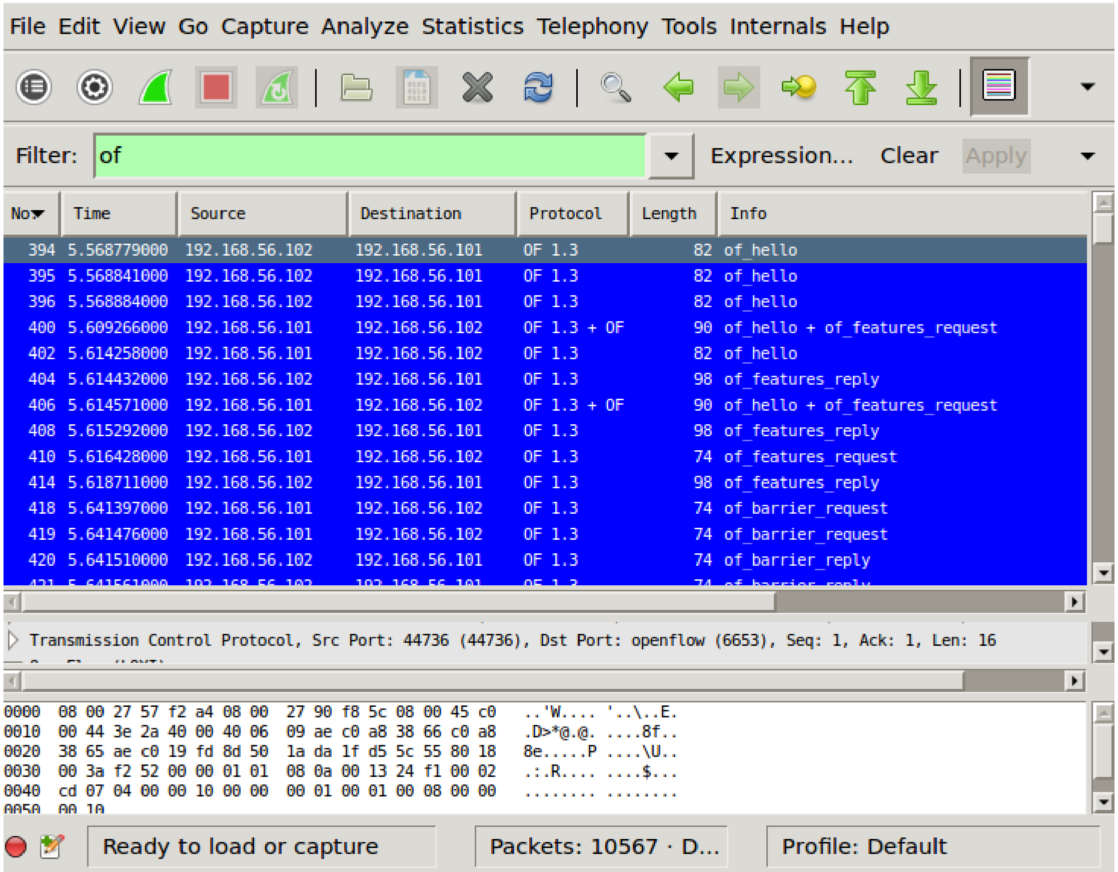






In addition, Wireshark tool will allow to analyze the packets of the network.

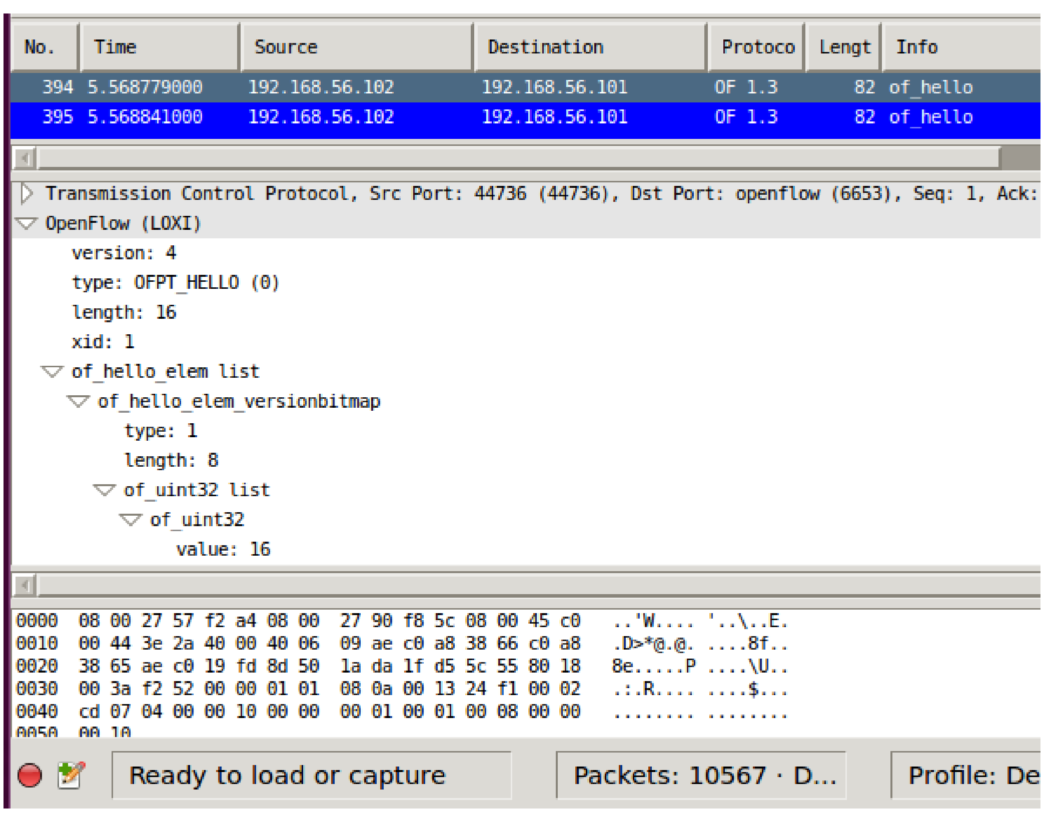
Setting as a filter the “of” key, which stands for OpenFlow protocol, then pressing the “apply” button will show only OpenFlow packets. The figure bellow presents filtered OpenFlow packets.



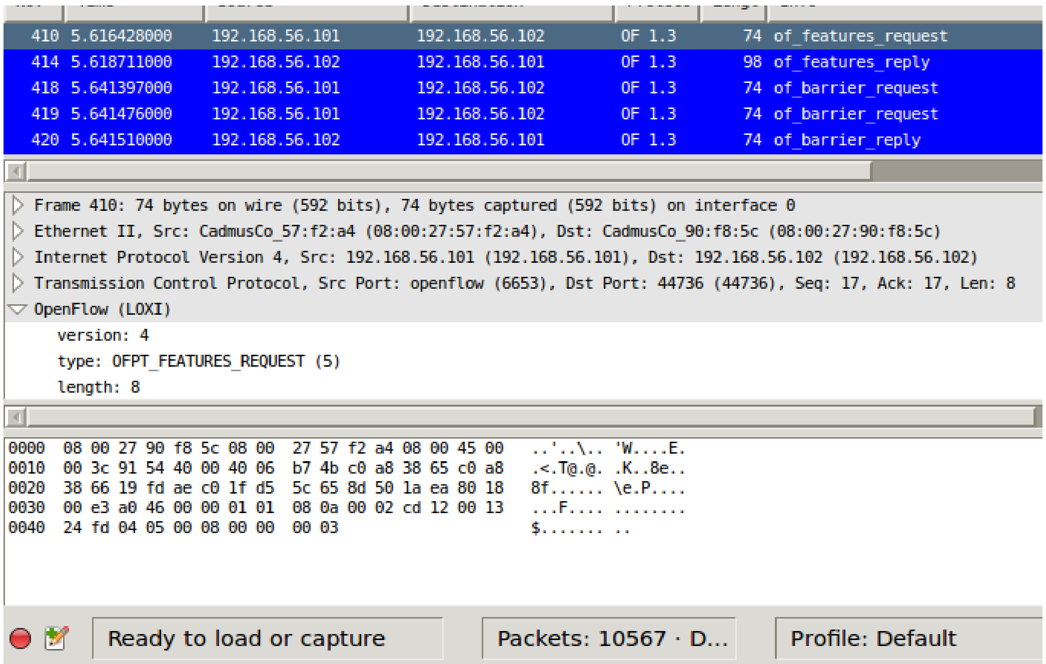
Wireshark verifies that there is packet exchange between the ODL controller 192.168.56.101 and virtual network topology from Mininet 192.168.56.102 These packets are called “of_hello” are of type OFPT_HELLO.

The communication is initialized during the TCP handshake, the controller sends its version number to each switch through the of_hello packet, whereupon each switch responses with its supported version number through the of_hello packet. Finally, the controller requests to see the available ports throught of_features_request. Since there are three switches three pair of OFPT_HELLO-OFTP_FEATUES_REQUEST generated.

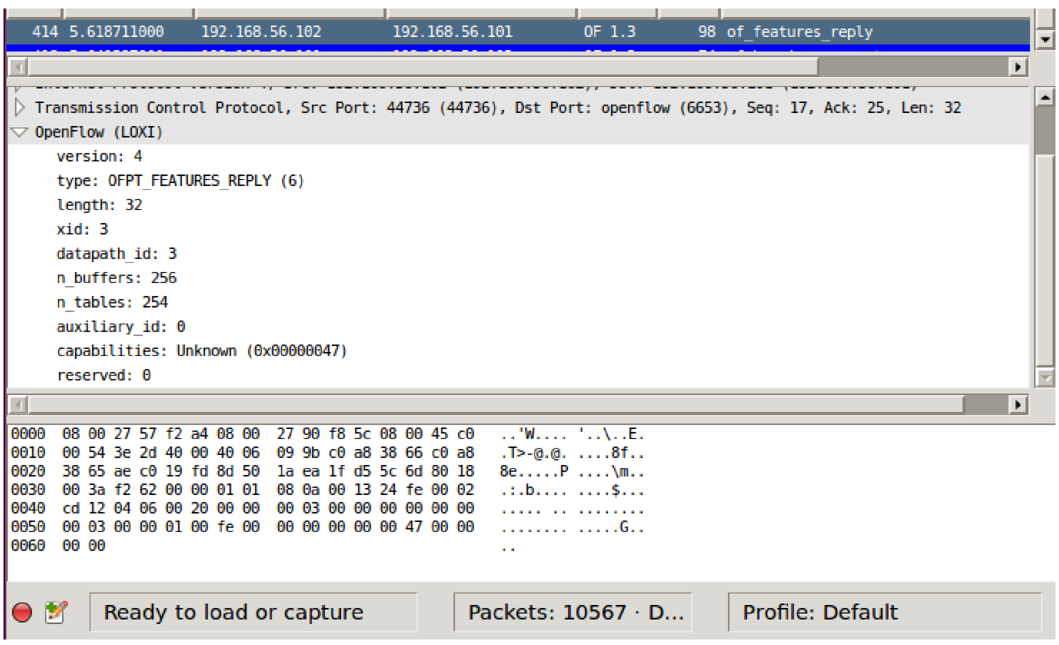
The **OF_HELLO** packet contains, version, type, length , of_hello_elemets, xid.



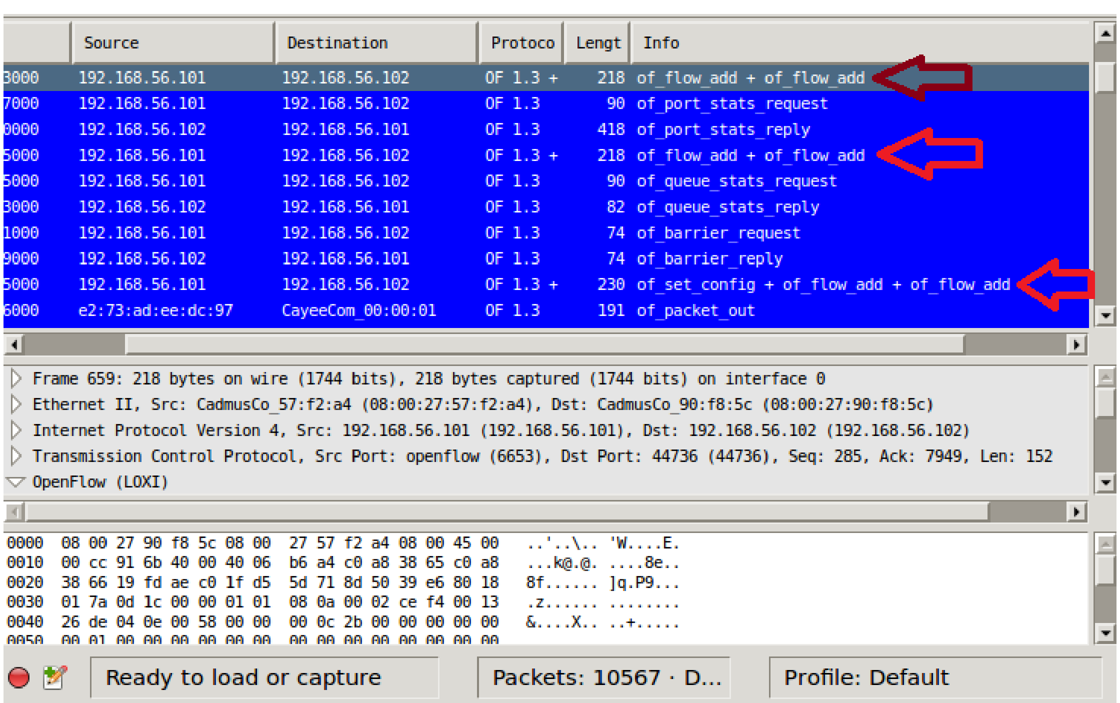
The **OFTP_FEATUES_REQUEST** packet contains also version, type length and xid.



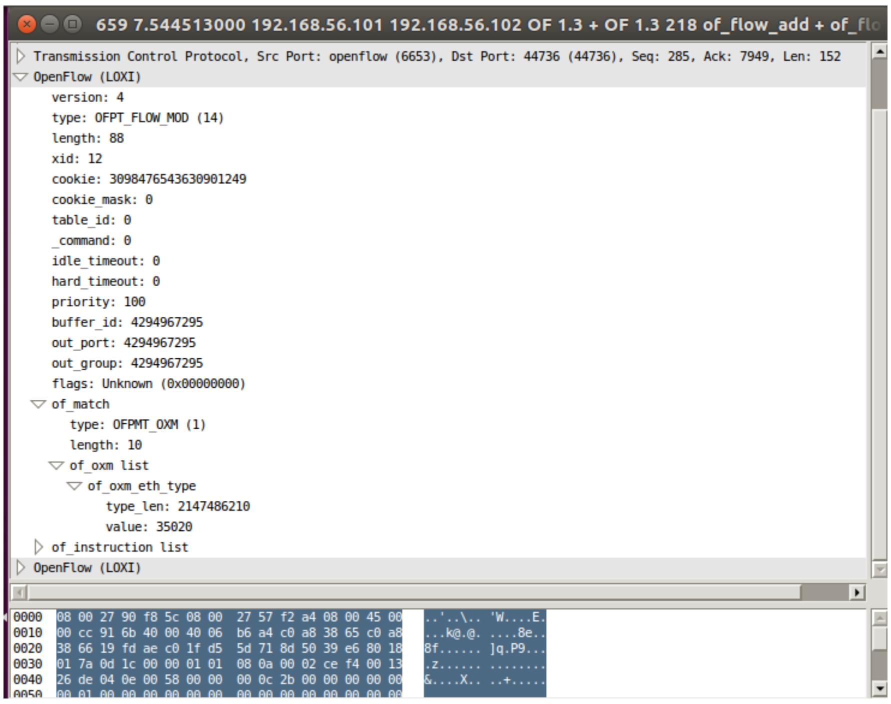
The content of the **OFTP_FEATURES_REPLY** packet

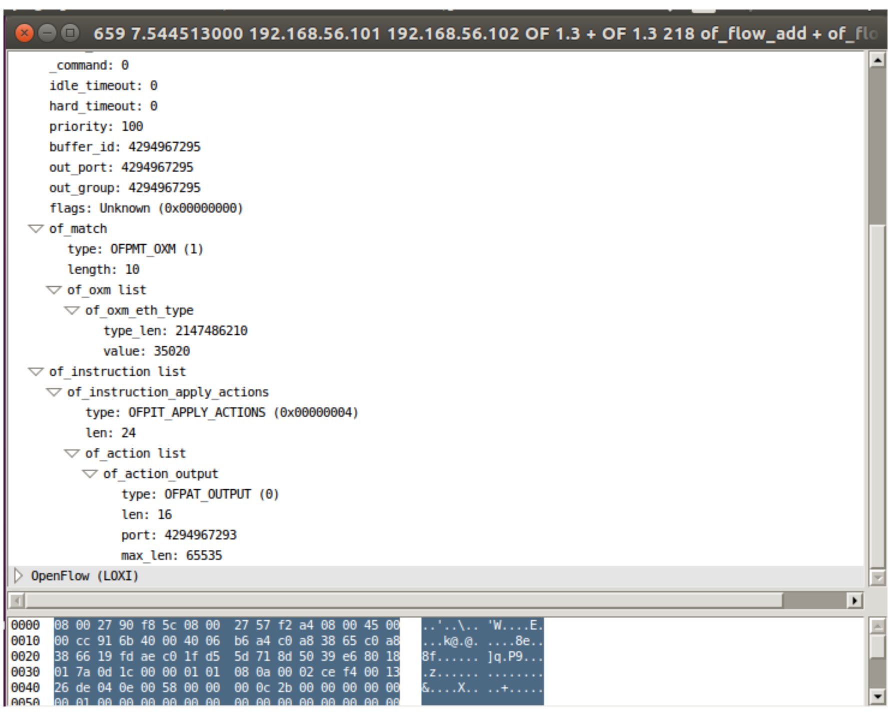


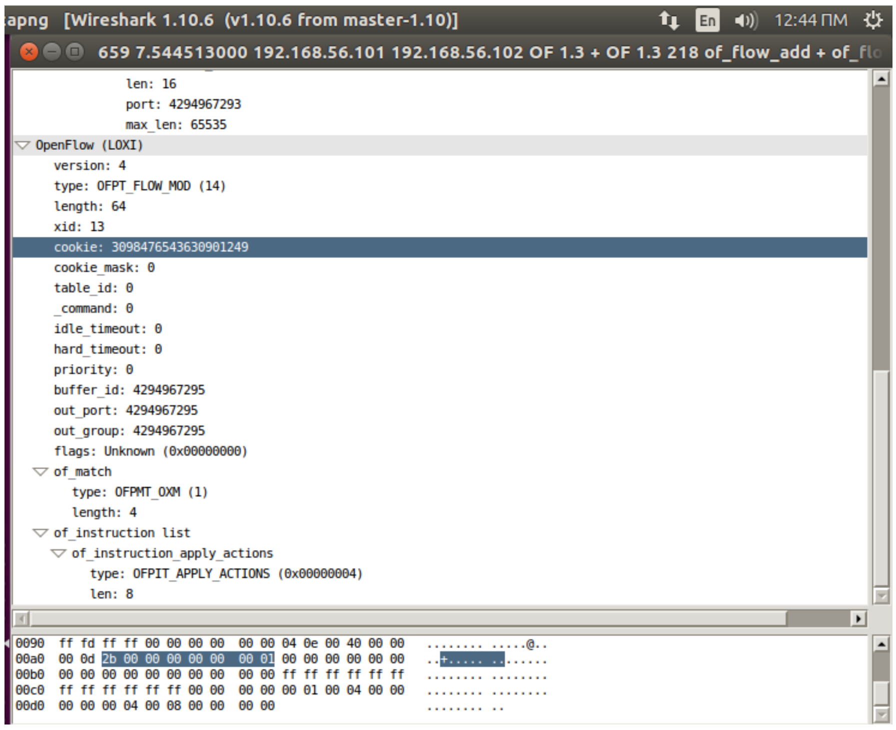
Two pair of add flow mod exist in packet analyzation.



