CSCI 353: Assignment 3

Revision history:
4/4 Release
4/5 Modified the VM details
4/6 Fixed the link, question numbering, and submission instructions

1.Introduction

This project aims to introduce basic concepts that will be used in the future projects. The goal is that you become familiar with the infrastructure of Virtual Machines that will be used for this course and the network emulation tool ***Mininet***. In this project we will implement a local network with programmable switches. At the end of the project you will have set up a software-defined network (SDN) capable of interconnecting a limited number of end-hosts grouped on a sub-network (more on SDN in Section 2.2).

2.Local networks and L2 forwarding

Local networks interconnect a limited number of end-hosts, generally tens to hundreds, through devices that execute L2 forwarding, most commonly switches (for wired networks) and access points (for wireless networks). To forward packets from source to destination, such equipment analyze only the MAC addresses and, based on internal rules, make the best decision.

In this assignment we are interested in working with wired local networks where end-hosts are connected by many switches. When the number of end-hosts increases, the forwarding based on MAC addresses does not scale and networks are divided into sub-networks. Forwarding between subnets is done through L3 forwarders, called routers.

Figure 1 illustrates a scenario of a network divided into three subnets. Each subnet contains on average 3 to 4 switches, and each switch connects a small number of end-hosts, only some of which are shown in the figure.

The solution to be implemented in this assignment will provide connectivity between all end-hosts on a single subnet. The location of the end-hosts (which switch they are connected to) is unknown. And connectivity must be maintained if end-hosts move to a different location.

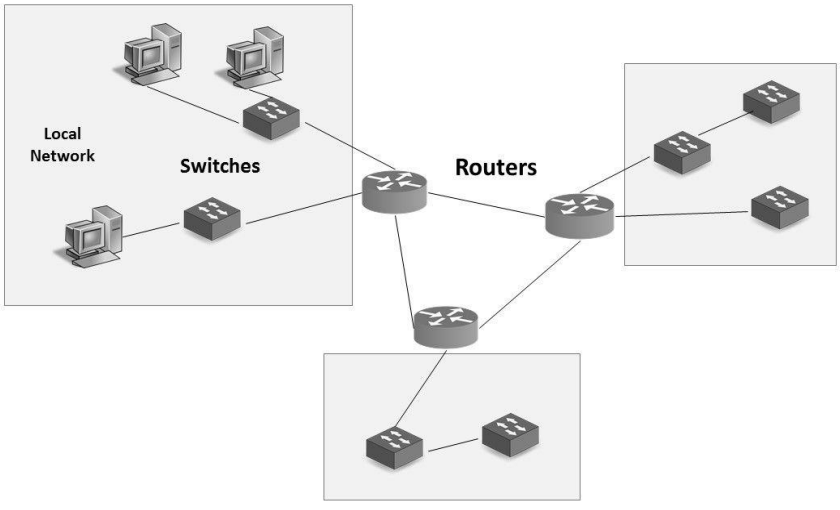


Figure 1 - Example of a network comprised of 3 subnets. Each subnet has a few switches that interconnect the end-hosts. Switches are L2 forwarders and routers are L3 forwarders

2.1. Computing a valid forwarding state in a local network

To create a valid forwarding state in a local network, we must avoid loops in the topology. Loops in an uncontrolled topology lead to a rapid depletion of network bandwidth (***why?***).

In general the operation of L2 switches can be split into three phases: (i) spanning tree calculation, (ii) flooding, and (iii) learning a forwarding table. We explain each phase below.

To avoid loops all switches need to negotiate a spanning tree[3] based on the physical topology and disable the links that are not necessary. The spanning tree calculation can be executed in a distributed or centralized manner, which is explained in details later.

After the spanning tree calculation, all switches simply forward any received packet to all neighboring interfaces on the spanning tree, except the one where the packet arrived. This flooding process guarantees that the packet will reach the intended destination, but it generates unnecessary messages, and the performance of the network may drastically reduce as the number of end-hosts increases.

