Project 4: SDNs

Due: 11:59 PM, Dec 11, 2014

Contents

1 Introduction

Software-defined networking, or SDN, is a new paradigm for running networks. As you have seen so far in this course, the network is divided into the control and data planes. The control plane is the set of protocols and configurations that set up the forwarding elements (hosts, switches, and routers) so that they can forward packets. This includes, for example, ARP resolution, DNS, DHCP, the Spanning Tree Protocol, MAC learning, NAT and access control configuration, as well as all of the routing protocols.

Usually, switches and routers have to run all of these protocols, detect topology changes, issue heartbeats, manage caches, timeouts, etc. Meanwhile, in many cases network administrators achieve desired goals with the network indirectly, by tweaking parameters in the routing protocols like link weights and local BGP preference. While the data plane is nicely organized in the familiar layered scheme, the aggregate structure of the control plane is a lot less clean.

SDN is a radical departure from this organization. The main idea is a separation of the control plane from the forwarding elements. SDN switches and routers do not run control plane protocols and mostly only forward packets based on matching of packet predicates to a set of forwarding rules. They export a simple API to configure these rules, as well as some feedback about current and past packets. The currently accepted standard for this API is the OpenFlow protocol, which has been implemented by dozens of switch vendors and has fostered a rich software ecosystem. The intelligence of the control plane is (logically) centralized in a *network controller*. The controller decides which rules to install based on its configuration, and on a global view of the network topology and flows.

In this assignment you will implement the logic in such a controller to manage the efficient switching of packets among hosts in a large LAN with multiple switches and potential loops. You will write the code for an SDN controller application that will compute and install shortest path routes among all of the hosts in your network.

SDN as described is suitable for networks under a single administrative domain (e.g., the network in a single AS), but there are ongoing research projects to use its flexibility across domains, integrating with and perhaps even replacing BGP.

2 Overview

As stated above, your task is to write code that will run in an SDN controller to compute, install, and maintain shortest paths on a large local area subnet. Given a packet destined to an MAC address, your network will use a shortest path among the switches to deliver it to the host.

The hosts in the project will not be changed in any way, it is only the switches in the network that will behave differently. While all the hosts in this project will be in the same subnet, we will not use any broadcasts, including for ARP.

When a host wants to send a packet to the IP address of another host in the network, it will first, as it usually does, issue an ARP request. When this reaches the first switch, though, the switch will send the ARP request to the controller instead of flooding the request. The controller, who knows the topology, will respond to the ARP request, through the same switch, to the original sender, with the MAC address of the destination. The controller will also have installed rules on the switches for forwarding to each destination MAC.

2.1 Components

You will run the code for this project in an emulated network inside of a single Linux VM. You will use the Mininet[1] network emulator, which is designed to emulate arbitrary topologies of emulated OpenFlow[2] switches and Linux hosts. It uses container-based virtualization for very light-weight emulated nodes. The switches in your network run the open source Open vSwitch[3] switch software, which implements the Openflow protocol. The switches connect to an Openflow network controller, and you will use Floodlight[4], a relatively mature Java-based controller. We will use OpenFlow

[1] `http://mininet.org`
[2] `https://www.opennetworking.org/sdn-resources/onf-specifications/openflow`
[3] `http://openvswitch.org`
[4] `http://projectfloodlight.org`

version 1.0 for this project.

Code you run on Mininet is ready to run with no changes in real networks.

3 Setup

We have prepared VM images for you to do this project. There are basically two options, you can use pre-configured VMs in the department (we have one running for each team), or you can download an .ova image for running in your own computer using VirtualBox.

See the Appendix on how to get started with these two options.

Once you've ssh'd into the VM, you can follow these steps to run your control application:

a. Compile Floodlight and your applications:

```
$ cd ~/openflow
$ ant
```

This will produce a jar file `FloodlightWithApps.jar` that includes the compiled code for Floodlight and your SDN applications.

b. Start Floodlight and your SDN applications:

```
$ java -jar FloodlightWithApps.jar -cf shortestPathSwitching.prop
```

where the `prop` file configures your application.