OFTP_FLOW_ MOD message which does not has matching rules and sends the packet to the controller via instruction apply actions since it is not know how to handle the packet. All this action is presented in figures in detail.







Since an Openflow based topology is created relevant data about the network can be retrieved from feature inventory: nodes of the OpenFlow of the ODL.

Using the Restconf API of the ODL we retrieve the nodes fetching related data from bellow end-point. Note that, the flows data behavior must be similar to the packet anatomy from Wireshark tool described before.

http://localhost:8181/restconf/operational/opendaylight-inventory:nodes/

Three switches network impy to free nodes with **openflow:1**, **openflow:2** and **openflow:3** for the OpenFlow protocol.

```
{ ⊟
   "nodes":{ ⊟
      "node":[ ⊟
         { ⊟
            "id":"openflow:1",
            "node-connector":[ ⊟
               { ⊞ },
               { ⊞ },
               { ⊞ }
            ],
            "flow-node-inventory:port-number":59600,
            "flow-node-inventory:serial-number":"None",
            "flow-node-inventory:table":[ ⊞ ],
            "flow-node-inventory:hardware":"Open vSwitch",
            "flow-node-inventory:description":"None",
            "flow-node-inventory:software":"2.0.2",
            "flow-node-inventory:switch-features":{ ⊞ },
            "flow-node-inventory:manufacturer":"Nicira, Inc.",
            "flow-node-inventory:ip-address":"192.168.56.102",
            "flow-node-inventory:snapshot-gathering-status-start":{ ⊞ },
            "flow-node-inventory:snapshot-gathering-status-end":{ ⊞ }
         },
         { ⊟
            "id":"openflow:2",
            "node-connector":[ ⊟
               { ⊞ },
               { ⊞ },
               { ⊞ },
               { ⊞ }
            ],
            "flow-node-inventory:port-number":59598,
            "flow-node-inventory:serial-number":"None",
            "flow-node-inventory:table":[ ⊞ ],
            "flow-node-inventory:hardware":"Open vSwitch",
            "flow-node-inventory:description":"None",
            "flow-node-inventory:software":"2.0.2",
            "flow-node-inventory:switch-features":{ ⊞ },
            "flow-node-inventory:manufacturer":"Nicira, Inc.",
            "flow-node-inventory:ip-address":"192.168.56.102",
            "flow-node-inventory:snapshot-gathering-status-start":{ ⊞ },
            "flow-node-inventory:snapshot-gathering-status-end":{ ⊞ }
         },
         { ⊟
            "id":"openflow:3",
            "node-connector":[ ⊟
               { ⊞ },
               { ⊞ },
               { ⊞ }
            ],
            "flow-node-inventory:port-number":59596,
            "flow-node-inventory:serial-number":"None",
            "flow-node-inventory:table":[ ⊞ ],
            "flow-node-inventory:hardware":"Open vSwitch",
            "flow-node-inventory:description":"None",
            "flow-node-inventory:software":"2.0.2",
            "flow-node-inventory:switch-features":{ ⊞ },
            "flow-node-inventory:manufacturer":"Nicira, Inc.",
            "flow-node-inventory:ip-address":"192.168.56.102",
            "flow-node-inventory:snapshot-gathering-status-start":{ ⊞ },
            "flow-node-inventory:snapshot-gathering-status-end":{ ⊞ }
         }
      ]
   }
}
```


Looking in detail, the **node-connector** implies to port connections for the OpenFlow protocol. Thus switch 1 is connected with switch 2.

```
{ ⊟
   "nodes":{ ⊟
      "node":[ ⊟
         { ⊟
            "id":"openflow:1",
            "node-connector":[ ⊟
               { ⊟
                  "id":"openflow:1:1",
                  "flow-node-inventory:supported":"",
                  "flow-node-inventory:peer-features":"",
                  "flow-node-inventory:port-number":1,
                  "flow-node-inventory:advertised-features":"",
                  "flow-node-inventory:hardware-address":"a2:97:7d:ed:c7:1c",
                  "flow-node-inventory:current-feature":"ten-gb-fd copper",
                  "flow-node-inventory:current-speed":10000000,
                  "flow-node-inventory:configuration":"",
                  "flow-node-inventory:maximum-speed":0,
                  "flow-node-inventory:name":"s1-eth1",
                  "flow-node-inventory:state":{ ⊞ },
                  "opendaylight-port-statistics:flow-capable-node-connector-statistics":{ ⊞ }
               },
               { ⊟
                  "id":"openflow:1:2",
                  "flow-node-inventory:supported":"",
                  "flow-node-inventory:peer-features":"",
                  "flow-node-inventory:port-number":2,
                  "flow-node-inventory:advertised-features":"",
                  "flow-node-inventory:hardware-address":"6a:72:60:a6:5a:6e",
                  "flow-node-inventory:current-feature":"ten-gb-fd copper",
                  "flow-node-inventory:current-speed":10000000,
                  "flow-node-inventory:configuration":"",
                  "flow-node-inventory:maximum-speed":0,
                  "flow-node-inventory:name":"s1-eth2",
                  "flow-node-inventory:state":{ ⊞ },
                  "opendaylight-port-statistics:flow-capable-node-connector-statistics":{ ⊞ }
               },
               { ⊟
                  "id":"openflow:1:LOCAL",
                  "flow-node-inventory:supported":"",
                  "flow-node-inventory:peer-features":"",
                  "flow-node-inventory:port-number":4294967294,
                  "flow-node-inventory:advertised-features":"",
                  "flow-node-inventory:hardware-address":"b6:8c:30:e9:94:42",
                  "flow-node-inventory:current-feature":"",
                  "flow-node-inventory:current-speed":0,
                  "flow-node-inventory:configuration":"",
                  "flow-node-inventory:maximum-speed":0,
                  "flow-node-inventory:name":"s1",
                  "flow-node-inventory:state":{ ⊞ },
                  "opendaylight-port-statistics:flow-capable-node-connector-statistics":{ ⊞ }
               }
            ],
            "flow-node-inventory:port-number":59600,
            "flow-node-inventory:serial-number":"None",
            "flow-node-inventory:table":[ ⊞ ],
            "flow-node-inventory:hardware":"Open vSwitch",
            "flow-node-inventory:description":"None",
            "flow-node-inventory:software":"2.0.2",
            "flow-node-inventory:switch-features":{ ⊞ },
            "flow-node-inventory:manufacturer":"Nicira, Inc.",
            "flow-node-inventory:ip-address":"192.168.56.102",
            "flow-node-inventory:snapshot-gathering-status-start":{ ⊞ },
            "flow-node-inventory:snapshot-gathering-status-end":{ ⊞ }
         },
```


Next, digging deeper and going into to **openflow 1:1** which is the switch’s port 1 packet statistics details are provided it.

```
{
  "id":"openflow:1:1",
  "flow-node-inventory:supported":"",
  "flow-node-inventory:peer-features":"",
  "flow-node-inventory:port-number":1,
  "flow-node-inventory:advertised-features":"",
  "flow-node-inventory:hardware-address":"a2:97:7d:ed:c7:1c",
  "flow-node-inventory:current-feature":"ten-gb-fd copper",
  "flow-node-inventory:current-speed":10000000,
  "flow-node-inventory:configuration":"",
  "flow-node-inventory:maximum-speed":0,
  "flow-node-inventory:name":"s1-eth1",
  "flow-node-inventory:state":{
    "blocked":false,
    "link-down":false,
    "live":false
  },
  "opendaylight-port-statistics:flow-capable-node-connector-statistics":{
    "receive-frame-error":0,
    "packets":{
      "received":0,
      "transmitted":326
    },
    "collision-count":0,
    "transmit-errors":0,
    "bytes":{
      "received":0,
      "transmitted":27710
    },
    "duration":{
      "nanosecond":219000000,
      "second":1624
    },
    "receive-crc-error":0,
    "receive-drops":0,
    "receive-errors":0,
    "receive-over-run-error":0,
    "transmit-drops":0
  }
},
```


Analyzing a random node for example the **openflow:1** node from **table=0**, the matching rules, action sets of each flow follows the OpenFlow protocol rules and the expected result based on Wireshark analysis.

http://192.168.56.101:8181/restconf/operational/opendaylight-inventory:nodes/node/openflow:1/table/0/


```
{
  "flow-node-inventory:table": [
    {
      "id": 0,
      "opendaylight-flow-table-statistics:flow-table-statistics": {
        "active-flows": 4,
        "packets-looked-up": 9144,
        "packets-matched": 9144
      },
      "flow": [
        {
          "id": "#UF$TABLE*0-3",
          "priority": 100,
          "opendaylight-flow-statistics:flow-statistics": {
            "packet-count": 606,
            "byte-count": 51510,
            "duration": {
              "nanosecond": 712000000,
              "second": 3025
```

```
        }
      },
      "table_id": 0,
      "cookie_mask": 0,
      "hard-timeout": 0,
      "match": {
        "ethernet-match": {
          "ethernet-type": {
            "type": 35020
          }
        }
      },
      "cookie": 3098476543630901000,
      "flags": "",
      "instructions": {
        "instruction": [
          {
            "order": 0,
            "apply-actions": {
              "action": [
                {
                  "order": 0,
                  "output-action": {
                    "max-length": 65535,
                    "output-node-connector": "CONTROLLER"
                  }
                }
              ]
            }
          }
        ]
      },
      "idle-timeout": 0
    },
    {
      "id": "#UF$TABLE*0-4",
      "priority": 2,
      "opendaylight-flow-statistics:flow-statistics": {
        "packet-count": 0,
        "byte-count": 0,
        "duration": {
          "nanosecond": 804000000,
          "second": 3021
        }
      },
      "table_id": 0,
      "cookie_mask": 0,
      "hard-timeout": 0,
      "match": {
        "in-port": "1"
      },
      "cookie": 3098476543630901000,
      "flags": "",
      "instructions": {
        "instruction": [
          {
            "order": 0,
            "apply-actions": {
              "action": [
                {
                  "order": 0,
                  "output-action": {
                    "max-length": 65535,
                    "output-node-connector": "2"
```

```
                    }
                  },
                  {
                    "order": 1,
                    "output-action": {
                      "max-length": 65535,
                      "output-node-connector": "CONTROLLER"
                    }
                  }
                ]
              }
            }
          ]
        },
        "idle-timeout": 0
      },
      {
        "id": "L2switch-0",
        "priority": 0,
        "opendaylight-flow-statistics:flow-statistics": {
          "packet-count": 0,
          "byte-count": 0,
          "duration": {
            "nanosecond": 715000000,
            "second": 3025
          }
        },
        "table_id": 0,
        "cookie_mask": 0,
        "hard-timeout": 0,
        "match": {},
        "cookie": 3098476543630901000,
        "flags": "",
        "idle-timeout": 0
      },
      {
        "id": "L2switch-1",
        "priority": 2,
        "opendaylight-flow-statistics:flow-statistics": {
          "packet-count": 0,
          "byte-count": 0,
          "duration": {
            "nanosecond": 804000000,
            "second": 3021
          }
        },
        "table_id": 0,
        "cookie_mask": 0,
        "hard-timeout": 0,
        "match": {
          "in-port": "2"
        },
        "cookie": 3098476543630901000,
        "flags": "",
        "instructions": {
          "instruction": [
            {
              "order": 0,
              "apply-actions": {
                "action": [
                  {
                    "order": 0,
                    "output-action": {
                      "max-length": 65535,
```

```
                        "output-node-connector": "1"
                      }
                    },
                    {
                      "order": 1,
                      "output-action": {
                        "max-length": 65535,
                        "output-node-connector": "CONTROLLER"
                      }
                    }
                  ]
                }
              }
            ]
          },
          "idle-timeout": 0
        }
      ]
    }
  ]
}
```

The next links presents the network topology from the aspect of OpenFlow protocol.

http://localhost:8181/restconf/operational/network-topology:network-topology

```
{ ⊟
   "network-topology":{ ⊟
      "topology":[ ⊟
         { ⊟
            "topology-id":"flow:1",
            "node":[ ⊟
               { ⊟
                  "node-id":"openflow:1",
                  "opendaylight-topology-inventory:inventory-node-ref":"/opendaylight-inventory:nodes/opendaylight-inventory:node[opendaylight-inventory:id='openflow:1']",
                  "termination-point":[ ⊟
                     { ⊞ },
                     { ⊟
                        "tp-id":"openflow:1:2",
                        "opendaylight-topology-inventory:inventory-node-connector-ref":"/opendaylight-inventory:nodes/opendaylight-inventory:node[opendaylight-inventory:id='openflow:1']/opendaylight-inventory:node-connector[opendaylight-inventory:id='openflow:1:2']"
                     },
                     { ⊞ }
                  ]
               },
               { ⊞ },
               { ⊞ }
            ],
            "link":[ ⊟
               { ⊟
                  "link-id":"openflow:3:2",
                  "source":{ ⊟
                     "source-tp":"openflow:3:2",
                     "source-node":"openflow:3"
                  },
                  "destination":{ ⊟
                     "dest-tp":"openflow:2:3",
                     "dest-node":"openflow:2"
                  }
               },
               { ⊟
                  "link-id":"openflow:2:3",
                  "source":{ ⊟
                     "source-tp":"openflow:2:3",
                     "source-node":"openflow:2"
                  },
                  "destination":{ ⊟
                     "dest-tp":"openflow:3:2"
                     "dest-node":"openflow:3"
                  }
               },
               { ⊞ },
               { ⊞ }
```


Finally, using Mininet command details about the network are retrieved for each switch and each link between them.

```
s1        Link encap:Ethernet  HWaddr 6a:d6:e9:04:5a:41
          UP BROADCAST RUNNING  MTU:1500  Metric:1
          RX packets:1115 errors:0 dropped:1115 overruns:0 frame:0
          TX packets:0 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:107040 (107.0 KB)  TX bytes:0 (0.0 B)

s2        Link encap:Ethernet  HWaddr b6:b2:7e:64:39:49
          UP BROADCAST RUNNING  MTU:1500  Metric:1
          RX packets:1115 errors:0 dropped:1115 overruns:0 frame:0
          TX packets:0 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:107040 (107.0 KB)  TX bytes:0 (0.0 B)

s3        Link encap:Ethernet  HWaddr 2a:30:94:1e:c4:47
          UP BROADCAST RUNNING  MTU:1500  Metric:1
          RX packets:0 errors:0 dropped:0 overruns:0 frame:0
          TX packets:0 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:0 (0.0 B)  TX bytes:0 (0.0 B)
```

```
s1-eth2   Link encap:Ethernet  HWaddr 5a:40:d5:c0:4b:19
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:1115 errors:0 dropped:0 overruns:0 frame:0
          TX packets:1115 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:94775 (94.7 KB)  TX bytes:94775 (94.7 KB)

s2-eth2   Link encap:Ethernet  HWaddr ca:fc:56:b9:c3:00
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:1115 errors:0 dropped:0 overruns:0 frame:0
          TX packets:1115 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:94775 (94.7 KB)  TX bytes:94775 (94.7 KB)

s2-eth3   Link encap:Ethernet  HWaddr 12:b4:93:71:43:0d
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:1115 errors:0 dropped:0 overruns:0 frame:0
          TX packets:1115 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:94775 (94.7 KB)  TX bytes:94775 (94.7 KB)

s3-eth2   Link encap:Ethernet  HWaddr 1a:90:4c:73:58:5b
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:1115 errors:0 dropped:0 overruns:0 frame:0
          TX packets:1115 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:94775 (94.7 KB)  TX bytes:94775 (94.7 KB)

mininet@mininet-vm:~$
```

Mininet allows you to use the "**dpctl"** command to communicate with the virtual switch and get the status of the flows. The next figure shows this command output and verifies the existence of flows for flow table 0.

```
s2-eth2<->s1-eth2 (OK OK)
s3-eth2<->s2-eth3 (OK OK)
mininet> nodes
available nodes are:
c0 h1 h2 h3 s1 s2 s3
mininet> dpctl dump-flows -O OpenFlow13
*** s1 ------------------------------------------------------------------------
OFPST_FLOW reply (OF1.3) (xid=0x2):
 cookie=0x2b00000000000000, duration=1330.951s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=1 a
ctions=output:2,CONTROLLER:65535
 cookie=0x2b00000000000001, duration=1330.951s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=2 a
ctions=output:1,CONTROLLER:65535
 cookie=0x2b00000000000000, duration=1334.859s, table=0, n_packets=268, n_bytes=22780, priority=100,dl_
type=0x88cc actions=CONTROLLER:65535
 cookie=0x2b00000000000000, duration=1334.862s, table=0, n_packets=0, n_bytes=0, priority=0 actions=dro
p
*** s2 ------------------------------------------------------------------------
OFPST_FLOW reply (OF1.3) (xid=0x2):
 cookie=0x2b00000000000004, duration=1330.95s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=3 ac
tions=output:1,output:2,CONTROLLER:65535
 cookie=0x2b00000000000002, duration=1330.953s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=1 a
ctions=output:2,output:3,CONTROLLER:65535
 cookie=0x2b00000000000003, duration=1330.952s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=2 a
ctions=output:1,output:3,CONTROLLER:65535
 cookie=0x2b00000000000002, duration=1334.789s, table=0, n_packets=534, n_bytes=45390, priority=100,dl_
type=0x88cc actions=CONTROLLER:65535
 cookie=0x2b00000000000002, duration=1334.797s, table=0, n_packets=0, n_bytes=0, priority=0 actions=dro
p
*** s3 ------------------------------------------------------------------------
OFPST_FLOW reply (OF1.3) (xid=0x2):
 cookie=0x2b00000000000005, duration=1330.947s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=1 a
ctions=output:2,CONTROLLER:65535
 cookie=0x2b00000000000006, duration=1330.946s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=2 a
ctions=output:1,CONTROLLER:65535
 cookie=0x2b00000000000001, duration=1334.864s, table=0, n_packets=268, n_bytes=22780, priority=100,dl_
type=0x88cc actions=CONTROLLER:65535
 cookie=0x2b00000000000001, duration=1334.864s, table=0, n_packets=0, n_bytes=0, priority=0 actions=dro
p
mininet>
```

As yet, the process that has been presented registers the OpenFlow-enabled switches with the ODL and are stores related data to inventory and network topology. The registration process is accomplished via an OpenFlow HELLO packet coming from the OpenFlow switch to the ODL controller. Then ODL controller accepts the request and check whether the switch is allowed to be part of ODL's SDN domain. The verification of the expect result is same in Wireshark dissection, CLI commands outputs of mininet and from flow entries of the OpenFlow protocol.