A way of improving performance is with a learning process and construction of a forwarding table. For all packets that a switch receive, it creates/updates a new entry on this table linking the incoming port with the source MAC address. In the future, the switch can use this entry to forward packets to that MAC address only via that port. This way, all packets with destination address present in the forward table do not need to be flooded anymore.

Figure 2 summarizes this 3-phase process.

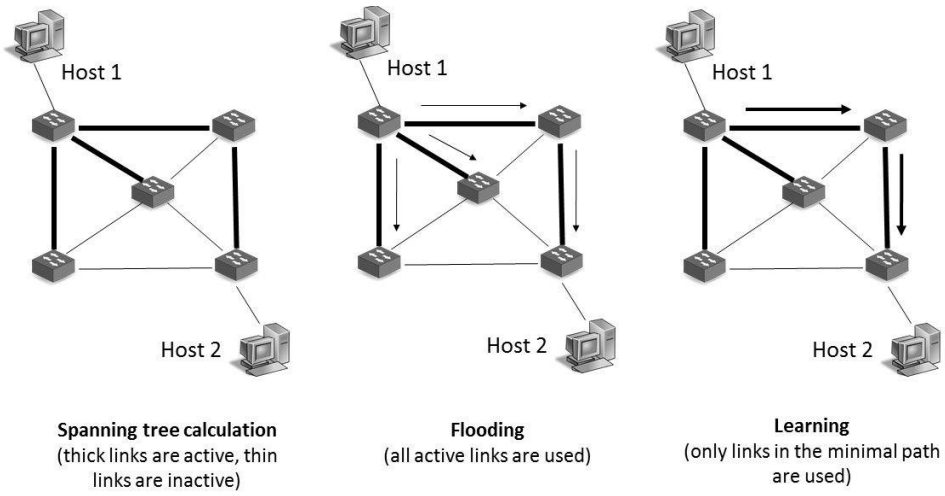


Figure 2 - Operation of a L2 switch

2.2. Distributed vs. Centralized management

The most common way of computing the spanning tree and creating the optimized forwarding table is employing distributed algorithms. Each switch executes a standardized ***Spanning Tree Protocol (STP)*** and, based on local information, populates the forwarding table. The STP was initially specified in IEEE 802.1D and a new optimized version (***RSTP***) has been incorporated into IEEE 802.1Q-2014 standard.

Even though distributed algorithms have many advantages, the incurred overhead in terms of control messages can bring disadvantages. The second way of operating an L2 local network is with a centralized architecture. Each switch communicates with a controller using standardized protocols (e.g. ***OpenFlow***). The central controller has global knowledge of the location and status of the network (switches, end-hosts, etc.) and is able to compute optimal forwarding decisions. Such decisions are transmitted back to the switches and can be used to construct optimal forwarding tables. This paradigm is called ***Software-Defined Networking (SDN)***.

In SDN the forwarding decisions can be changed according to different optimization criteria, which creates a vast exploration field for researchers, students and network operators. In this assignment we will learn how to programmatically create the forwarding table on switches for a local network using the OpenFlow protocol.

2.3. Programming the forwarding tables with *OpenFlow*

OpenFlow (OF) is a standard communication interface to control the forwarding layers of an SDN. It is currently defined by the Open Networking Foundation[4]. The communication between OpenFlow switches and the controller is bidirectional and uses TCP. The controllers should listen on TCP port 6653 for switches that want to set up a connection.

The forwarding tables in switches are usually implemented in hardware for fast lookup. Each entry in this table can be decomposed in two parts: ***match*** and ***action***. The ***match*** is a combination of rules that filters packets based on several fields, from layer 2 to layer 4, as well as the port where the packet was received. All packets that match an entry on the forwarding table form a flow. For each flow a given ***action*** is specified, which can be simply to drop the packet, forward it to a specific output port, or encapsulate it and forward to the controller as an OFPacketIn message. Figure 3 depicts the structure of a forwarding table.