When Floodlight starts, you should see output like the following:

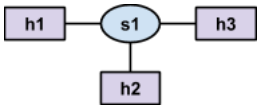
```
23:18:45.874 INFO [n.f.c.m.FloodlightModuleLoader:main] Loading modules from file shortestPathSwitching.prop
23:18:46.277 INFO [n.f.c.i.Controller:main] Controller role set to MASTER
23:18:46.285 INFO [n.f.c.i.Controller:main] Flush switches on reconnect -- Disabled
23:18:46.302 INFO [ArpServer:main] Initializing ArpServer...
23:18:46.302 INFO [ShortestPathSwitching:main] Initializing ShortestPathSwitching...
23:18:48.533 INFO [n.f.l.i.LinkDiscoveryManager:main] Setting autoportfast feature to OFF
23:18:48.579 INFO [ArpServer:main] Starting ArpServer...
23:18:48.580 INFO [ShortestPathSwitching:main] Starting ShortestPathSwitching...
23:18:48.700 INFO [o.s.s.i.c.FallbackCCProvider:main] Cluster not yet configured; using fallback local configuration
23:18:48.701 INFO [o.s.s.i.SyncManager:main] [32767] Updating sync configuration ClusterConfig
    [allNodes={32767=Node [hostname=localhost, port=6642, nodeId=32767, domainId=32767]},
    authScheme=NO_AUTH, keyStorePath=null, keyStorePassword is unset]
23:18:48.790 INFO [o.s.s.i.r.RPCService:main] Listening for internal floodlight RPC on localhost/127.0.0.1:6642
23:18:48.978 INFO [n.f.c.i.Controller:main] Listening for switch connections on 0.0.0.0/0.0.0.0:6633
```

Keep the terminal with Floodlight open, as you will need to see the output for debugging. Use another terminal for the next step.

c. Start Mininet:

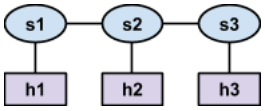
```
$ sudo ./run_mininet.py single,3
```

The above command will create a topology with a single SDN switch (`s1`) and three hosts (`h1` - `h3`) directly connected to the switch:

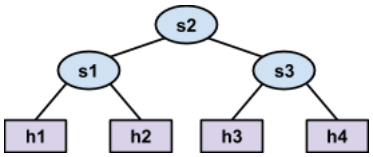


You can change the number of hosts by changing the numeric value included in the argument to the `run_mininet.py` script. You can also start Mininet with six other topologies:

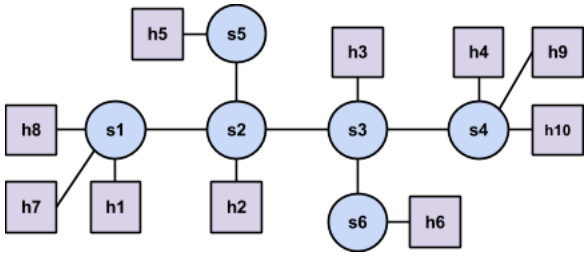
- `linear,n`: a chain of `n` switches with one host connected to each switch; for example, `linear,3` produces the following topology:



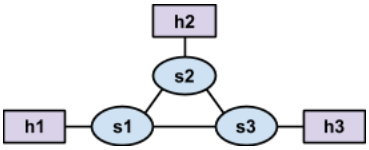
- `tree,n`: a tree of depth `n` with a single root switch (`s1`) and two hosts connected to each leaf switch; for example, `tree,2` produces the following topology:



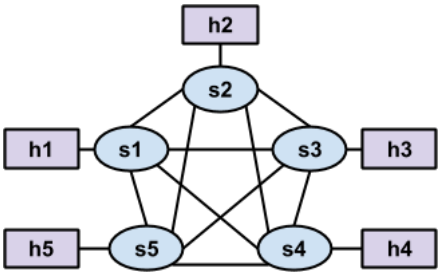
- `assign1` creates the following topology (the name is this way for historical reasons):