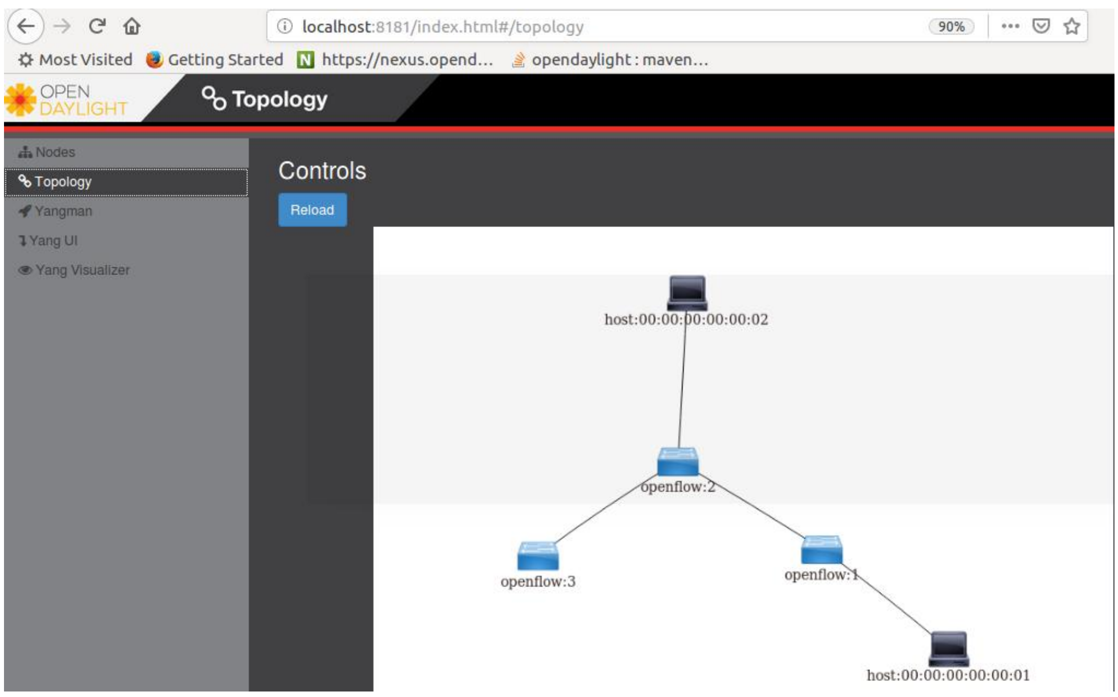
Moving to the next step, the handling of host connection and traffic generation will be presented. For this scenario the "***ping"*** command of the Mininet tool will be used.

The next figure shows how a h1 from switch 1 (s1) pings the h2 of switch (s2).

```
mininet> h1 ping h2
PING 10.0.0.2 (10.0.0.2) 56(84) bytes of data.
64 bytes from 10.0.0.2: icmp_seq=1 ttl=64 time=598 ms
64 bytes from 10.0.0.2: icmp_seq=2 ttl=64 time=96.3 ms
64 bytes from 10.0.0.2: icmp_seq=3 ttl=64 time=3.83 ms
64 bytes from 10.0.0.2: icmp_seq=4 ttl=64 time=1.11 ms
64 bytes from 10.0.0.2: icmp_seq=5 ttl=64 time=7.62 ms
64 bytes from 10.0.0.2: icmp_seq=6 ttl=64 time=1.22 ms
64 bytes from 10.0.0.2: icmp_seq=7 ttl=64 time=1.15 ms
64 bytes from 10.0.0.2: icmp_seq=8 ttl=64 time=2.06 ms
64 bytes from 10.0.0.2: icmp_seq=9 ttl=64 time=1.16 ms
64 bytes from 10.0.0.2: icmp_seq=10 ttl=64 time=2.41 ms
```

The first figure of the DLUX UI included only the switches, but after the connection between the hosts h1 and h2 the hosts of the switches s1 and s2 have been generated.

The explanation for hosts appearance after ping is related to how the ODL handles the connection between the hosts. There are several steps in order to retrieve the response from h2 host. ODL starts to identify the existence of the hosts only when there is a request for connection between them. Next the process of the host connection will be analyzed in detail.



The SDN controller knows the exiting switches and not for hosts, but the switches do not know how to handle the received frame that contains for destination a specific MAC address or the broadcast MAC.

All starts, when the h1 notices that it does not know the MAC address the h2 then, it sends ARP (Address Resolution Protocol) packet (frame layer 2) to switch s1 to find the IP address of the h2. This packet received from the switch does not has IP source and destination is just a broadcast frame.

However, when the switch s1 receives the ARP packet it checks in its flow tables for this broadcast frame if exists any matching flow entry, in this case it does not find any and then it encapsulates the packet in an OpenFlow **packet_in** packet and sends it to the ODL controller. The ODL decides what to do with this packet utilizing the Arp Handler feature.

Once the ARP packet is forwarded to all the switch ports and the ARP reply is forwarded back to host 1, which was the main ARP queried, host 1 starts sending layer 3 ICMP packets to host 2. The packets have a source and destination IP address as well as a MAC address. Again, the OVS switch does not know how to forward the packet as it does not have any flow entry for host 1 and host 2 MAC addresses yet.

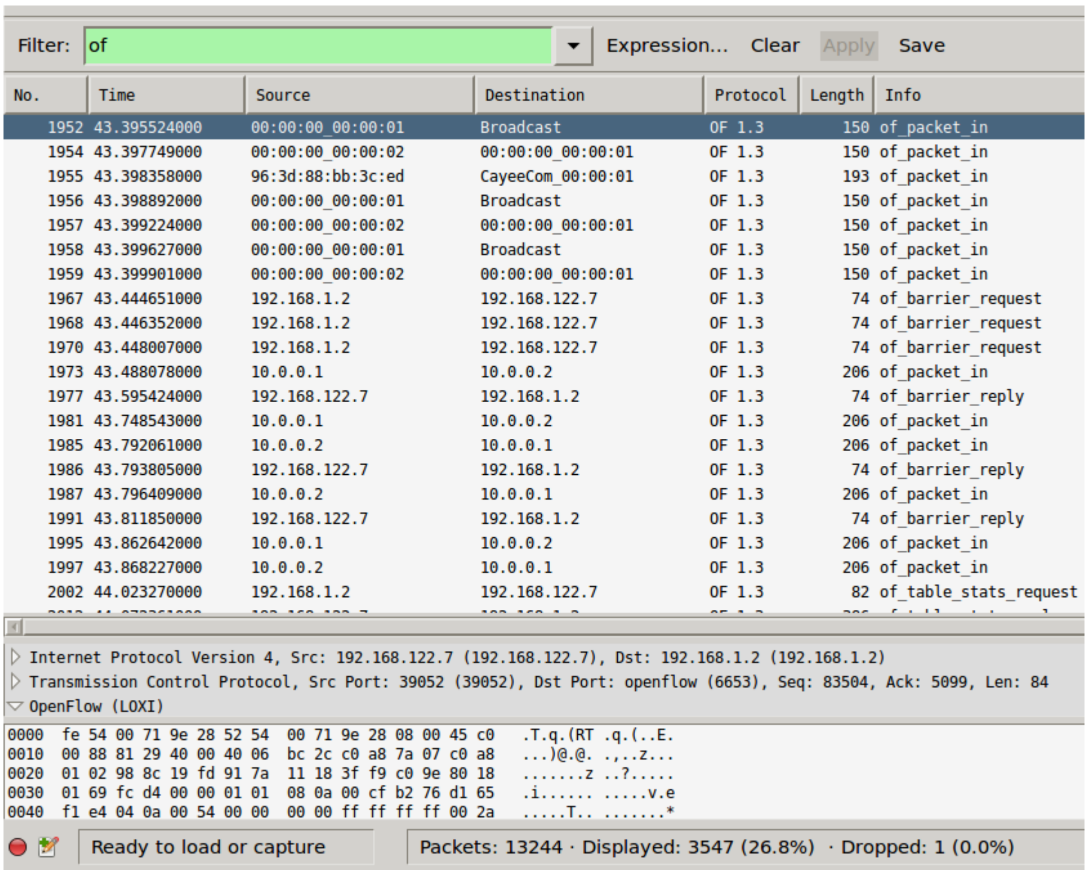
The explanation for this step is that the controller sends the ARP packet to every switches port. Each switch knows about the connected hosts to its ports, as a result h2 responses to the h1.

Then the response packet that comes contains for source the MAC address of the h2 and destination the h1.

However, the controller has no prior knowledge of these MAC addresses. As a result, a **flow_mod** packet is sent from the controller to the switch, in order to add a flow to its flow table. Then, the ICMP packets are send from h1 to h2. Since the flow tables are not empty, the ping continues without controller corporation. The next figure shows the steps of the host h1 and h2 connection.

The packets in lines 1952, 1956, 1958 describe how the packets are broadcasted, next, in line the 1957 verifies that the response comes from source address 00:00:00:00:00:02. After that the flow add packets is forwarded from ODL to switches. Finally, we see that the final packets exchanging is completed from IP address 10.0.0.1 to 10.0.0.2 and backward.

The l2-switch module that is install in ODL is responsible to handle the received packets from switches. As a result, when the controller receives the packets it forwards the packets to all ports.



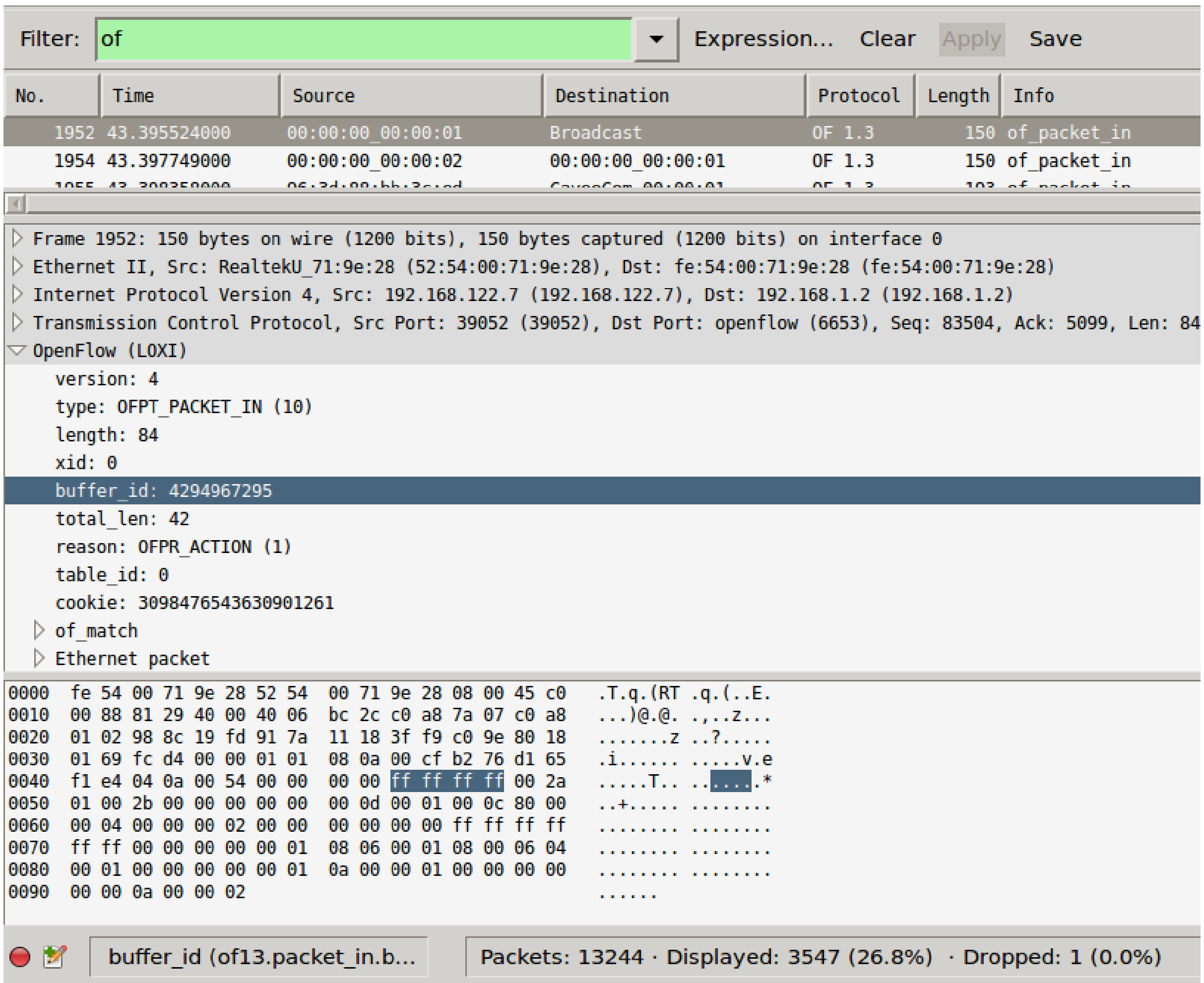
Filter: of | Expression... Clear Apply Save

No.	Time	Source	Destination	Protocol	Length	Info
1952	43.395524000	00:00:00_00:00:01	Broadcast	OF 1.3	150	of_packet_in
1954	43.397749000	00:00:00_00:00:02	00:00:00_00:00:01	OF 1.3	150	of_packet_in
1955	43.398358000	96:3d:88:bb:3c:ed	CayeeCom_00:00:01	OF 1.3	193	of_packet_in
1956	43.398892000	00:00:00_00:00:01	Broadcast	OF 1.3	150	of_packet_in
1957	43.399224000	00:00:00_00:00:02	00:00:00_00:00:01	OF 1.3	150	of_packet_in
1958	43.399627000	00:00:00_00:00:01	Broadcast	OF 1.3	150	of_packet_in
1959	43.399901000	00:00:00_00:00:02	00:00:00_00:00:01	OF 1.3	150	of_packet_in
1967	43.444651000	192.168.1.2	192.168.122.7	OF 1.3	74	of_barrier_request
1968	43.446352000	192.168.1.2	192.168.122.7	OF 1.3	74	of_barrier_request
1970	43.448007000	192.168.1.2	192.168.122.7	OF 1.3	74	of_barrier_request
1973	43.488078000	10.0.0.1	10.0.0.2	OF 1.3	206	of_packet_in
1977	43.595424000	192.168.122.7	192.168.1.2	OF 1.3	74	of_barrier_reply
1981	43.748543000	10.0.0.1	10.0.0.2	OF 1.3	206	of_packet_in
1985	43.792061000	10.0.0.2	10.0.0.1	OF 1.3	206	of_packet_in
1986	43.793805000	192.168.122.7	192.168.1.2	OF 1.3	74	of_barrier_reply
1987	43.796409000	10.0.0.2	10.0.0.1	OF 1.3	206	of_packet_in
1991	43.811850000	192.168.122.7	192.168.1.2	OF 1.3	74	of_barrier_reply
1995	43.862642000	10.0.0.1	10.0.0.2	OF 1.3	206	of_packet_in
1997	43.868227000	10.0.0.2	10.0.0.1	OF 1.3	206	of_packet_in
2002	44.023270000	192.168.1.2	192.168.122.7	OF 1.3	82	of_table_stats_request