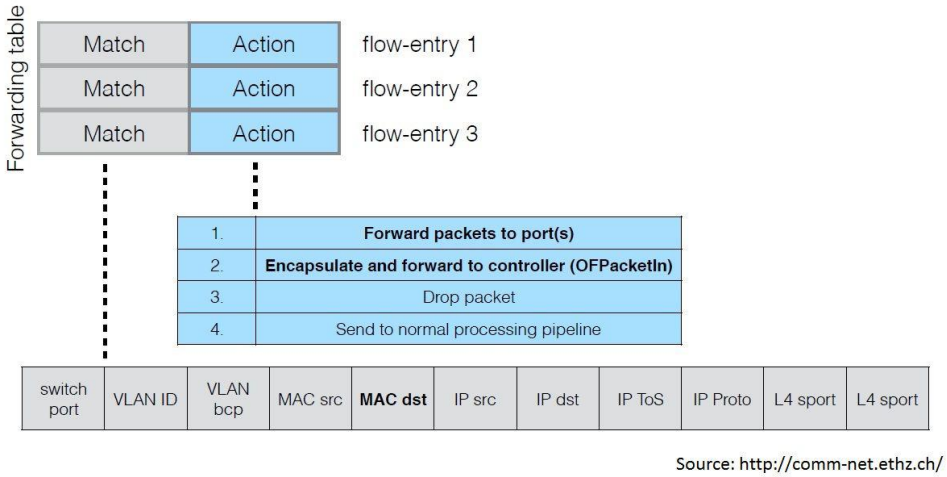


Figure 3 - Forwarding table on switches.

The OpenFlow protocol specifies several types of messages to be exchanged between switches and controllers. In this assignment we are interested in using three types of messages:

OF_PacketIn, ***OF_PacketOut*** and ***OF_FlowMod***[5].

- ***OF_PacketIn* message**

  This message is used when switches need to send data packets to the controller. This type of message is mainly used when a switch receives a packet that does not match any entry in the forwarding table. Upon receiving an ***OF_PacketIn*** message, the controller has to decide the best forwarding decision and program the switch's forwarding table. This last step is executed with ***OF_FlowMod*** messages. After programming the forward table, the controller can send the packet back to the switch (using ***OF_PacketOut*** message), and the switch should now have a forwarding table entry to properly handle it.

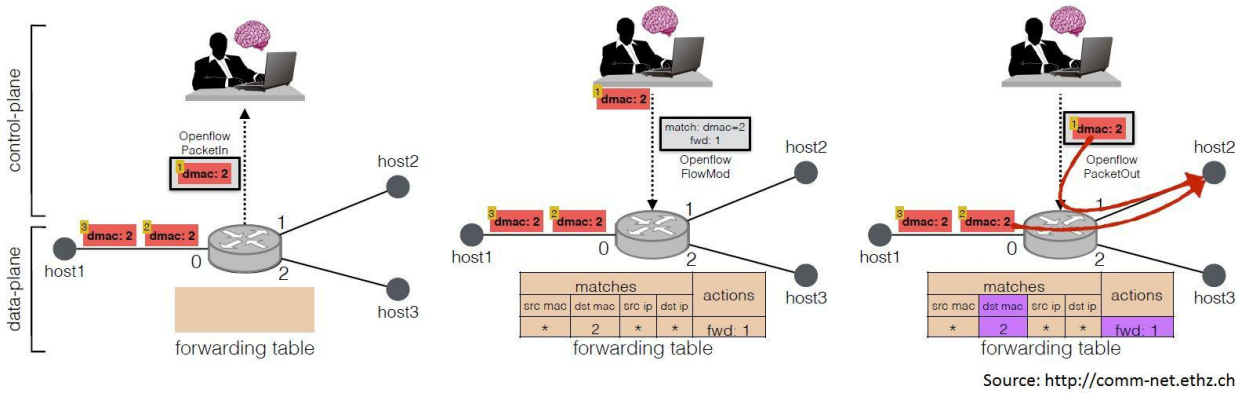
- ***OF_PacketOut* message**

  This message is used when the controller needs to send a data packet to a switch. This is generally employed in response to a previously received ***OF_PacketIn*** message, right after the corresponding entry is programmed in the switch's forwarding table.