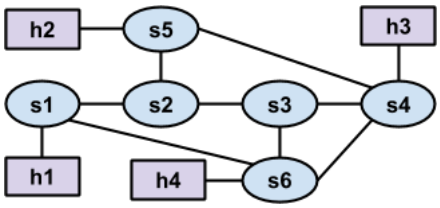
- `triangle` creates the following topology:



- `mesh,n`: a complete graph with `n` switches and one host attached to each switch; for example, `mesh,5` produces the following topology:



- `someloops`: creates the following topology:



Once mininet has started, you should see Floodlight produce output like the following:

```
23:24:10.304 INFO [n.f.c.i.OFChannelHandler:New I/O server worker #2-1] New switch connection from /127.0.0.1:58911
23:24:10.329 INFO [n.f.c.i.OFChannelHandler:New I/O server worker #2-1] Disconnected switch [/127.0.0.1:58911 DPID[?]]
23:24:11.016 INFO [n.f.c.i.OFChannelHandler:New I/O server worker #2-2] New switch connection from /127.0.0.1:58912
23:24:11.101 INFO [n.f.c.i.OFChannelHandler:New I/O server worker #2-2] Switch OFSwitchBase
    [/127.0.0.1:58912 DPID[00:00:00:00:00:00:00:01]] bound to class class
    net.floodlightcontroller.core.internal.OFSwitchImpl, writeThrottle=false,
    description OFDescriptionStatistics [Vendor: Nicira, Inc., Model: Open vSwitch,
    Make: None, Version: 2.0.2, S/N: None]
23:24:11.104 INFO [n.f.c.OFSwitchBase:New I/O server worker #2-2] Clearing all flows on switch
    OFSwitchBase [/127.0.0.1:58912 DPID[00:00:00:00:00:00:00:01]]
23:24:11.107 WARN [n.f.c.i.C.s.notification:main] Switch 00:00:00:00:00:00:00:01 connected.
23:24:11.108 INFO [ShortestPathSwitching:main] Switch s1 added
23:24:11.138 INFO [ShortestPathSwitching:Topology Updates] Link s1:0 -> host updated
23:24:11.211 INFO [ShortestPathSwitching:Topology Updates] Link s1:1 -> host updated
23:24:11.212 INFO [ShortestPathSwitching:Topology Updates] Link s1:3 -> host updated
```

d. You can now run commands (e.g., ping) and the like. Notice that initially ping will not work, as your switches do not know how to do anything. After your controller installs the correct rules, things should work.

You should **always** start Floodlight and your SDN applications **before** starting mininet. Also, we recommend that you restart Floodlight and your SDN applications whenever you restart mininet.

4 Shortest-path Switching

Your task is to build a global shortest-path switching table and install forwarding rules on the switches to implement these paths. You will build this table on the controller based on global topology information the controller gathers.

Differently from regular L2 switches or L3 routers, SDN switches don't hold MAC learning tables or routing tables. Rather, they use a more general *flow table* structure which can replace these and other constructs. Each entry, or rule, in a flow table has match criteria that defines (on the basis of fields in Ethernet, IP, TCP, UDP, and other headers) which packets the rule applies to. Each entry also has one or more instructions/actions which should be taken for each packet that matches the rule.

Your switching module will install entries that match packets based on their destination MAC address (and Ethernet type), and execute an output action to send the packet out a specific port on the SDN switch.

The match criteria serves the same purpose as the destination and mask fields in a traditional route table, and the output action servers the same purpose as the interface field in a traditional route table. In the aggregate, your network will resemble a network in which all switches have converged with the spanning tree protocol and MAC learning, with one important difference: your topology is

not constrained to a tree, as you are installing paths individually and loops should not be a problem. In fact, you must test that your solution works on topologies with loops.