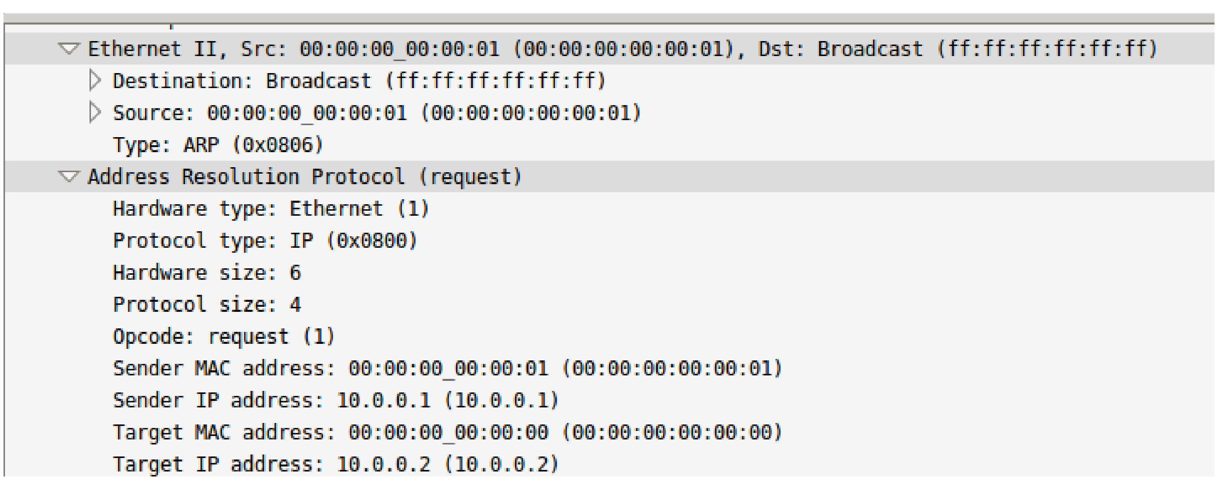
```
▷ Internet Protocol Version 4, Src: 192.168.122.7 (192.168.122.7), Dst: 192.168.1.2 (192.168.1.2)
▷ Transmission Control Protocol, Src Port: 39052 (39052), Dst Port: openflow (6653), Seq: 83504, Ack: 5099, Len: 84
▽ OpenFlow (LOXI)
0000  fe 54 00 71 9e 28 52 54  00 71 9e 28 08 00 45 c0   .T.q.(RT .q.(..E.
0010  00 88 81 29 40 00 40 06  bc 2c c0 a8 7a 07 c0 a8   ...)@.@. .,..z...
0020  01 02 98 8c 19 fd 91 7a  11 18 3f f9 c0 9e 80 18   .......z ..?.....
0030  01 69 fc d4 00 00 01 01  08 0a 00 cf b2 76 d1 65   .i...... .....v.e
0040  f1 e4 04 0a 00 54 00 00  00 00 ff ff ff ff 00 2a   .....T.. .......*
```

Ready to load or capture | Packets: 13244 · Displayed: 3547 (26.8%) · Dropped: 1 (0.0%)

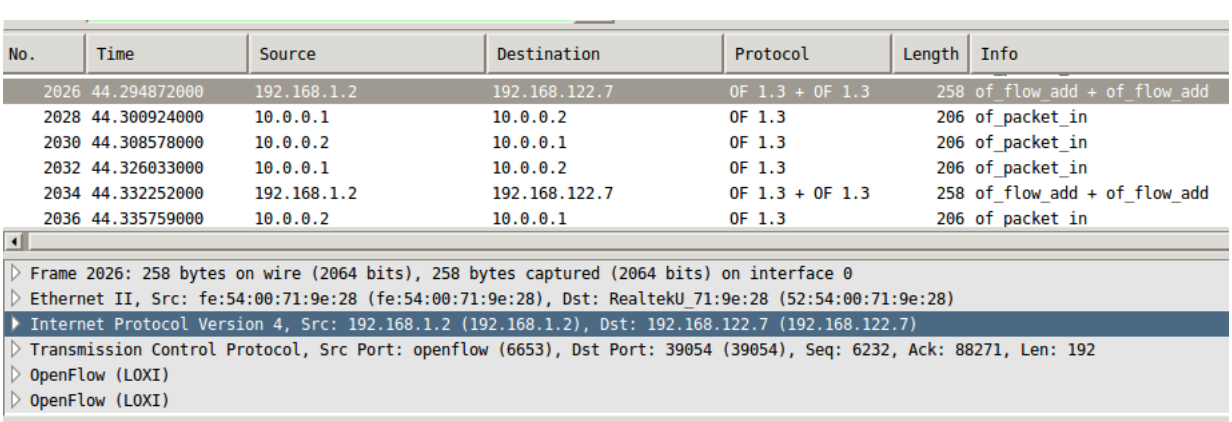
The ***of_packet_in*** contains: version, type, xid, buffer_id, total_len, reason, table_id, of_match, Ethernet packet. The most important field of the packet that is the Ethernet packet.



The figure bellow verifies that the of_packet_in packet Source MAC address is 00:00:00:00:00:01 and destination is the broadcast frame (ff:ff:ff:ff:ff:ff). In ARP part the Source IP address 10.0.01 and Destination IP address is 10.0.0.2.



The of_packet_in packet is broadcasted to OpenDaylight controller and since the l2switch module is installed it starts to take control of the of_packet_in packet. L2switch module also does not know where the target host h2 is located. The only information that is retrieved from l2switch is the source and target ip address along with MAC address when it reads the packet. So, it uses the ofpt_flow_mod packet of table with id 0 in order to clarify to switches how to broadcast the packet to all active ports.



The content of the OpenFlow ofpt_flow_mod packet is presented in the figured.

```
▽ OpenFlow (LOXI)
    version: 4
    type: OFPT_FLOW_MOD (14)
    length: 96
    xid: 8200
    cookie: 3026418949592973312
    cookie_mask: 0
    table_id: 0
    _command: 0
    idle_timeout: 600
    hard_timeout: 300
    priority: 10
    buffer_id: 4294967295
    out_port: 4294967295
    out_group: 4294967295
    flags: Unknown (0x00000000)
  ▽ of_match
      type: OFPMT_OXM (1)
      length: 24
    ▽ of_oxm list
      ▽ of_oxm_eth_dst
          type_len: 2147485190
          value: 00:00:00_00:00:02 (00:00:00:00:00:02)
      ▽ of_oxm_eth_src
          type_len: 2147485702
          value: 00:00:00_00:00:01 (00:00:00:00:00:01)
  ▽ of_instruction list
    ▽ of_instruction_apply_actions
        type: OFPIT_APPLY_ACTIONS (0x00000004)
        len: 24
      ▽ of_action list
        ▽ of_action_output
            type: OFPAT_OUTPUT (0)
            len: 16
            port: 1
            max_len: 65535
```

```
▽ OpenFlow (LOXI)
    version: 4
    type: OFPT_FLOW_MOD (14)
    length: 96
    xid: 8201
    cookie: 3026418949592973313
    cookie_mask: 0
    table_id: 0
    _command: 0
    idle_timeout: 600
    hard_timeout: 300
    priority: 10
    buffer_id: 4294967295
    out_port: 4294967295
    out_group: 4294967295
    flags: Unknown (0x00000000)
  ▽ of_match
      type: OFPMT_OXM (1)
      length: 24
    ▽ of_oxm list
      ▽ of_oxm_eth_dst
          type_len: 2147485190
          value: 00:00:00_00:00:01 (00:00:00:00:00:01)
      ▽ of_oxm_eth_src
          type_len: 2147485702
          value: 00:00:00_00:00:02 (00:00:00:00:00:02)
  ▽ of_instruction list
    ▽ of_instruction_apply_actions
        type: OFPIT_APPLY_ACTIONS (0x00000004)
        len: 24
      ▽ of_action list
        ▽ of_action_output
            type: OFPAT_OUTPUT (0)
            len: 16
            port: 2
            max_len: 65535
```

The flows above verify that there are two active ports, port 1 and port 2.

```
▽ OpenFlow (LOXI)
    version: 4
    type: OFPT_FLOW_MOD (14)
    length: 96
    xid: 7550
    cookie: 3026418949592973314
    cookie_mask: 0
    table_id: 0
    _command: 0
    idle_timeout: 600
    hard_timeout: 300
    priority: 10
    buffer_id: 4294967295
    out_port: 4294967295
    out_group: 4294967295
    flags: Unknown (0x00000000)
  ▽ of_match
      type: OFPMT_OXM (1)
      length: 24
    ▽ of_oxm list
      ▽ of_oxm_eth_dst
          type_len: 2147485190
          value: 00:00:00_00:00:02 (00:00:00:00:00:02)
      ▽ of_oxm_eth_src
          type_len: 2147485702
          value: 00:00:00_00:00:01 (00:00:00:00:00:01)
  ▽ of_instruction list
    ▽ of_instruction_apply_actions
        type: OFPIT_APPLY_ACTIONS (0x00000004)
        len: 24
      ▽ of_action list
        ▽ of_action_output
            type: OFPAT_OUTPUT (0)
            len: 16
            port: 2
            max_len: 65535
```

```
▽ OpenFlow (LOXI)
    version: 4
    type: OFPT_FLOW_MOD (14)
    length: 96
    xid: 7551
    cookie: 3026418949592973315
    cookie_mask: 0
    table_id: 0
    _command: 0
    idle_timeout: 600
    hard_timeout: 300
    priority: 10
    buffer_id: 4294967295
    out_port: 4294967295
    out_group: 4294967295
    flags: Unknown (0x00000000)
  ▽ of_match
      type: OFPMT_OXM (1)
      length: 24
    ▽ of_oxm list
      ▽ of_oxm_eth_dst
          type_len: 2147485190
          value: 00:00:00_00:00:01 (00:00:00:00:00:01)
      ▽ of_oxm_eth_src
          type_len: 2147485702
          value: 00:00:00_00:00:02 (00:00:00:00:00:02)
  ▽ of_instruction list
    ▽ of_instruction_apply_actions
        type: OFPIT_APPLY_ACTIONS (0x00000004)
        len: 24
      ▽ of_action list
        ▽ of_action_output
            type: OFPAT_OUTPUT (0)
            len: 16
            port: 1
            max_len: 65535
```

Verification through **dpctl dump-flows** command.

```
mininet> dump
<Host h1: h1-eth0:10.0.0.1 pid=2277>
<Host h2: h2-eth0:10.0.0.2 pid=2279>
<Host h3: h3-eth0:10.0.0.3 pid=2281>
<OVSSwitch{'protocols': 'OpenFlow13'} s1: lo:127.0.0.1,s1-eth1:None,s1-eth2:None pid=2286>
<OVSSwitch{'protocols': 'OpenFlow13'} s2: lo:127.0.0.1,s2-eth1:None,s2-eth2:None,s2-eth3:None pid=2289>
<OVSSwitch{'protocols': 'OpenFlow13'} s3: lo:127.0.0.1,s3-eth1:None,s3-eth2:None pid=2292>
<RemoteController{'ip': '192.168.1.2'} c0: 192.168.1.2:6653 pid=2271>
mininet>
```

```
mininet> dpctl dump-flows -O OpenFlow13
*** s1 ------------------------------------------------------------------------
OFPST_FLOW reply (OF1.3) (xid=0x2):
 cookie=0x2b00000000000000, duration=5199.639s, table=0, n_packets=58, n_bytes=5404, priority=2,in_port
=1 actions=output:2,CONTROLLER:65535
 cookie=0x2b00000000000001, duration=5199.639s, table=0, n_packets=58, n_bytes=5404, priority=2,in_port
=2 actions=output:1,CONTROLLER:65535
 cookie=0x2b00000000000000, duration=5203.547s, table=0, n_packets=1042, n_bytes=88570, priority=100,dl
_type=0x88cc actions=CONTROLLER:65535
 cookie=0x2a00000000000023, duration=235.317s, table=0, n_packets=247, n_bytes=23870, idle_timeout=600,
 hard_timeout=300, priority=10,dl_src=00:00:00:00:00:01,dl_dst=00:00:00:00:00:02 actions=output:2
 cookie=0x2a00000000000022, duration=235.317s, table=0, n_packets=247, n_bytes=23870, idle_timeout=600,
 hard_timeout=300, priority=10,dl_src=00:00:00:00:00:02,dl_dst=00:00:00:00:00:01 actions=output:1
 cookie=0x2b00000000000000, duration=5203.55s, table=0, n_packets=0, n_bytes=0, priority=0 actions=drop
*** s2 ------------------------------------------------------------------------
OFPST_FLOW reply (OF1.3) (xid=0x2):
 cookie=0x2b00000000000004, duration=5199.637s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=3 a
ctions=output:1,output:2,CONTROLLER:65535
 cookie=0x2b00000000000002, duration=5199.64s, table=0, n_packets=58, n_bytes=5404, priority=2,in_port=
1 actions=output:2,output:3,CONTROLLER:65535
 cookie=0x2b00000000000003, duration=5199.639s, table=0, n_packets=58, n_bytes=5404, priority=2,in_port
=2 actions=output:1,output:3,CONTROLLER:65535
 cookie=0x2b00000000000002, duration=5203.476s, table=0, n_packets=2082, n_bytes=176970, priority=100,d
l_type=0x88cc actions=CONTROLLER:65535
 cookie=0x2a0000000000001f, duration=235.333s, table=0, n_packets=247, n_bytes=23870, idle_timeout=600,
 hard_timeout=300, priority=10,dl_src=00:00:00:00:00:01,dl_dst=00:00:00:00:00:02 actions=output:1
 cookie=0x2a0000000000001e, duration=235.333s, table=0, n_packets=247, n_bytes=23870, idle_timeout=600,
 hard_timeout=300, priority=10,dl_src=00:00:00:00:00:02,dl_dst=00:00:00:00:00:01 actions=output:2
 cookie=0x2b00000000000002, duration=5203.484s, table=0, n_packets=0, n_bytes=0, priority=0 actions=dro
p
*** s3 ------------------------------------------------------------------------
OFPST_FLOW reply (OF1.3) (xid=0x2):
 cookie=0x2b00000000000005, duration=5199.635s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=1 a
ctions=output:2,CONTROLLER:65535
 cookie=0x2b00000000000006, duration=5199.634s, table=0, n_packets=108, n_bytes=10024, priority=2,in_po
rt=2 actions=output:1,CONTROLLER:65535
 cookie=0x2b00000000000001, duration=5203.552s, table=0, n_packets=1042, n_bytes=88570, priority=100,dl
_type=0x88cc actions=CONTROLLER:65535
 cookie=0x2b00000000000001, duration=5203.552s, table=0, n_packets=0, n_bytes=0, priority=0 actions=dro
```

After MAC addresses learning the packets are forwarded directly to the target ports.

Analyzing the **openflow:1** and **openflow:3** nodes of **table=0,** matching rules, action sets of each flow follows the OpenFlow protocol again after the ping command. New flows added to table=0 after L2 MAC address learning and the packets are forwarded to specific port instead of the first scenario where each packet was sent to controller.

http://192.168.56.101:8181/restconf/operational/opendaylight-inventory:nodes/node/openflow:1/table/0/


```
{
  "flow-node-inventory:table": [
    {
      "id": 0,
      "opendaylight-flow-table-statistics:flow-table-statistics": {
        "active-flows": 6,
        "packets-looked-up": 12086,
        "packets-matched": 12086
      },
      "flow": [
        {
          "id": "#UF$TABLE*0-3",
          "priority": 100,
          "opendaylight-flow-statistics:flow-statistics": {
            "packet-count": 842,
            "byte-count": 71570,
            "duration": {
              "nanosecond": 700000000,
              "second": 4201
            }
```

```
        },
        "table_id": 0,
        "cookie_mask": 0,
        "hard-timeout": 0,
        "match": {
          "ethernet-match": {
            "ethernet-type": {
              "type": 35020
            }
          }
        },
        "cookie": 3098476543630901000,
        "flags": "",
        "instructions": {
          "instruction": [
            {
              "order": 0,
              "apply-actions": {
                "action": [
                  {
                    "order": 0,
                    "output-action": {
                      "max-length": 65535,
                      "output-node-connector": "CONTROLLER"
                    }
                  }
                ]
              }
            }
          ]
        },
        "idle-timeout": 0
      },
      {
        "id": "#UF$TABLE*0-4",
        "priority": 2,
        "opendaylight-flow-statistics:flow-statistics": {
          "packet-count": 18,
          "byte-count": 1652,
          "duration": {
            "nanosecond": 792000000,
            "second": 4197
          }
        },
        "table_id": 0,
        "cookie_mask": 0,
        "hard-timeout": 0,
        "match": {
          "in-port": "1"
        },
        "cookie": 3098476543630901000,
        "flags": "",
        "instructions": {
          "instruction": [
            {
              "order": 0,
              "apply-actions": {
                "action": [
                  {
                    "order": 0,
                    "output-action": {
                      "max-length": 65535,
                      "output-node-connector": "2"
                    }
```

```
                    },
                    {
                        "order": 1,
                        "output-action": {
                            "max-length": 65535,
                            "output-node-connector": "CONTROLLER"
                        }
                    }
                ]
            }
        }
    ]
},
"idle-timeout": 0
},
{
    "id": "L2switch-0",
    "priority": 0,
    "opendaylight-flow-statistics:flow-statistics": {
        "packet-count": 0,
        "byte-count": 0,
        "duration": {
            "nanosecond": 703000000,
            "second": 4201
        }
    },
    "table_id": 0,
    "cookie_mask": 0,
    "hard-timeout": 0,
    "match": {},
    "cookie": 3098476543630901000,
    "flags": "",
    "idle-timeout": 0
},
{
    "id": "L2switch-11",
    "priority": 10,
    "opendaylight-flow-statistics:flow-statistics": {
        "packet-count": 174,
        "byte-count": 16772,
        "duration": {
            "nanosecond": 422000000,
            "second": 167
        }
    },
    "table_id": 0,
    "cookie_mask": 0,
    "hard-timeout": 300,
    "match": {
        "ethernet-match": {
            "ethernet-source": {
                "address": "00:00:00:00:00:01"
            },
            "ethernet-destination": {
                "address": "00:00:00:00:00:02"
            }
        }
    },
    "cookie": 3026418949592973300,
    "flags": "",
    "instructions": {
        "instruction": [
            {
                "order": 0,
```

```
            "apply-actions": {
              "action": [
                {
                  "order": 0,
                  "output-action": {
                    "max-length": 65535,
                    "output-node-connector": "2"
                  }
                }
              ]
            }
          }
        ]
      },
      "idle-timeout": 600
    },
    {
      "id": "L2switch-1",
      "priority": 2,
      "opendaylight-flow-statistics:flow-statistics": {
        "packet-count": 18,
        "byte-count": 1652,
        "duration": {
          "nanosecond": 792000000,
          "second": 4197
        }
      },
      "table_id": 0,
      "cookie_mask": 0,
      "hard-timeout": 0,
      "match": {
        "in-port": "2"
      },
      "cookie": 3098476543630901000,
      "flags": "",
      "instructions": {
        "instruction": [
          {
            "order": 0,
            "apply-actions": {
              "action": [
                {
                  "order": 0,
                  "output-action": {
                    "max-length": 65535,
                    "output-node-connector": "1"
                  }
                },
                {
                  "order": 1,
                  "output-action": {
                    "max-length": 65535,
                    "output-node-connector": "CONTROLLER"
                  }
                }
              ]
            }
          }
        ]
      },
      "idle-timeout": 0
    },
    {
      "id": "L2switch-10",
```