- ***OF_FlowMod* message**

  This message is used when the controller needs to modify the switch's forwarding table. It can be used to insert, remove or update an entry, and it must specify both a ***match*** rule and an ***action***.

Figure 4 shows an example of OpenFlow in action. In Figure 4a the switch needs to forward a packet with destination MAC address 2, but its forwarding table is empty. As a consequence, the packet is encapsulated into an ***OF_PacketIn*** message and forwarded to the controller. The controller knows where address 2 is located and decides to insert an entry that forwards all packet with this destination address to port 1. The ***OF_FlowMod*** with the corresponding match and action fields is sent to the switch, as in Figure 4b. Finally, the packet is forwarded back to the switch (inside an ***OF_PacketOut*** message), which is finally able to transmit it to the destination node. The switch can forward subsequent packets that also match the entry (e.g., packets 2 and 3) directly without forwarding them to the controller.



(a) OF_PacketIn: when an OpenFlow switch does not know where to forward a packet, it sends it to the controller using an OF_PacketIn message.

(b) OF_FLowMod: when the controller received an OF_PacketIn message it decides to modify the forwarding table of a switch. This is done with an OF_FlowMod message.

(c) OF_PacketOut: when the new forwarding entry is added to the switch, the current packet is sent back from the controller to the switch using OF_PacketOut message. New packets will be properly forwarded without interference of the controller.

Figure 4 - Programming a switch with OpenFlow

3. Using the provided Virtual Machine

To make the development of this assignment easier, we have prepared a Virtual Machine (VM) with all necessary tools.
The image (an OVA file) can be downloaded from:

https://drive.google.com/file/d/0B7d-UhaXDd9bUDBHYWNXUi1FREk/view

Important: this this a 1.5 GB file, so we recommend you to download from campus network.

We recommend you to use Virtualbox 5.0 (not the newest version 5.1). You can download it at https://www.virtualbox.org/wiki/Download_Old_Builds_5_0.
VMware should also work, but we have not tested it.

This VM has an Ubuntu 14.04 without graphical interface. You can login using credentials: ***username: user***
password: cs353

All the required files are located inside ***/home/user***. If you want to run multiple terminals (you will likely need to), you can use the linux tool ***screen***.

4. The Mininet emulator

Mininet is an open-source network emulator used for research and experimentation. It allows you to create a virtual network composed of hosts, switches, controllers and links. It runs on Linux and offers support for many protocols, including OpenFlow. Instead of spending thousands of dollars on expensive switches and hours setting up a real network - which would be really cool, by the way! - we can virtualize everything and work on a fully functional network in minutes.

You can start a network with Mininet via its console interface or with a high-level Python API. We are going to explore the console interface, but for the assignment you are supposed to use a script provided by us to create your network.
Mininet is executed with command `sudo mn`. After you have logged into your VM, try to execute the following sequence of commands.

```
$ sudo mn
mininet> help
mininet> nodes
mininet> net
mininet> h1 ifconfig -a
mininet> h1 ping -c 10 h2
mininet> pingall
mininet> xterm h1
mininet> exit
```

If Mininet is executed without arguments (like it is done above), it creates a simple topology with two hosts connected to one switch and one controller. The command `help` displays all commands that can be used on Mininet. The commands `nodes` and `net` display, respectively, information about the nodes on the network (hosts, switches and controllers) and the network interfaces of these nodes. You can get more information about the network

interfaces with command `<host> ifconfig -a`. Command `<host1> ping -c 10 <host2>` sends 10 ping messages (ICMP) from host h1 to host h2, and `pingall` tests the connectivity between all hosts on the network. The command `xterm <host>` opens up a terminal interface to the end-host and allows you to execute any Linux-like command on it. Finally, command `exit` closes the emulator.

If you want to get a deep understanding of the mininet environment which has been used for this assignment, you can go to the hidden folder *.mininet* in the home folder of the user.