After the rules are all installed, the process a host will go through to send an IP packet to a destination IP address is as follows:

a. Host OS determines that the node is in the same subnet (will always be true in this assignment). This means the node will send the packet to the IP destination as an Ethernet frame destined to the MAC address of the destination (as opposed to the MAC address of a gateway or router).

b. Host OS issues an ARP request to determine the destination MAC address (if not already cached at the OS)

c. The first switch to see the ARP request, rather than broadcasting it, sends it to the controller as a `PacketIn` message

d. The Floodlight module `ArpServer` (which we provide, see the `util` package) will respond with the if this host has sent any Ethernet frames before

e. The host OS will send the IP packet to the destination's MAC address

f. At each switch along the path to the destination (as determined previously by your code), the packet will match on the destination MAC address and be forwarded on the correct port.

4.1 Code overview

You will complete the implementation of a Floodlight module in the file `ShortestPathSwitching.java` in the `edu.brown.cs.sdn.apps.sps`.

The file we provided already contains code to:

- Access host and topology information from other modules (or applications) included with Floodlight – see the `getHosts()`, `getSwitches()`, and `getLinks()` methods.
- Receive notifications about changes in the network: see the `deviceAdded()`, `deviceRemoved()`, `deviceMoved()`, `switchAdded()`, `switchRemoved()`, and `linkDiscoveryUpdate()` methods

We have also provided code in the `edu.brown.cs.sdn.apps.utils` package for:

- A Floodlight module that responds to ARP requests from hosts – see `ArpServer.java`
- Telling a switch to install a rule in the flow table, remove rules from the flow table, and send a packet – see `SwitchCommands.java`.

In this project we will install rules to reach all hosts we know about. In the launch script for mininet we have added instructions for all hosts to issue an `arping`, which allows the controller to learn about the hosts' presence and populate its ARP cache.

4.2 To-Do's

You need to complete the To-Do's in `ShortestPathSwitching.java` to install and remove flow table entries from SDN switches such that traffic is forwarded to a host using the shortest path.

You should use either the Bellman-Ford or Djikstra algorithms to compute the shortest paths to reach a host h from every other host $h' \in H$, $h \neq h'$ (H is the set of all hosts). You can use the `getHosts()`, `getSwitches()`, and `getLinks()` methods to get the topology information that you need to provide as input to the Bellman-Ford algorithm.

Once you have determined the shortest path to reach host h from h', you must install a rule in the flow table in every switch in the path. The rule should match IP packets (i.e., Ethernet type is IPv4) whose destination MAC is the MAC address assigned to host h. You can specify this in Floodlight by creating a new `OFMatch` object and calling the set methods for the appropriate fields. The rules action should be to output packets on the appropriate port in order to reach the next switch in the path. You can specify this in Floodlight by creating an `OFInstructionApplyActions` object whose set of actions consists of a single `OFActionOutput` object with the appropriate port number.

SDN switches have multiple flow tables. You should install rules in the table specified in the table class variable in the `ShortestPathSwitching` class. Also, your rules should never timeout and have a default priority (both defined as constants in the SwitchCommands class).

When the topology changes you will have to recompute a subset of the paths. For this assignment you may choose to recompute all of the topology or be more efficient and only remove and install the rules that need to change.

4.3 Testing and Debugging

You should test your code by sending traffic between various hosts in the network topology – mininets built-in pingall command is very useful for this. While you MUST handle loops in the topology correctly, you can assume that the topology is connected, i.e., we will not test your code with topologies where a host is unreachable from other hosts.

To help you debug, you can view the contents of an SDN switchs flow tables by running the following command in your mininet VM (not in mininet itself):

```
sudo ovs-ofctl -O OpenFlow13 dump-flows s1
```

This will output the contents of s1's flow tables. Change the last argument to output the flow tables from a different switch.