"priority": 10,
"opendaylight-flow-statistics:flow-statistics": {
"packet-count": 174,
"byte-count": 16772,
"duration": {
"nanosecond": 422000000,
"second": 167
}
},
"table_id": 0,
"cookie_mask": 0,
"hard-timeout": 300,
"match": {
"ethernet-match": {
"ethernet-source": {
"address": "00:00:00:00:00:02"
},
"ethernet-destination": {
"address": "00:00:00:00:00:01"
}
}
},
"cookie": 3026418949592973300,
"flags": "",
"instructions": {
"instruction": [
{
"order": 0,
"apply-actions": {
"action": [
{
"order": 0,
"output-action": {
"max-length": 65535,
"output-node-connector**": "1"**
}
}
]
}
}
]
},
"idle-timeout": 600
}
]
}
]
}

http://192.168.56.101:8181/restconf/operational/opendaylight-inventory:nodes/node/openflow:2/table/0/

{
"flow-node-inventory:table": [
{
"id": 0,
"opendaylight-flow-table-statistics:flow-table-statistics": {
"active-flows": 7,
"packets-looked-up": 12598,
"packets-matched": 12596
},
"flow": [
{

```
      "id": "#UF$TABLE*0-5",
      "priority": 2,
      "opendaylight-flow-statistics:flow-statistics": {
        "packet-count": 18,
        "byte-count": 1652,
        "duration": {
          "nanosecond": 641000000,
          "second": 4315
        }
      },
      "table_id": 0,
      "cookie_mask": 0,
      "hard-timeout": 0,
      "match": {
        "in-port": "1"
      },
      "cookie": 3098476543630901000,
      "flags": "",
      "instructions": {
        "instruction": [
          {
            "order": 0,
            "apply-actions": {
              "action": [
                {
                  "order": 0,
                  "output-action": {
                    "max-length": 65535,
                    "output-node-connector": "2"
                  }
                },
                {
                  "order": 1,
                  "output-action": {
                    "max-length": 65535,
                    "output-node-connector": "3"
                  }
                },
                {
                  "order": 2,
                  "output-action": {
                    "max-length": 65535,
                    "output-node-connector": "CONTROLLER"
                  }
                }
              ]
            }
          }
        ]
      },
      "idle-timeout": 0
    },
    {
      "id": "L2switch-6",
      "priority": 10,
      "opendaylight-flow-statistics:flow-statistics": {
        "packet-count": 296,
        "byte-count": 28504,
        "duration": {
          "nanosecond": 271000000,
          "second": 285
        }
      },
      "table_id": 0,
```

```
        "cookie_mask": 0,
        "hard-timeout": 300,
        "match": {
          "ethernet-match": {
            "ethernet-source": {
              "address": "00:00:00:00:00:02"
            },
            "ethernet-destination": {
              "address": "00:00:00:00:00:01"
            }
          }
        },
        "cookie": 3026418949592973300,
        "flags": "",
        "instructions": {
          "instruction": [
            {
              "order": 0,
              "apply-actions": {
                "action": [
                  {
                    "order": 0,
                    "output-action": {
                      "max-length": 65535,
                      "output-node-connector": "2"
                    }
                  }
                ]
              }
            }
          ]
        },
        "idle-timeout": 600
      },
      {
        "id": "L2switch-7",
        "priority": 10,
        "opendaylight-flow-statistics:flow-statistics": {
          "packet-count": 296,
          "byte-count": 28504,
          "duration": {
            "nanosecond": 271000000,
            "second": 285
          }
        },
        "table_id": 0,
        "cookie_mask": 0,
        "hard-timeout": 300,
        "match": {
          "ethernet-match": {
            "ethernet-source": {
              "address": "00:00:00:00:00:01"
            },
            "ethernet-destination": {
              "address": "00:00:00:00:00:02"
            }
          }
        },
        "cookie": 3026418949592973300,
        "flags": "",
        "instructions": {
          "instruction": [
            {
              "order": 0,
```

```
                "apply-actions": {
                  "action": [
                    {
                      "order": 0,
                      "output-action": {
                        "max-length": 65535,
                        "output-node-connector": "1"
                      }
                    }
                  ]
                }
              }
            ]
          },
          "idle-timeout": 600
        },
        {
          "id": "#UF$TABLE*0-2",
          "priority": 100,
          "opendaylight-flow-statistics:flow-statistics": {
            "packet-count": 1728,
            "byte-count": 146880,
            "duration": {
              "nanosecond": 477000000,
              "second": 4319
            }
          },
          "table_id": 0,
          "cookie_mask": 0,
          "hard-timeout": 0,
          "match": {
            "ethernet-match": {
              "ethernet-type": {
                "type": 35020
              }
            }
          },
          "cookie": 3098476543630901000,
          "flags": "",
          "instructions": {
            "instruction": [
              {
                "order": 0,
                "apply-actions": {
                  "action": [
                    {
                      "order": 0,
                      "output-action": {
                        "max-length": 65535,
                        "output-node-connector": "CONTROLLER"
                      }
                    }
                  ]
                }
              }
            ]
          },
          "idle-timeout": 0
        },
        {
          "id": "L2switch-2",
          "priority": 0,
          "opendaylight-flow-statistics:flow-statistics": {
            "packet-count": 0,
```

```
            "byte-count": 0,
            "duration": {
               "nanosecond": 485000000,
               "second": 4319
            }
         },
         "table_id": 0,
         "cookie_mask": 0,
         "hard-timeout": 0,
         "match": {},
         "cookie": 3098476543630901000,
         "flags": "",
         "idle-timeout": 0
      },
      {
         "id": "L2switch-3",
         "priority": 2,
         "opendaylight-flow-statistics:flow-statistics": {
            "packet-count": 18,
            "byte-count": 1652,
            "duration": {
               "nanosecond": 640000000,
               "second": 4315
            }
         },
         "table_id": 0,
         "cookie_mask": 0,
         "hard-timeout": 0,
         "match": {
            "in-port": "2"
         },
         "cookie": 3098476543630901000,
         "flags": "",
         "instructions": {
            "instruction": [
               {
                  "order": 0,
                  "apply-actions": {
                     "action": [
                        {
                           "order": 0,
                           "output-action": {
                              "max-length": 65535,
                              "output-node-connector": "1"
                           }
                        },
                        {
                           "order": 1,
                           "output-action": {
                              "max-length": 65535,
                              "output-node-connector": "3"
                           }
                        },
                        {
                           "order": 2,
                           "output-action": {
                              "max-length": 65535,
                              "output-node-connector": "CONTROLLER"
                           }
                        }
                     ]
                  }
               }
            ]
```

```
            },
            "idle-timeout": 0
          },
          {
            "id": "L2switch-4",
            "priority": 2,
            "opendaylight-flow-statistics:flow-statistics": {
              "packet-count": 0,
              "byte-count": 0,
              "duration": {
                "nanosecond": 638000000,
                "second": 4315
              }
            },
            "table_id": 0,
            "cookie_mask": 0,
            "hard-timeout": 0,
            "match": {
              "in-port": "3"
            },
            "cookie": 3098476543630901000,
            "flags": "",
            "instructions": {
              "instruction": [
                {
                  "order": 0,
                  "apply-actions": {
                    "action": [
                      {
                        "order": 0,
                        "output-action": {
                          "max-length": 65535,
                          "output-node-connector": "1"
                        }
                      },
                      {
                        "order": 1,
                        "output-action": {
                          "max-length": 65535,
                          "output-node-connector": "2"
                        }
                      },
                      {
                        "order": 2,
                        "output-action": {
                          "max-length": 65535,
                          "output-node-connector": "CONTROLLER"
                        }
                      }
                    ]
                  }
                }
              ]
            },
            "idle-timeout": 0
          }
        ]
      }
    ]
}
```

8 Host isolation with Virtual Tenant Network (VTN)

Virtual Tenant Network (VTN) is one of the key modules of ODL. It has many features, such as virtual routers and bridges. An OpenDaylight Plugin that interacts with other modules to implement the components of the VTN model. It also provides a REST interface to configure VTN components in OpenDaylight. VTN Manager is implemented as one plugin to the OpenDaylight. This provides a REST interface to create/update/delete VTN components [23]. will be used along with a custom network topology to create VLANs to set a lab for isolating host traffic between different VLANs.

VTN features overview:

- **odl-vtn-manager** provides VTN Manager's JAVA API. For creation of virtual bridges
- **odl-vtn-manager-rest** provides VTN Manager's REST API.

```
opendaylight-user@root>feature:install odl-vtn-manager odl-vtn-manager-rest
opendaylight-user@root>feature:list |  grep vtn
odl-vtn-manager-rest                           | 0.7.2            | x         | Started     | odl-vtn-
manager-rest                         | OpenDaylight :: VTN Manager :: REST API
odl-vtn-manager                                | 0.7.2            | x         | Started     | vtn-mana
ger-0.7.2                            | OpenDaylight :: VTN Manager :: Java API
features-vtn-manager                           | 0.7.2            |           | Uninstalled | features
-vtn-manager                         | features-vtn-manager
odl-vtn-manager-neutron                        | 0.7.2            |           | Uninstalled | odl-vtn-
manager-neutron                      | OpenDaylight :: VTN Manager :: Neutron Interface
opendaylight-user@root>
```

Following the previous step new Mininet VM and ODL controller are hosted in hypervisor. The IP address of the ODL controller is 192.168.56.101 and Mininet's VM IP address is 192.168.56.102 respectively.

```
sdn@sdn-opendaylight:~$ ifconfig
enp0s3    Link encap:Ethernet  HWaddr 08:00:27:f3:2a:7b
          inet addr:10.0.2.15  Bcast:10.0.2.255  Mask:255.255.255.0
          inet6 addr: fe80::3982:5697:585c:259a/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:1122450 errors:0 dropped:0 overruns:0 frame:0
          TX packets:403262 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:1090508082 (1.0 GB)  TX bytes:25336006 (25.3 MB)

enp0s8    Link encap:Ethernet  HWaddr 08:00:27:d1:47:dd
          inet addr:192.168.56.101  Bcast:192.168.56.255  Mask:255.255.255.0
          inet6 addr: fe80::8862:802d:5ece:411/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:14570 errors:0 dropped:0 overruns:0 frame:0
          TX packets:3412 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:5906832 (5.9 MB)  TX bytes:483264 (483.2 KB)

lo        Link encap:Local Loopback
          inet addr:127.0.0.1  Mask:255.0.0.0
          inet6 addr: ::1/128 Scope:Host
          UP LOOPBACK RUNNING  MTU:65536  Metric:1
          RX packets:4336 errors:0 dropped:0 overruns:0 frame:0
          TX packets:4336 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1
          RX bytes:6665958 (6.6 MB)  TX bytes:6665958 (6.6 MB)

sdn@sdn-opendaylight:~$
```

```
-rw-rw-r--  1 mininet mininet 21504 Mar 21  2017 util.py
-rw-r--r--  1 root    root    21872 Mar 21  2017 util.pyc
-rw-rw-r--  1 mininet mininet  2356 Sep 19 00:48 vlan.py
mininet@mininet-vm:~/mininet/mininet$
mininet@mininet-vm:~/mininet/mininet$
mininet@mininet-vm:~/mininet/mininet$
mininet@mininet-vm:~/mininet/mininet$
mininet@mininet-vm:~/mininet/mininet$ cd
mininet@mininet-vm:~$ ifocnfig
No command 'ifocnfig' found, did you mean:
 Command 'ifconfig' from package 'net-tools' (main)
ifocnfig: command not found
mininet@mininet-vm:~$ ifconfig
eth0      Link encap:Ethernet  HWaddr 08:00:27:53:75:d9
          inet addr:192.168.56.102  Bcast:192.168.56.255  Mask:255.255.255.0
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:9468 errors:0 dropped:0 overruns:0 frame:0
          TX packets:4480 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:2267336 (2.2 MB)  TX bytes:4957528 (4.9 MB)

lo        Link encap:Local Loopback
          inet addr:127.0.0.1  Mask:255.0.0.0
          UP LOOPBACK RUNNING  MTU:65536  Metric:1
          RX packets:4645 errors:0 dropped:0 overruns:0 frame:0
          TX packets:4645 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:2733100 (2.7 MB)  TX bytes:2733100 (2.7 MB)

mininet@mininet-vm:~$
```

A custom network topoly is created for this use case. VLANs are configured between the h1,h2,h2 with VLAN id =100 and VLAN id = 200 for h4,h5,h6.

```
#!/usr/bin/python

from mininet.node import Host, RemoteController
from mininet.topo import Topo
import apt

#package check Start
cache = apt.Cache()
if cache['vlan'].is_installed:
print "Vlan installed"
else:
print "ERROR:VLAN package not installed please run sudo apt-get install vlan"
exit(1)
#package check End

class VLANHost( Host ):
	def config( self, vlan=1, **params ):
	"""Configure VLANHost according to (optional) parameters:
	vlan: VLAN ID for default interface"""
	r = super( Host, self ).config( **params )
	intf = self.defaultIntf()
	# remove IP from default, "physical" interface
	self.cmd( 'ifconfig %s inet 0' % intf )
	# create VLAN interface
	self.cmd( 'vconfig add %s %d' % ( intf, vlan ) )
	# assign the host's IP to the VLAN interface
	self.cmd( 'ifconfig %s.%d inet %s' % ( intf, vlan, params['ip'] ) )
	# update the intf name and host's intf map
	newName = '%s.%d' % ( intf, vlan )
	# update the (Mininet) interface to refer to VLAN interface name
	intf.name = newName
	# add VLAN interface to host's name to intf map
	self.nameToIntf[ newName ] = intf
	return r

class MyTopo( Topo ):
"Simple topology example."
```

```
def __init__( self ):

"Create custom topo."

# Initialize topology

Topo.__init__( self )

# Add hosts and switches

host1=self.addHost( 'h1', cls=VLANHost, vlan=100)

host2=self.addHost( 'h2', cls=VLANHost, vlan=200)

host3=self.addHost( 'h3', cls=VLANHost, vlan=100)

host4=self.addHost( 'h4', cls=VLANHost, vlan=200)

host5=self.addHost( 'h5', cls=VLANHost, vlan=100)

host6=self.addHost( 'h6', cls=VLANHost, vlan=200)

s1 = self.addSwitch( 's1' )

s2 = self.addSwitch( 's2' )

s3 = self.addSwitch( 's3' )


self.addLink(s1,host1)

self.addLink(s1,host2)

self.addLink(s1,s2)

self.addLink(s2,host3)

self.addLink(s2,host4)

self.addLink(s2,s3)

self.addLink(s3,host5)

self.addLink(s3,host6)

topos = { 'simplevlan': ( lambda: MyTopo() ) }
```

```
sdn@sdn-opendaylight:~$ scp vlan.py mininet@192.168.56.102:~/mininet/mininet/
mininet@192.168.56.102's password:
vlan.py                                       100% 2229     2.2KB/s   00:00
sdn@sdn-opendaylight:~$
```

```
-rw-rw-r--  1 mininet mininet 60242 Mar 21  2017 node.py
-rw-r--r--  1 root    root    58065 Mar 21  2017 node.pyc
-rw-rw-r--  1 mininet mininet  2776 Mar 21  2017 term.py
-rw-r--r--  1 root    root     3140 Mar 21  2017 term.pyc
drwxrwxr-x  2 mininet mininet  4096 Mar 21  2017 test/
-rw-rw-r--  1 mininet mininet  2912 Mar 21  2017 topolib.py
-rw-rw-r--  1 mininet mininet 12536 Mar 21  2017 topo.py
-rw-rw-r--  1 mininet mininet 21504 Mar 21  2017 util.py
-rw-r--r--  1 root    root    21872 Mar 21  2017 util.pyc
-rw-rw-r--  1 mininet mininet  2356 Sep 19 00:48 vlan.py
mininet@mininet-vm:~/mininet/mininet$
```