How does start_mininet.py work?

Start_mininet.py can be considered as an alternative to the "sudo mn" command. Mininet can be started with some custom arguments which specify the details about your topology and network. You can write your custom functions to enable mininet to read topology files and act based on that. It uses the libraries which are inside the .mininet directory under the home folder of default user. The script of default way to spin up mininet "sudo mn" is located in .mininet/mininet/bin folder. You can modify that if you want to change the default behavior.

How do I define a topology and network in mininet?

You can design a topology.txt file in whatever format which seems okay to you. You will then need to design a function to parse that topology and get the information about hosts, network devices and links. This information can be passed to the libraries such as net.py, node.py etc located inside .mininet/mininet/mininet directory in the VM provided. You can also define your networks in the same file.

There are multiple ways to configure IP addresses in mininet.

1. By default mininet uses 10.0.0.0/8 network to allocate IPs to hosts. It is specified in the net.py library. You can modify the IP base to a different value. OR While starting the mininet with default configurations (sudo mn command) you can specify IP base with the --ipbase parameter
2. When writing your custom script to start mininet, you can provide any IP range you like
3. You can alter the IP addresses of the hosts once they have spun up. By issueing commands such as *"h1 ifconfig eth0 10.2.3.4*"

You should practice some of these commands and explore the features of Mininet. A full documentation can be found at https://github.com/mininet/mininet/wiki/Documentation.

4.1. Using Mininet with Python API and Ryu controller

Mininet provides a high-level Python API for automating the creation and configuration of networks. You can find the API reference at http://api.mininet.org. We have provided you with a script (start_mininet.py) which uses the Python interface and builds a virtual network based on a given topology of switches.

You can build the network and run it with the following command:

```
$ sudo python start_mininet.py
```

The script creates the switches and links based on the file topology.txt[7]. One end-host is connected to each switch and, finally, a remote controller is also created. The first time that you run the command above you should read an error saying that Mininet was "Unable to contact the remote controller…" and your network should not run properly. The goal of this assignment is to implement a controller for the network we are building.

Important: after exiting Mininet, you have to clean it up before re-launching with
command `$sudo mn -c`

Mininet supports a number of SDN controllers. We are going to use Ryu[8] in this assignment. Ryu is a Python-based SDN controller that supports many different protocols, including OpenFlow. You can find a tutorial on how to program Ryu at https://github.com/osrg/ryu/wiki/OpenFlow_Tutorial.

We also provide you with a simple Ryu controller called dumb_ryu_controller.py that you can use to start off your assignment. Try this simple Ryu controller with the command below and re-run the Mininet network (with start_mininet.py script). You should be able to ping all nodes.

```
$ ryu-manager dumb_ryu_controller.py
```

The simple controller simply responds to each OF_PacketIN message with a OF_PacketOut message to be flooded to all ports of the switch. This action is taken by method `packet_in_handler()` , which is called every time an OF_PacketIn message is received.

This solution works in our scenario because the default topology (on file topology.txt) does not have loops. As we will see in the questions, this controller is not effective for topologies with loops.

If you want mininet to communicate with the ryu controller, you need to start the ryu controller first and then start the mininet session. When you start the ryu controller, it will start up and hang. Hence you either need to do both operations in separate terminals or use the linux screen feature.

4.2. Python networkx library

To ease the task of creating a spanning tree and calculating the best action that should be taken by the switch, we use a Python library called `networkx`[9], which implements a number of operations and data structures on graphs.

When our controller (dumb_ryu_controller) loads the topology, it adds two attributes to the nodes. Both attributes are dictionaries. The first is called ***ports,*** and it has the node IDs as key mapping to the port number of the switch that should be used to reach the node. The second is called ***mactoport*** and it maps the node MAC address (used as key) to the number of the port on the switch.
You can use these data structures to facilitate the implementation of the forwarding rules.

5. Questions

The questions are divided in **three parts**. In the first part you will **evaluate the performance of our simple Ryu controller** (dumb_ryu_controller). In the second part you will **implement a learning controller**. And in the third part you will **implement an spanning tree calculation algorithm**for your learning controller.

