Semester Project - SDN assisted DMM

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Part I

Project Context and Environement

Mobile communications systems revolutionized the way people communicate, joining together communications and mobility. A long way in a remarkably short time has been achieved in the history of wireless. Looking past, wireless access technologies have followed different evolutionary paths aimed at unified target: performance and efficiency in high mobile environment. Nowadays the trend is to visualize the network.
Another challenge is the growing number of Internet-connected users, devices and applications such as the pool of available addresses for the original version of the Internet Protocol, known as IPv4, is being rapidly depleted. The solution come with IPv6 protocol that uses 128-bit addresses and provides such a vast number of addresses that it can only be expressed mathematically: 3.4 x. Ipv6 is not only a good approach but also helps to :

- Solve security issues throw IPSec, which provides confidentiality, authentication and data integrity.
- Simplify Network configuration throw address auto-configuration mechanism.
- Save the bandwidth because IPv6 supports multicast rather than broadcast.
- Reduce the size of routing tables and make routing more efficient and hierarchical.
- Simplify packet header makes packet processing more efficient.
- Support new services like VoIP.

In this section we will first understand the mobility management in mobile IPv6 then in proxy mobile IPv6. After that, we will show the limitations of those technologies to move to explain the concept of distributed mobility management in the SDN context.

1 Mobility Management Standardized solutions

Internet traffic has increased steeply in recent years, due in great part to social platforms and peer-to-peer networks. In addition, users' wireless access represents an ever-growing portion of such demand, thus posing a paradigm shift in the flow of Internet information, for which most deployed architectures are not prepared for. This evolution in user traffic demand is tackled by a different approach for IP mobility, called Distributed Mobility Management, that is focusing on moving the mobility anchors from the core network and pushing them closer to the users, at the edge of the network. So, let's first focus on the way mobility is treated is mobile IPv6 and then in proxy mobile IPv6.

1.1 Mobile IPv6

1.1.1 Principle

The figure below shows the network components in mobile IPv6:

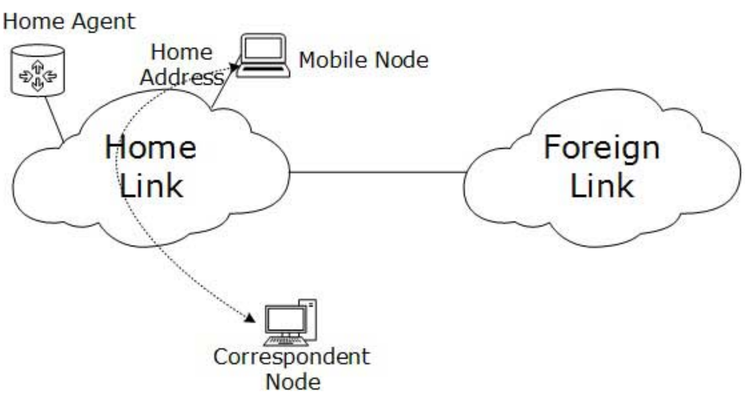


Figure 1: Mobile IPv6 general overview

let's define each one of them:

Mobile Node
: A node that can change its point of attachment from one link to another, while still being reachable via its home address.

Correspondent Node
: A peer node with which a mobile node is communicating. The correspondent node may be either mobile or stationary.

Home Link
: This link is configured with the home subnet prefix and this is where the Mobile IPv6 device gets its Home Address.

Foreign Link

Any link other than the mobile node's home link.

Home Agent

A router on a mobile node's home link with which the mobile node has registered its current care-of address. While the mobile node is away from home, the home agent intercepts packets on the home link destined to the mobile node's home address, encapsulates them, and tunnels them to the mobile node's registered care-of address.

Home Address

A unicast routable address assigned to a mobile node, used as the permanent address of the mobile node. This address is within the mobile node's home link. Standard IP routing mechanisms will deliver packets destined for a mobile node's home address to its home link. Mobile nodes can have multiple home addresses, for instance, when there are multiple home prefixes on the home link.

Care-of Address

A unicast routable address associated with a mobile node while visiting a foreign link the subnet prefix of this IP address is a foreign subnet prefix. Among the multiple care-of addresses that a mobile node may have at any given time (e.g., with different subnet prefixes), the one registered with the mobile node's home agent for a given home address is called its "primary" care-of address.