Triggering Event Handlers

- You can trigger the `linkDiscoveryUpdate()` event handler by running any of the following commands in mininet (substituting switch and host names as desired):
  - `link s1 s2 down` – takes down the link between `s1` and `s2`; you can assume the network is a connected graph, so you should never take down a link that would result in a disconnected graph
  - `link s1 s2 up` – brings up the link between `s1` and `s2`

  - `link s1 h1 down` – takes down the link between `s1` and `h1`; this will also result in a `deviceRemoved(...)` event and the `isAttachedToSwitch()` method for the `Host` object for `h1` will now return false
  - `link s1 h1 up` – brings up the link between `s1` and `h1`; this will also result in a `deviceMoved(...)` event and the `isAttachedToSwitch()` method for the `Host` object for `h1` will now return `true`

- You can trigger the `deviceRemoved(...)` event handler by taking down a link between a switch and a host, as described above
- You can trigger the `deviceMoved(...)` event handler by bringing up a link between a switch and a host, as described above
- You can trigger the `switchRemoved(...)` event handler by running the following command in a regular terminal window (**not in mininet**): `sudo ovs-vsctl del-br s1`

Note that once a switch is removed, you cannot easily add it back without restarting mininet. You can assume the network is a connected graph, so you should never remove a switch that would result in a disconnected graph.

Known Issues

- When you issue a `link ... down` command, sometimes we have seen mininet ressurect the link. This seems to be a problem with mininet. In case this happens, bringing the link down a second time seems to kill it for good.
- In the VirtualBox image, it is possible that the system will start an openvswitch-controller process by default, which means your Floodlight controller will not be able to bind to port 6633. To prevent it from starting the next time you boot up, do

  ```
  sudo update-rc.d -f openvswitch-controller remove
  ```

5 Capstone Credit

If you are taking this course for capstone, one of the options for the capstone project is to implement an extra feature in this assignment. The following are some options, though you may suggest your own as well:

a. Implement flooding without loops (essentially calculate and install a spanning tree for broadcasts).

b. Implement ECMP on networks with multiple paths (determine the number of paths between two nodes) and install rules that match on, say, even and odd TCP ports!

If you want to do this project as part of a capstone, come talk to us before you do.

6 Handing In

You will only hand in the contents of the `edu/brown/cs/sdn/apps/sps` directory. Thus, when you are ready to hand in, copy the contents of that directory to a department machine and run

```
/course/cs168/bin/cs168_handin sdn
```

7 Acknowledgments

The code for this project is based on an assignment from Prof. Aditya Akella for CS640, Computer Networks, from the University of Wisconsin, Madison, with some changes. Special thanks to Aaron Kimball for help with setting it up.

Appendix A Getting up and running with the VMs

A.1 VMs in the department network

We have prepared VMs in the department for each team. To log into your VM from the department, simply run:

```
$ kinit
$ ssh mininetN
```

where N is your team's number.

This VM has mininet installed and ready to run, and it also has a copy of the project skeleton which you can modify. Once you log in, you can follow the workflow on Section 3. Note that the `openflow` directory is a Git repository, to make it easier to push and pull between department machines, if you so choose.

A.2 VM Image in VirtualBox

Alternatively, you can download the VirtualBox VM image[5] we have provided on the course site and run it on your own laptop. To do this, you should go to File and Import Appliance... on VirtualBox.

This VM uses mininet as username and password.

To ssh into the VM from your host computer, log in first using the GUI, open a terminal, and type `ifconfig`. This will show you the IP addresses of the VM. You will be able to connect to one of them from your host computer via ssh.

The VM also has Eclipse installed, which you can use inside the VirtualBox graphical console or remotely via X.

[5] `https://cs.brown.edu/courses/cs168/f14/content/src/Mininet_VM.ova`

Please let us know if you find any mistakes, inconsistencies, or confusing language in this or any other CS168 document by filling out the anonymous feedback form:

`http://cs.brown.edu/courses/cs168/f14/feedback.html`.