5.1. Evaluate the performance of simple Ryu controller

Part 1

First run the network with the default topology without loops (the first topology on the file topology.txt). Execute a ping from host 1 to host 4 transmitting 10 packets. Now, repeat the same experiment with the second topology with loops (you have to edit the file topology.txt and uncomment the second topology).

On the report answer the following questions:

Question 1 - What are the final statistics for the ping command on the loopless topology? (copy and paste the last two lines of ping command output)

Question 2 - What are the same statistics on the topology with loops? (copy and paste the last two lines of ping command output)

Question 3 - In 1-2 sentences, what causes any differences in the ping results on the loopless vs loop-y topology?

5.2. Implement a learning controller

Part 2

You have to change the Ryu controller and make it work on any type of topology (including but not limited to the given topology with loops). You need to re-implement the method `packet_in_handler()` on `dumb_ryu_controller.py` to create a learning controller. Your controller has to insert the correct entries on the switch using `OF_FlowMod` messages. You should use the spanning tree calculated by method `compute_spanning_tree()` and stored at variable `ST`. For this question, you do not need to modify the `compute_spanning_tree()` method, just use the tree that is given to you. You have to make sure that Mininet gets 100% success when command pingall is executed, on any topology including but not limited to the included ones.

Hint: You should use the example ryu/ryu/app/simple_switch.py as a starting point for implementing your learning controller.

On the report answer the following question.

Question 4 - With the way of computing forwarding tables that you implemented, is it possible for a malicious host to intercept packets from someone else? If it is possible, without changing the spanning tree calculation, what could you do to prevent that? If it is not possible, what prevents it?

You also have to submit the source code with your learning controller, which must have your implementation for function **packet_in_handler()**.

Name your source code as learning_controller_1.py.

It will be tested against 3 different topologies, with and without loops. if your network get 100% success with command pingall (you get half the points if the success rate is above 50% and 0 points if it is below).

5.3. Implement a spanning tree algorithm

Part 3

You have to re-implement the function `compute_spanning_tree()` on `dumb_ryu_controller.py` and replace the line where networkx library is used by your own implementation of any spanning tree calculation algorithm. ***You cannot use any other library that performs the calculation for you***. But you can use any algorithm that you may find easy or interesting to use. And there is no need to worry about efficiency, the only requirement is that your algorithm correctly calculate a valid spanning tree. You have to make sure that Mininet gets 100% success when command pingall is executed, including but not limited to the included ones.

On the report answer the following questions.

Question 5 - Describe how your algorithm works. If it has a name, also give the name.

Question 6 - Show the complexity of your algorithm in Big-O notation. Considered variables **n** as the # of nodes, **m** as the # of links, **s** as the # of switches and **d** as the maximum number of interfaces in a switch.

Question 7 - Give one advantage of a centralized algorithm (like yours) over a distributed algorithm (like STP). Give one disadvantage of centralized over distributed.

You also have to submit the source code with your learning controller, which must have your implementation for functions **packet_in_handler() AND compute_spanning_tree()**.

Name your source code as learning_controller_2.py.

It will be tested against 3 different topologies, with and without loops. Do not implement any brute-force solution.

Code and Collaboration Policy

You are encouraged to refer to the socket programming tutorials. You can discuss the assignment and coding strategies with your classmates. However, your solution must be coded and written by yourself. Please refer to the plagiarism policy in the course syllabus. The submissions will be run through code similarity tests. Any flagged submissions will result in a failing score. Keeping your code private is your responsibility. You are strongly encouraged to pair and test your client and server implementations with your peers in class.

Submission Instructions

You need to submit 3 files compressed into one. Three files are:
A report with explanation to all the questions as mentioned in the instructions named report.pdf
Two python scripts named as learning_controller_1.py and learning_controller_2.py for part 2 and 3.
Compressed file name should be lastname_firstname.tar.gz

Deadlines

Due on April 25th by 6pm