Connection from ODL_VM to MININET VM to forward the X server

```
sdn@sdn-opendaylight:~$ ssh -X mininet@192.168.56.102
mininet@192.168.56.102's password:
Welcome to Ubuntu 14.04.4 LTS (GNU/Linux 4.2.0-27-generic i686)

 * Documentation:  https://help.ubuntu.com/
Last login: Fri Sep 20 22:56:47 2019
/usr/bin/xauth:  file /home/mininet/.Xauthority does not exist
mininet@mininet-vm:~$ ll
total 72
drwxr-xr-x 10 mininet mininet 4096 Sep 21 00:00 ./
drwxr-xr-x  3 root    root    4096 Aug  3  2016 ../
-rw-------  1 mininet mininet   56 Sep 21 00:00 .Xauthority
-rw-------  1 mininet mininet  408 Mar 21  2017 .bash_history
-rw-r--r--  1 mininet mininet  220 Aug  3  2016 .bash_logout
-rw-r--r--  1 mininet mininet 3655 Mar 21  2017 .bashrc
drwx------  2 mininet mininet 4096 Mar 21  2017 .cache/
-rw-rw-r--  1 mininet mininet   85 Mar 21  2017 .gitconfig
-rw-r--r--  1 mininet mininet  675 Aug  3  2016 .profile
-rw-------  1 root    root    1024 Mar 21  2017 .rnd
drwxrwxr-x  2 mininet mininet 4096 Mar 21  2017 .wireshark/
-rw-rw-r--  1 mininet mininet 1630 Mar 21  2017 install-mininet-vm.sh
drwxrwxr-x 17 mininet mininet 4096 Mar 21  2017 loxigen/
drwxrwxr-x 13 mininet mininet 4096 Mar 21  2017 mininet/
drwxrwxr-x 14 mininet mininet 4096 Mar 21  2017 oflops/
drwxrwxr-x 11 mininet mininet 4096 Mar 21  2017 oftest/
drwxrwxr-x 19 mininet mininet 4096 Mar 21  2017 openflow/
drwxrwxr-x  7 mininet mininet 4096 Mar 21  2017 pox/
mininet@mininet-vm:~$ cd
```

sudo mn --controller=remote,ip=192.168.56.101 --custom ~/mininet/mininet/vlan.py --topo simplevlan --mac --switch ovsk,protocols=Openflow13

```
mininet@mininet-vm:~$ sudo mn --controller=remote,ip=192.168.56.101 --custom ~/mininet/min
inet/vlan.py --topo simplevlan --mac --switch ovsk,protocols=OpenFlow13
Vlan installed
*** Creating network
*** Adding controller
Connecting to remote controller at 192.168.56.101:6653
*** Adding hosts:
h1 h2 h3 h4 h5 h6
*** Adding switches:
s1 s2 s3
*** Adding links:
(s1, h1) (s1, h2) (s1, s2) (s2, h3) (s2, h4) (s2, s3) (s3, h5) (s3, h6)
*** Configuring hosts
h1 h2 h3 h4 h5 h6
*** Starting controller
c0
*** Starting 3 switches
s1 s2 s3 ...
*** Starting CLI:
```

```
mininet> net
h1 h1-eth0.100:s1-eth1
h2 h2-eth0.200:s1-eth2
h3 h3-eth0.100:s2-eth2
h4 h4-eth0.200:s2-eth3
h5 h5-eth0.100:s3-eth2
h6 h6-eth0.200:s3-eth3
s1 lo:  s1-eth1:h1-eth0.100 s1-eth2:h2-eth0.200 s1-eth3:s2-eth1
s2 lo:  s2-eth1:s1-eth3 s2-eth2:h3-eth0.100 s2-eth3:h4-eth0.200 s2-eth4:s3-eth1
s3 lo:  s3-eth1:s2-eth4 s3-eth2:h5-eth0.100 s3-eth3:h6-eth0.200
c0
mininet> links
s1-eth1<->h1-eth0.100 (OK OK)
s1-eth2<->h2-eth0.200 (OK OK)
s1-eth3<->s2-eth1 (OK OK)
s2-eth2<->h3-eth0.100 (OK OK)
s2-eth3<->h4-eth0.200 (OK OK)
s2-eth4<->s3-eth1 (OK OK)
s3-eth2<->h5-eth0.100 (OK OK)
s3-eth3<->h6-eth0.200 (OK OK)
mininet> nodes
available nodes are:
c0 h1 h2 h3 h4 h5 h6 s1 s2 s3
mininet>
```

Using the mininet command "**dump**" verify that the switches send their packet only to the controller and ports that are directly connected to them.

```
p
mininet> dpctl dump-flows -O OpenFlow13
*** s1 ------------------------------------------------------------------------
OFPST_FLOW reply (OF1.3) (xid=0x2):
 cookie=0x2b00000000000007, duration=2220.909s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=3 a
ctions=output:2,output:1
 cookie=0x2b00000000000009, duration=2220.908s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=1 a
ctions=output:3,output:2,CONTROLLER:65535
 cookie=0x2b00000000000008, duration=2220.909s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=2 a
ctions=output:3,output:1,CONTROLLER:65535
 cookie=0x2b00000000000001, duration=2224.871s, table=0, n_packets=446, n_bytes=37910, priority=100,dl_
type=0x88cc actions=CONTROLLER:65535
 cookie=0x2b00000000000000, duration=2224.871s, table=0, n_packets=0, n_bytes=0, priority=0 actions=dro
p
*** s2 ------------------------------------------------------------------------
OFPST_FLOW reply (OF1.3) (xid=0x2):
 cookie=0x2b00000000000000, duration=2220.925s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=3 a
ctions=output:2,output:1,output:4,CONTROLLER:65535
 cookie=0x2b00000000000002, duration=2220.918s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=1 a
ctions=output:3,output:2,output:4
 cookie=0x2b00000000000003, duration=2220.916s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=4 a
ctions=output:3,output:2,output:1
 cookie=0x2b00000000000001, duration=2220.923s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=2 a
ctions=output:3,output:1,output:4,CONTROLLER:65535
 cookie=0x2b00000000000002, duration=2224.874s, table=0, n_packets=892, n_bytes=75820, priority=100,dl_
type=0x88cc actions=CONTROLLER:65535
 cookie=0x2b00000000000002, duration=2224.874s, table=0, n_packets=0, n_bytes=0, priority=0 actions=dro
p
*** s3 ------------------------------------------------------------------------
OFPST_FLOW reply (OF1.3) (xid=0x2):
 cookie=0x2b00000000000006, duration=2220.914s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=3 a
ctions=output:2,output:1,CONTROLLER:65535
 cookie=0x2b00000000000005, duration=2220.916s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=1 a
ctions=output:2,output:3
 cookie=0x2b00000000000004, duration=2220.917s, table=0, n_packets=0, n_bytes=0, priority=2,in_port=2 a
ctions=output:1,output:3,CONTROLLER:65535
 cookie=0x2b00000000000000, duration=2224.874s, table=0, n_packets=446, n_bytes=37910, priority=100,dl_
type=0x88cc actions=CONTROLLER:65535
 cookie=0x2b00000000000001, duration=2224.874s, table=0, n_packets=0, n_bytes=0, priority=0 actions=dro
p
mininet>
```

Setting up the VTN modules in OpenDaylight

opendaylight-user@root>feature:install odl-vtn-manager odl-vtn-manager-rest

ODL provides a HTTP based REST API in order to interact with the ODL. Since VTN features are loaded to ODL restconf API valid end-points are provided for the user to construct payload and send them to the controller. The high-lighted features of the VTN project will be used in order to isolate the network for the SDN environment.

vtn(2015-03-28)	Show/Hide | List Operations | Expand Operations | Raw
vtn-config(2015-02-09)	Show/Hide | List Operations | Expand Operations | Raw
vtn-flow(2015-04-10)	Show/Hide | List Operations | Expand Operations | Raw
vtn-flow-condition(2015-03-13)	Show/Hide | List Operations | Expand Operations | Raw
vtn-flow-filter(2015-09-07)	Show/Hide | List Operations | Expand Operations | Raw
vtn-flow-impl(2015-03-13)	Show/Hide | List Operations | Expand Operations | Raw
vtn-inventory(2015-02-09)	Show/Hide | List Operations | Expand Operations | Raw
vtn-mac-map(2015-09-07)	Show/Hide | List Operations | Expand Operations | Raw
vtn-mac-table(2015-09-07)	Show/Hide | List Operations | Expand Operations | Raw
vtn-mapping(2015-10-01)	Show/Hide | List Operations | Expand Operations | Raw
vtn-path-map(2015-03-28)	Show/Hide | List Operations | Expand Operations | Raw
vtn-path-policy(2015-02-09)	Show/Hide | List Operations | Expand Operations | Raw
vtn-port-map(2015-09-07)	Show/Hide | List Operations | Expand Operations | Raw
vtn-static-topology(2015-08-01)	Show/Hide | List Operations | Expand Operations | Raw
vtn-topology(2015-02-09)	Show/Hide | List Operations | Expand Operations | Raw
vtn-vbridge(2015-09-07)	Show/Hide | List Operations | Expand Operations | Raw
vtn-version(2015-09-01)	Show/Hide | List Operations | Expand Operations | Raw
vtn-vinterface(2015-09-07)	Show/Hide | List Operations | Expand Operations | Raw
vtn-vlan-map(2015-09-07)	Show/Hide | List Operations | Expand Operations | Raw
vtn-vterminal(2015-09-07)	Show/Hide | List Operations | Expand Operations | Raw

Navigating to the end-point the vtn nodes are modeled

http://192.168.56.101:8181/restconf/operational/vtn-inventory:vtn-nodes

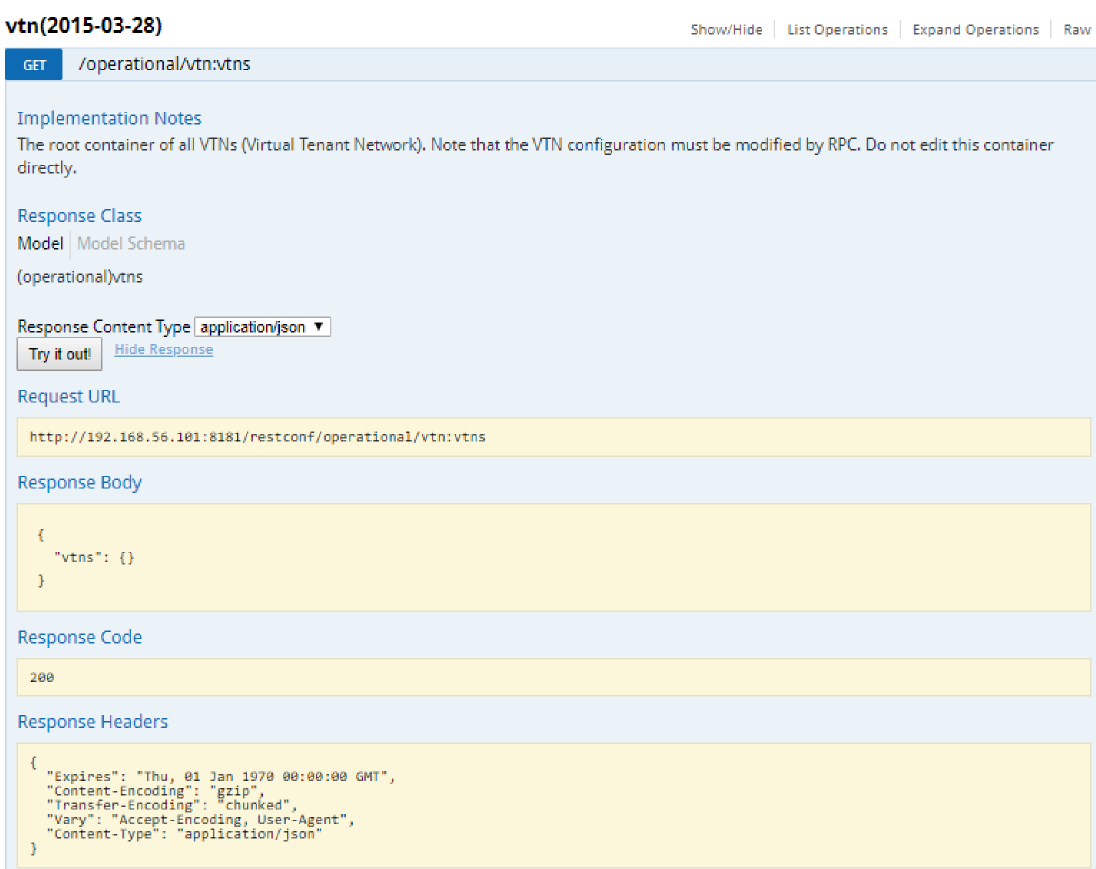
{
  "vtn-nodes":{

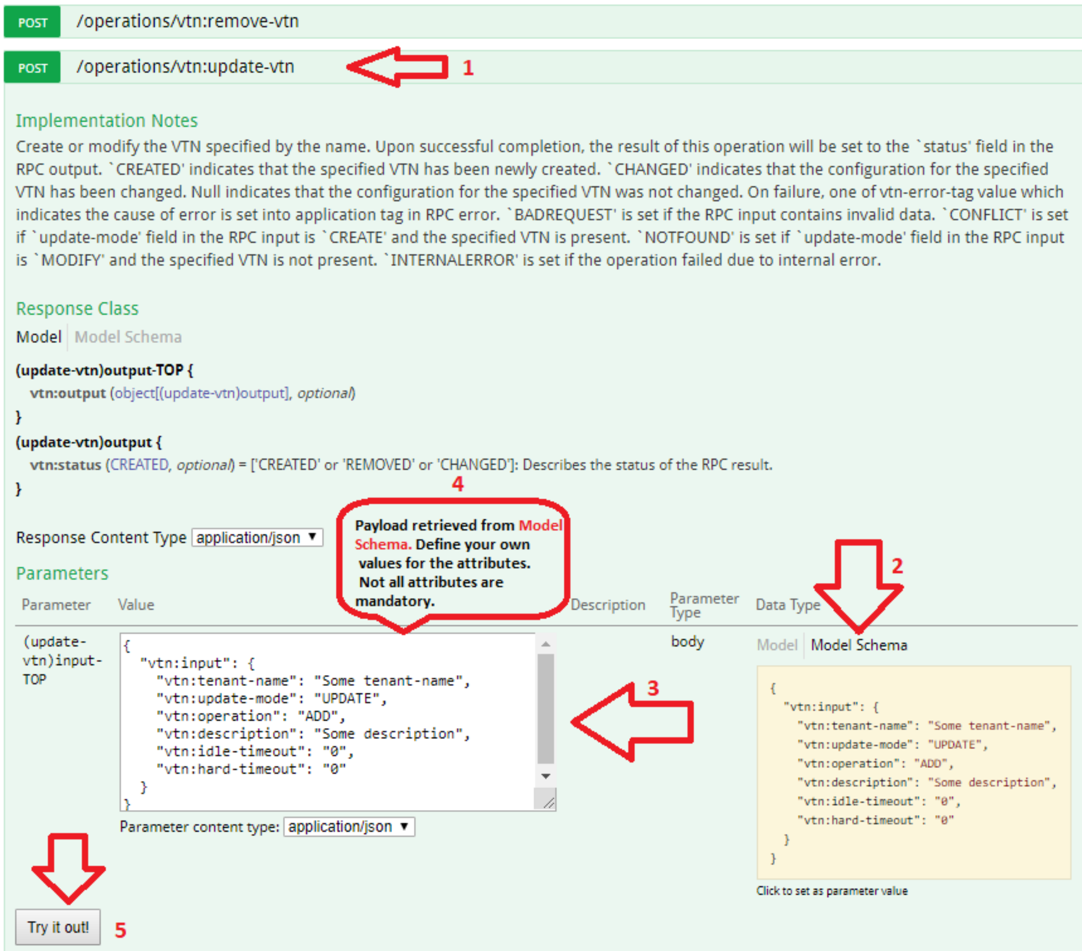
```
"vtn-node":[
  {
    "id":"openflow:3",
    "openflow-version":"OF13",
    "vtn-port":[
      {
        "id":"openflow:3:3",
        "cost":1000,
        "enabled":true,
        "name":"s3-eth3"
      },
      {
        "id":"openflow:3:2",
        "cost":1000,
        "enabled":true,
        "name":"s3-eth2"
      },
      {
        "id":"openflow:3:1",
        "cost":1000,
        "enabled":true,
        "name":"s3-eth1",
        "port-link":[
          {
            "link-id":"openflow:2:4",
            "peer":"openflow:2:4"
          },
          {
            "link-id":"openflow:3:1",
            "peer":"openflow:2:4"
          }
        ]
      }
    ]
  },
  {
    "id":"openflow:2",
    "openflow-version":"OF13",
    "vtn-port":[
      {
        "id":"openflow:2:4",
        "cost":1000,
        "enabled":true,
        "name":"s2-eth4",
        "port-link":[
          {
            "link-id":"openflow:2:4",
            "peer":"openflow:3:1"
          },
          {
            "link-id":"openflow:3:1",
            "peer":"openflow:3:1"
          }
        ]
```

```
    },
    {
      "id":"openflow:2:3",
      "cost":1000,
      "enabled":true,
      "name":"s2-eth3"
    },
    {
      "id":"openflow:2:2",
      "cost":1000,
      "enabled":true,
      "name":"s2-eth2"
    },
    {
      "id":"openflow:2:1",
      "cost":1000,
      "enabled":true,
      "name":"s2-eth1",
      "port-link":[
        {
          "link-id":"openflow:2:1",
          "peer":"openflow:1:3"
        },
        {
          "link-id":"openflow:1:3",
          "peer":"openflow:1:3"
        }
      ]
    }
  ]
},
{
  "id":"openflow:1",
  "openflow-version":"OF13",
  "vtn-port":[
    {
      "id":"openflow:1:3",
      "cost":1000,
      "enabled":true,
      "name":"s1-eth3",
      "port-link":[
        {
          "link-id":"openflow:2:1",
          "peer":"openflow:2:1"
        },
        {
          "link-id":"openflow:1:3",
          "peer":"openflow:2:1"
        }
      ]
    },
    {
      "id":"openflow:1:2",
      "cost":1000,
```

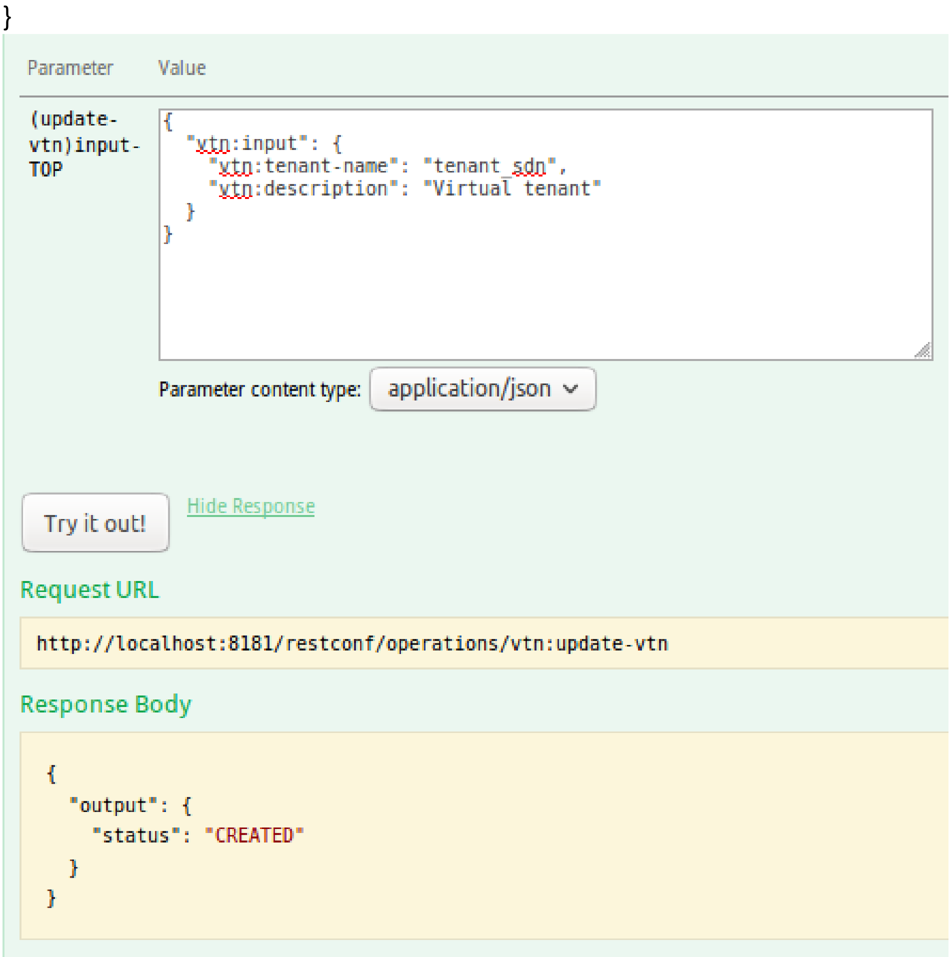
```
            "enabled":true,
            "name":"s1-eth2"
          },
          {
            "id":"openflow:1:1",
            "cost":1000,
            "enabled":true,
            "name":"s1-eth1"
          }
        ]
      }
    ]
  }
}
```


Using the Rest API to create a virtual tenant, virtual bridge and VLAN mapping



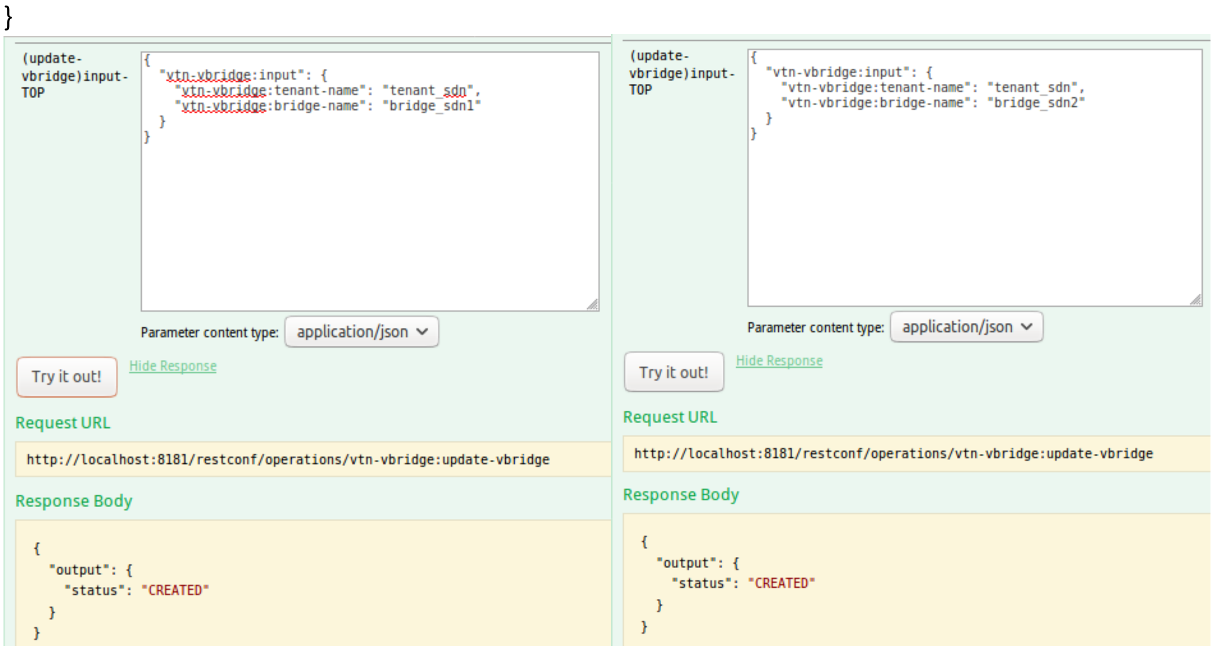



```
{
  "vtn:input": {
    "vtn:tenant-name": "tenant_sdn",
    "vtn:description": "Virtual tenant"
  }
}
```



Creating virtuall bridges bridge_sdn1 bridge_sdn2

```
{
  "vtn-vbridge:input": {
    "vtn-vbridge:tenant-name": "tenant_sdn",
    "vtn-vbridge:bridge-name": "bridge_sdn1"
  }
}
```

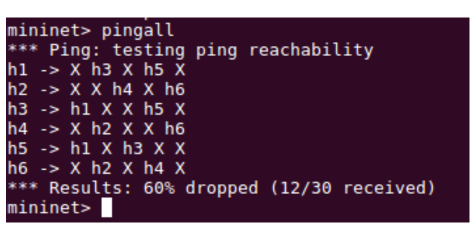


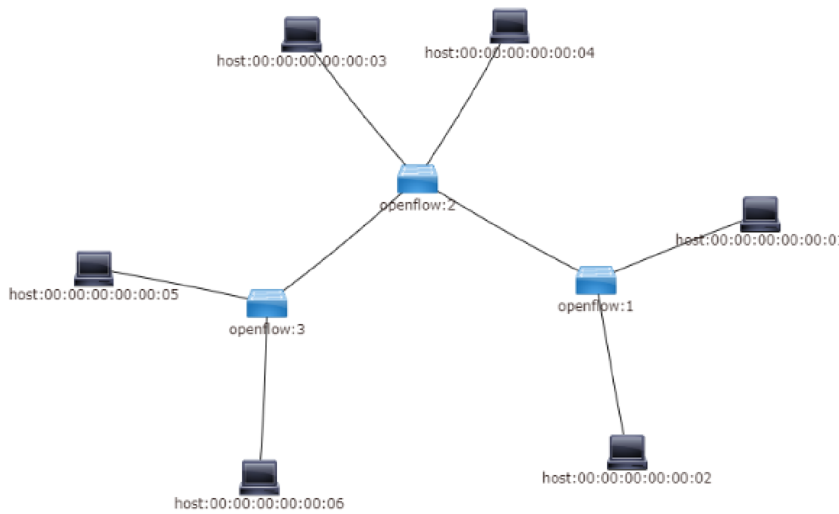
Mapping VLAN-id 100 to bridge_sdn1 and VLAN- id 200 to bridge_sdn2 respectively.

```
{
  "vtn-vlan-map:input": {
    "vtn-vlan-map:tenant-name": "tenant_sdn",
    "vtn-vlan-map:bridge-name": "bridge_sdn1",
    "vtn-vlan-map:vlan-id": "100"
  }
}
```

After mapping the new status of the network.

Sending traffic via “**pingall**” commad which generates traffic between hosts, MAC address learning process is triggered between them.





Using the “**dump**” command network isolation is achieved packets are broadcasted to only valid hosts.

Swich s1 flows:

```
*** s1 ------------------------------------------------------------------------
OFPST_FLOW reply (OF1.3) (xid=0x2):
 cookie=0x7f56000000000004, duration=144.839s, table=0, n_packets=2, n_bytes=148, idle_tim
eout=300, send_flow_rem priority=10,in_port=1,dl_vlan=100,dl_src=00:00:00:00:00:01,dl_dst=
00:00:00:00:00:05 actions=output:3
 cookie=0x7f56000000000006, duration=135.857s, table=0, n_packets=2, n_bytes=148, idle_tim
eout=300, send_flow_rem priority=10,in_port=2,dl_vlan=200,dl_src=00:00:00:00:00:02,dl_dst=
00:00:00:00:00:04 actions=output:3
 cookie=0x7f56000000000005, duration=135.883s, table=0, n_packets=4, n_bytes=296, send_flo
w_rem priority=10,in_port=3,dl_vlan=200,dl_src=00:00:00:00:00:04,dl_dst=00:00:00:00:00:02
actions=output:2
 cookie=0x7f56000000000008, duration=132.84s, table=0, n_packets=2, n_bytes=148, idle_time
out=300, send_flow_rem priority=10,in_port=2,dl_vlan=200,dl_src=00:00:00:00:00:02,dl_dst=0
0:00:00:00:00:06 actions=output:3
 cookie=0x7f56000000000001, duration=147.607s, table=0, n_packets=4, n_bytes=296, send_flo
w_rem priority=10,in_port=3,dl_vlan=100,dl_src=00:00:00:00:00:03,dl_dst=00:00:00:00:00:01
actions=output:1
 cookie=0x7f56000000000002, duration=147.603s, table=0, n_packets=2, n_bytes=148, idle_tim
eout=300, send_flow_rem priority=10,in_port=1,dl_vlan=100,dl_src=00:00:00:00:00:01,dl_dst=
00:00:00:00:00:03 actions=output:3
 cookie=0x7f56000000000003, duration=144.873s, table=0, n_packets=4, n_bytes=296, send_flo
w_rem priority=10,in_port=3,dl_vlan=100,dl_src=00:00:00:00:00:05,dl_dst=00:00:00:00:00:01
actions=output:1
 cookie=0x7f56000000000007, duration=132.872s, table=0, n_packets=4, n_bytes=296, send_flo
w_rem priority=10,in_port=3,dl_vlan=200,dl_src=00:00:00:00:00:06,dl_dst=00:00:00:00:00:02
actions=output:2
 cookie=0x2b0000000000001b, duration=702.487s, table=0, n_packets=52, n_bytes=2840, priori
ty=2,in_port=3 actions=output:2,output:1
 cookie=0x2b0000000000001d, duration=702.485s, table=0, n_packets=17, n_bytes=894, priorit
y=2,in_port=1 actions=output:3,output:2,CONTROLLER:65535
 cookie=0x2b0000000000001c, duration=702.486s, table=0, n_packets=13, n_bytes=710, priorit
y=2,in_port=2 actions=output:3,output:1,CONTROLLER:65535
 cookie=0x2b00000000000007, duration=708.358s, table=0, n_packets=946, n_bytes=80410, prio
rity=100,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x7f57ffffffffffff, duration=708.354s, table=0, n_packets=0, n_bytes=0, send_flow_
rem priority=0 actions=CONTROLLER:65535
```

Swich s2 flows:

```
OFPST_FLOW reply (OF1.3) (xid=0x2):
 cookie=0x7f56000000000004, duration=144.842s, table=0, n_packets=2, n_bytes=148, send_flow_rem priorit
y=10,in_port=1,dl_vlan=100,dl_src=00:00:00:00:00:01,dl_dst=00:00:00:00:00:05 actions=output:4
 cookie=0x7f56000000000006, duration=135.86s, table=0, n_packets=2, n_bytes=148, send_flow_rem priority
=10,in_port=1,dl_vlan=200,dl_src=00:00:00:00:00:02,dl_dst=00:00:00:00:00:04 actions=output:3
 cookie=0x7f56000000000003, duration=144.875s, table=0, n_packets=4, n_bytes=296, send_flow_rem priorit
y=10,in_port=4,dl_vlan=100,dl_src=00:00:00:00:00:05,dl_dst=00:00:00:00:00:01 actions=output:1
 cookie=0x7f5600000000000a, duration=126.843s, table=0, n_packets=2, n_bytes=148, idle_timeout=300, sen
d_flow_rem priority=10,in_port=2,dl_vlan=100,dl_src=00:00:00:00:00:03,dl_dst=00:00:00:00:00:05 actions=
output:4
 cookie=0x7f56000000000001, duration=147.608s, table=0, n_packets=4, n_bytes=296, idle_timeout=300, sen
d_flow_rem priority=10,in_port=2,dl_vlan=100,dl_src=00:00:00:00:00:03,dl_dst=00:00:00:00:00:01 actions=
output:1
 cookie=0x7f56000000000005, duration=135.884s, table=0, n_packets=4, n_bytes=296, idle_timeout=300, sen
d_flow_rem priority=10,in_port=3,dl_vlan=200,dl_src=00:00:00:00:00:04,dl_dst=00:00:00:00:00:02 actions=
output:1
 cookie=0x7f56000000000007, duration=132.874s, table=0, n_packets=4, n_bytes=296, send_flow_rem priorit
y=10,in_port=4,dl_vlan=200,dl_src=00:00:00:00:00:06,dl_dst=00:00:00:00:00:02 actions=output:1
 cookie=0x7f5600000000000b, duration=114.889s, table=0, n_packets=4, n_bytes=296, send_flow_rem priorit
y=10,in_port=4,dl_vlan=200,dl_src=00:00:00:00:00:06,dl_dst=00:00:00:00:00:04 actions=output:3
 cookie=0x7f56000000000009, duration=126.881s, table=0, n_packets=4, n_bytes=296, send_flow_rem priorit
y=10,in_port=4,dl_vlan=100,dl_src=00:00:00:00:00:05,dl_dst=00:00:00:00:00:03 actions=output:2
 cookie=0x7f56000000000008, duration=132.842s, table=0, n_packets=2, n_bytes=148, send_flow_rem priorit
y=10,in_port=1,dl_vlan=200,dl_src=00:00:00:00:00:02,dl_dst=00:00:00:00:00:06 actions=output:4
 cookie=0x7f56000000000002, duration=147.607s, table=0, n_packets=2, n_bytes=148, send_flow_rem priorit
y=10,in_port=1,dl_vlan=100,dl_src=00:00:00:00:00:01,dl_dst=00:00:00:00:00:03 actions=output:2
 cookie=0x7f5600000000000c, duration=114.841s, table=0, n_packets=2, n_bytes=148, idle_timeout=300, sen
d_flow_rem priority=10,in_port=3,dl_vlan=200,dl_src=00:00:00:00:00:04,dl_dst=00:00:00:00:00:06 actions=
output:4
 cookie=0x2b00000000000014, duration=702.5s, table=0, n_packets=13, n_bytes=710, priority=2,in_port=3 a
ctions=output:2,output:1,output:4,CONTROLLER:65535
 cookie=0x2b00000000000016, duration=702.499s, table=0, n_packets=26, n_bytes=1420, priority=2,in_port=
1 actions=output:3,output:2,output:4
 cookie=0x2b00000000000017, duration=702.494s, table=0, n_packets=26, n_bytes=1420, priority=2,in_port=
4 actions=output:3,output:2,output:1
 cookie=0x2b00000000000015, duration=702.5s, table=0, n_packets=15, n_bytes=858, priority=2,in_port=2 a
ctions=output:3,output:1,output:4,CONTROLLER:65535
 cookie=0x2b00000000000008, duration=708.284s, table=0, n_packets=1892, n_bytes=160820, priority=100,dl
_type=0x88cc actions=CONTROLLER:65535
 cookie=0x7f57ffffffffffff, duration=708.259s, table=0, n_packets=0, n_bytes=0, send_flow_rem priority=
0 actions=CONTROLLER:65535
```

Swich s3 flows:

```
*** s3 ------------------------------------------------------------------------
OFPST_FLOW reply (OF1.3) (xid=0x2):
 cookie=0x7f56000000000004, duration=144.844s, table=0, n_packets=2, n_bytes=148, send_flo
w_rem priority=10,in_port=1,dl_vlan=100,dl_src=00:00:00:00:00:01,dl_dst=00:00:00:00:00:05
actions=output:2
 cookie=0x7f56000000000009, duration=126.882s, table=0, n_packets=4, n_bytes=296, idle_tim
eout=300, send_flow_rem priority=10,in_port=2,dl_vlan=100,dl_src=00:00:00:00:00:05,dl_dst=
00:00:00:00:00:03 actions=output:1
 cookie=0x7f5600000000000b, duration=114.891s, table=0, n_packets=4, n_bytes=296, idle_tim
eout=300, send_flow_rem priority=10,in_port=3,dl_vlan=200,dl_src=00:00:00:00:00:06,dl_dst=
00:00:00:00:00:04 actions=output:1
 cookie=0x7f56000000000003, duration=144.876s, table=0, n_packets=4, n_bytes=296, idle_tim
eout=300, send_flow_rem priority=10,in_port=2,dl_vlan=100,dl_src=00:00:00:00:00:05,dl_dst=
00:00:00:00:00:01 actions=output:1
 cookie=0x7f56000000000008, duration=132.844s, table=0, n_packets=2, n_bytes=148, send_flo
w_rem priority=10,in_port=1,dl_vlan=200,dl_src=00:00:00:00:00:02,dl_dst=00:00:00:00:00:06
actions=output:3
 cookie=0x7f5600000000000a, duration=126.846s, table=0, n_packets=2, n_bytes=148, send_flo
w_rem priority=10,in_port=1,dl_vlan=100,dl_src=00:00:00:00:00:03,dl_dst=00:00:00:00:00:05
actions=output:2
 cookie=0x7f5600000000000c, duration=114.843s, table=0, n_packets=2, n_bytes=148, send_flo
w_rem priority=10,in_port=1,dl_vlan=200,dl_src=00:00:00:00:00:04,dl_dst=00:00:00:00:00:06
actions=output:3
 cookie=0x7f56000000000007, duration=132.871s, table=0, n_packets=4, n_bytes=296, idle_tim
eout=300, send_flow_rem priority=10,in_port=3,dl_vlan=200,dl_src=00:00:00:00:00:06,dl_dst=
00:00:00:00:00:02 actions=output:1
 cookie=0x2b0000000000001a, duration=702.493s, table=0, n_packets=13, n_bytes=710, priorit
y=2,in_port=3 actions=output:2,output:1,CONTROLLER:65535
 cookie=0x2b00000000000019, duration=702.495s, table=0, n_packets=54, n_bytes=2988, priori
ty=2,in_port=1 actions=output:2,output:3
 cookie=0x2b00000000000018, duration=702.496s, table=0, n_packets=13, n_bytes=710, priorit
y=2,in_port=2 actions=output:1,output:3,CONTROLLER:65535
 cookie=0x2b00000000000006, duration=708.519s, table=0, n_packets=946, n_bytes=80410, prio
rity=100,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x2b00000000000006, duration=708.489s, table=0, n_packets=0, n_bytes=0, priority=0
 actions=drop
mininet>
```

9 AAA (Authentication-Authorization, Accounting)

The AAA project provides authentication, authorization and accounting. This service is based on the **Apache Shiro** Java Security Framework. AAA plugin utilizes the **Shiro Realms** to support this service. Authentication verifies users who are granted access to the system resources. This function is achieved while providing valid credentials (user name and password). ODL controller's default user is the administrator. However, this service allows to create other users who also will have access the system. Authorization comes exactly after the authentication and specifies what an authenticated user can do in the system, in other words set user's permissions. Accounting is the process that keep records of the authenticated user in system.

The AAA service is easily configured by manipulating the realms. There are two methods to achieve this:

- Utilizing the idmtool configuration tool used in order to perform basic user management operations, allows to list, add, delete, change password, delete roles and add roles, and assignes to the users.
- Utilizing the odl-aaa-shiro feature from REST API
- Utilizing the odl-aaa-cli (command line interface) of karaf console

If the second option is selected in order to make any configuration, the odl-aa-shiro feature must be installed before ***restconf*** API. The main configuration file for AAA is located at "***etc/shiro.ini***" relative to the ODL Karaf home directory.

ODL provides the "**admin**" user, who is permitted to do any operation in the ODL controller this chapter will present how to create a user with specific permissions.

The next figure verifies the existing "**admin"** user in ODL using the **curl** command.

```
sdn@sdn-opendaylight:~$ curl -u admin:admin http://localhost:8181/auth/v1/users
{"users":[{"userid":"admin@sdn","name":"admin","description":"admin user","enabled":1,"ema
il":"","password":"**********","salt":"**********","domainid":"sdn"}]}sdn@sdn-opendaylight
:~$
```

Next, custom user configuration will be presented. In order to proceed CRUD operation on ODL users some additional tools will be used:

- **Firefox** web browser
- **Curl** command

The above tools are not mandatory, there are also alternatives for example, Chrome web browser could be used with Postman REST API client or a curl command instead. Also, the DLUX module will be installed for testing the applied configuration on users.

Installing AAA features executing the command **opendaylight-user@root>feature:install features-aaa**

```
opendaylight-user@root>feature:install features-aaa
```

```
opendaylight-user@root>feature:list | grep aaa
odl-aaa-netconf-plugin-no-cluster                 | 1.4.4            |          | Uninstalled | odl-aaa-
netconf-plugin-no-cluster             | OpenDaylight :: AAA :: ODL NETCONF Plugin - NO CL
odl-aaa-cert                                      | 0.7.4            |          | Started     | odl-aaa-
0.7.4                                 | ODL :: aaa :: odl-aaa-cert
features-aaa                                      | 0.7.4            | x        | Started     | features
-aaa                                  | ODL :: aaa :: features-aaa
odl-aaa-jersey-1                                  | 0.7.4            |          | Started     | odl-aaa-
jersey-1                              | ODL :: aaa :: odl-aaa-jersey-1
odl-aaa-netconf-plugin                            | 1.4.4            |          | Uninstalled | odl-aaa-
netconf-plugin                        | OpenDaylight :: AAA :: ODL NETCONF Plugin
odl-aaa-encryption-service                        | 0.7.4            |          | Started     | odl-aaa-
0.7.4                                 | ODL :: aaa :: odl-aaa-encryption-service
odl-aaa-api                                       | 0.7.4            |          | Started     | odl-aaa-
api                                   | ODL :: aaa :: odl-aaa-api
odl-aaa-cli                                       | 0.7.4            |          | Started     | odl-aaa-
cli                                   | ODL :: aaa :: odl-aaa-cli
odl-aaa-shiro                                     | 0.7.4            |          | Started     | odl-aaa-
0.7.4                                 | ODL :: aaa :: odl-aaa-shiro
```

Before starting, the existence of the only user (admin) is verified by the next figure.

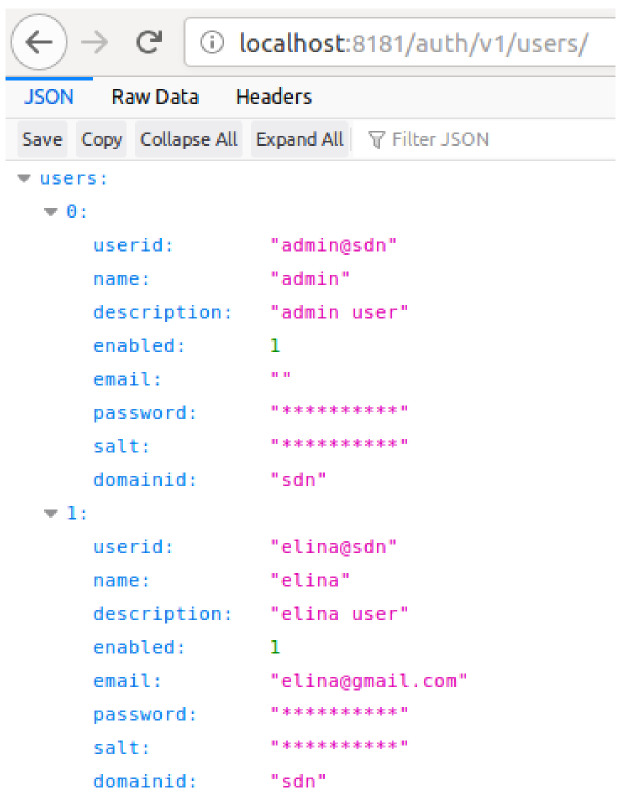
```
sdn@sdn-opendaylight:~$ curl -u admin:admin http://localhost:8181/auth/v1/users
{"users":[{"userid":"admin@sdn","name":"admin","description":"admin user","enabled":1,"ema
il":"","password":"**********","salt":"**********","domainid":"sdn"}]}sdn@sdn-opendaylight
:~$
```

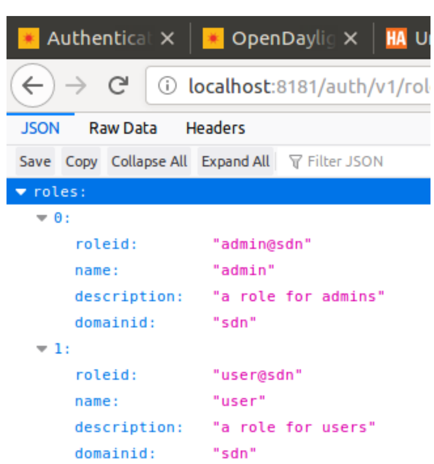
Now the creation of a new user "elina" will take place using the curl command.

JSON file payload models the data required to create the custom user.

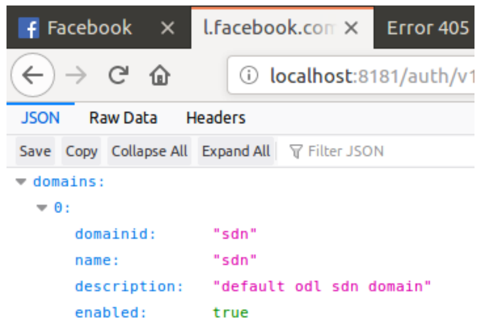
Sending the payload to the control via HTTP POST

The endpoint URL that configures the users is http://localhost:8181/auth/v1/users. User "elina" is created.



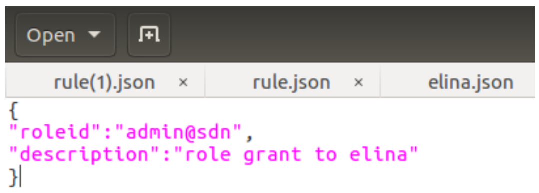


There is only one domain the default "sdn".

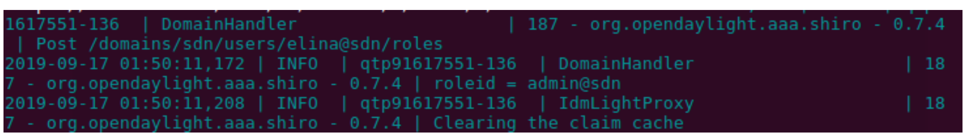


In order to enable the user “elina” to have access grand a role will be needed.

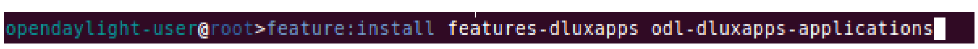
opendaylight-user@root>feature:install features-dluxapps odl-dluxapps-applications

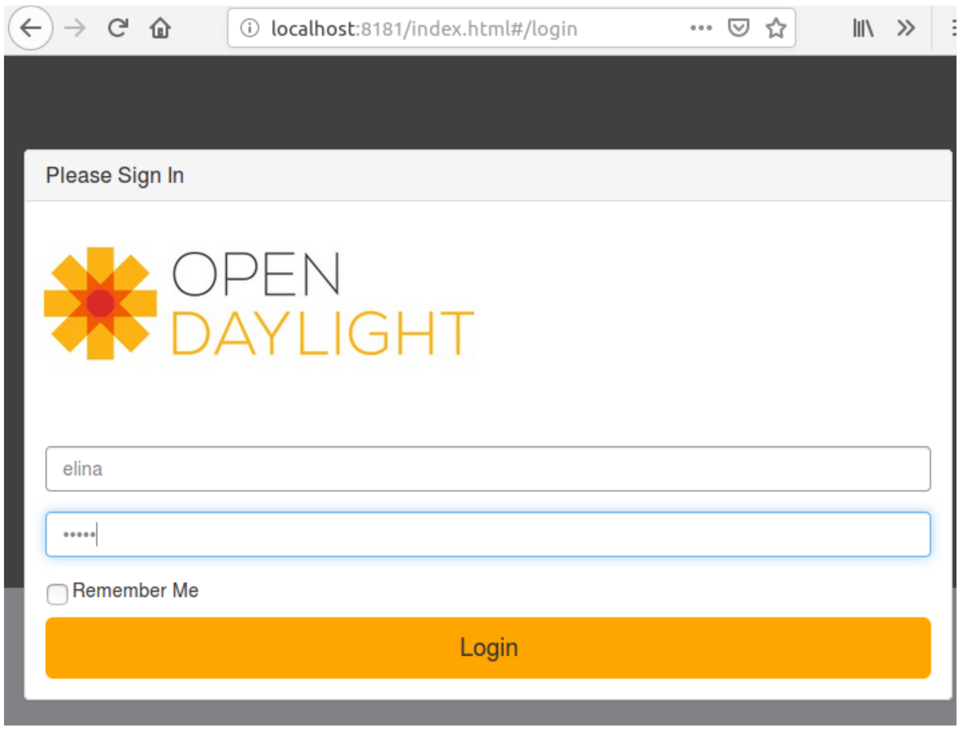


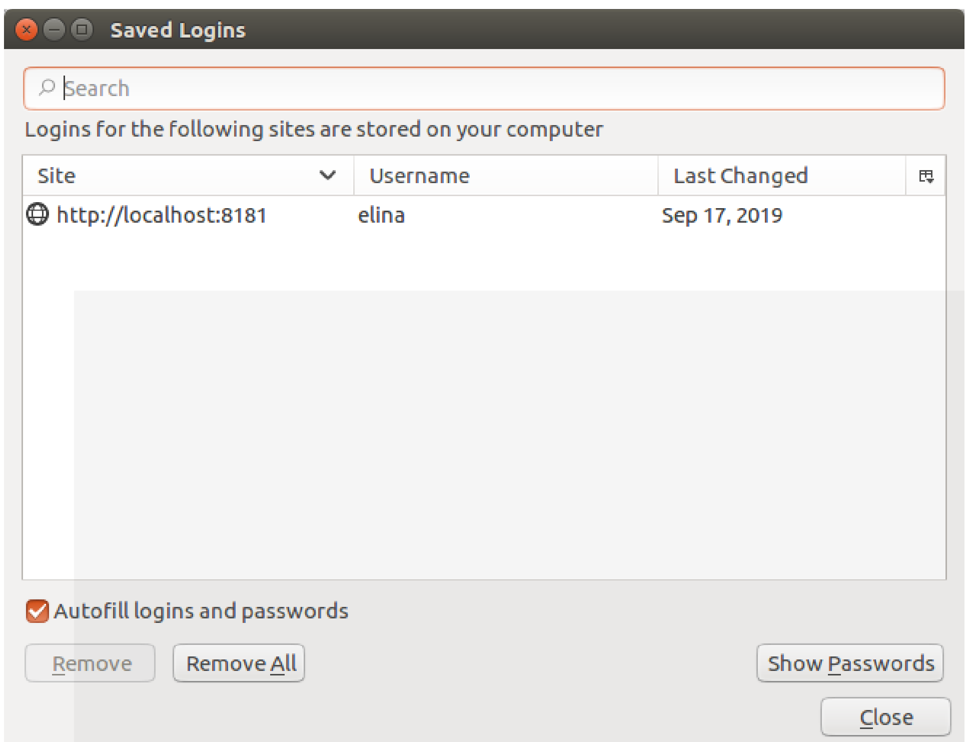
Verification of the action that is received from controller may be checked by logging system of the controller in running state.



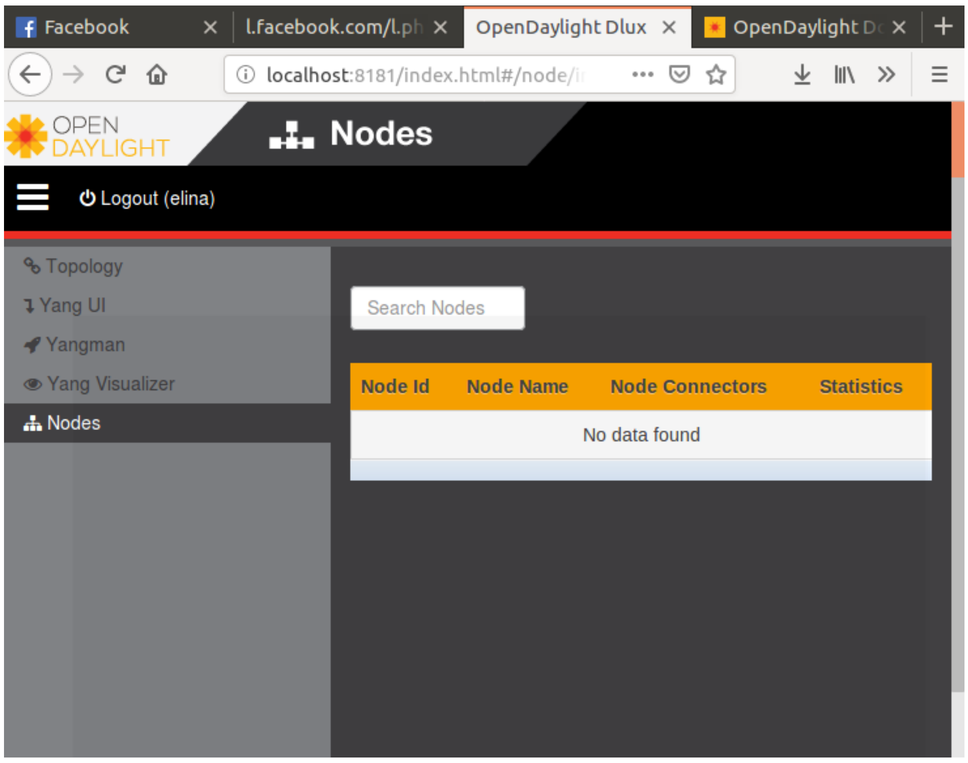
Finally to, in order to check if the user “elina” is functional **dlux** UI will be used as depicted in the next images.







The final image verifies the the user “elina” has access to the ODL applications.


Facebook
l.facebook.com/l.ph
OpenDaylight Dlux
OpenDaylight D
localhost:8181/index.html#/node/i
OPEN DAYLIGHT
Nodes
Logout (elina)
Topology
Yang UI
Yangman
Yang Visualizer
Nodes
Search Nodes
Node Id
Node Name
Node Connectors
Statistics
No data found

10 Conclusion

In this project SDN and OpenFlow basic specifications are presented. For practice an SDN lab was configured and set in order to have a functional environment to test build-in ODL services. The use cases that presented utilized the Mininet tool in order to act as data place and next the L2 Switch feature of the ODL is triggered launch the MAC learning. OpenFlow feature is fundamental for the L2 Switch, it managed all flows configuration for the service. Next network isolation is presented to isolate host connection using other ODL feature, the VTN and restconf API. Finally, AAA service of the ODL presented how to configure a custom user to define its own policies for the network.

11 References

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[14] https://docs.opendaylight.org/en/stable-fluorine/user-guide/l2switch-user-guide.html

[15] https://docs.opendaylight.org/en/stable-neon/user-guide/openflow-plugin-project-user-guide.htm

[16]nexus.opendaylight.org/content/sites/site/org.opendaylight.docs/master/userguide/manuals/userguide/bk-user-guide/content/_clustering_overview.html

[17] https://docs.opendaylight.org/en/latest/downloads.html

[18] https://docs.opendaylight.org/en/stable-oxygen/getting-started-guide/clustering.html

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