When a Mobile Node leaves its Home Link and is connected to some Foreign Link, the Mobility feature of IPv6 comes into play. After getting connected to a Foreign Link, the Mobile Node acquires an IPv6 address from the Foreign Link, this address is called Care-of Address. The Mobile Node sends a binding request to its Home Agent with the new Care-of Address. The Home Agent binds the Mobile Nodes Home Address with the Care-of Address, establishing a Tunnel between both. Whenever a Correspondent Node tries to establish connection with the Mobile Node (on its Home Address), the Home Agent intercepts the packet and forwards to Mobile Nodes Care-of Address over the tunnel already established. The figure below shows the tunnel :

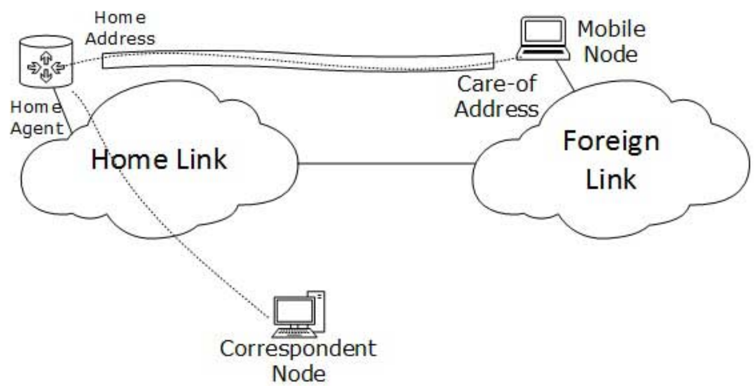


Figure 2: Tunneling in Mobile IPv6

1.1.2 Mobile IPv6 vs. Mobile IPv4

The design of Mobile IP support in IPv6 (Mobile IPv6) benefits both from the experiences gained from the development of Mobile IP support in IPv4 (Mobile IPv4) , and from the opportunities provided by IPv6. Mobile IPv6 thus shares many features with Mobile IPv4, but is integrated into IPv6 and offers many other improvements. This section summarizes the major differences between Mobile IPv4 and Mobile IPv6:

Mobile IPv6 operates without any support from local router (deployed as a foreign agent).

Security aspect no need to do a pre-arranged security associations while moving It is expected that route optimization can be deployed on a global scale between all mobile nodes and correspondent nodes.

In Mobile IPv6 the home agent address discovery mechanism is dynamic and returns a single reply to the mobile node. However in IPv4 the directed broadcast approach is used and returns separate replies from each home agent.

Most packets sent to a mobile node while away from home in Mobile IPv6 are sent using an IPv6 routing header rather than IP encapsulation, reducing the amount of resulting overhead compared to Mobile IPv4.

1.2 Proxy Mobile IPv6

Proxy Mobile IPv6 (or PMIPv6, or PMIP) is a network-based mobility management protocol standardized by IETF and is specified in RFC 5213. It is a protocol for building a common and access technology independent of mobile core networks, accommodating various access technologies such as WiMAX, 3GPP, 3GPP2 and WLAN based access architectures. Proxy Mobile IPv6 is the only network-based mobility management protocol standardized by IETF.

1.2.1 components

The figure 3 shows an Overview of PMIPv6 architecture:

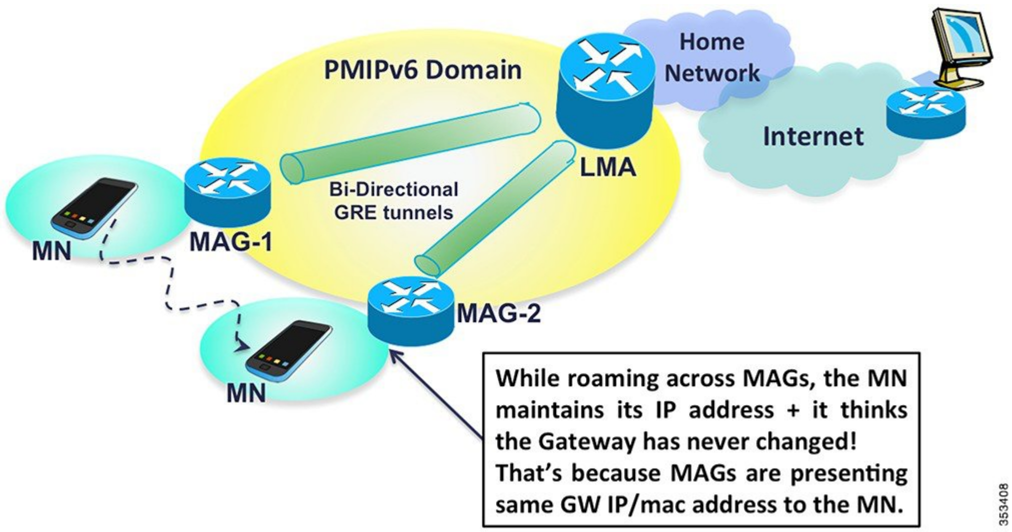


Figure 3: PMIPv6 architecture

These are some definitions of network components :

Local Mobility Anchor (LMA)
: it is similar to HA in MIPv6. It is the topological anchor point for the mobile node's home network prefix(es) and is the entity that manages the mobile node's binding state. LMA includes a binding cache entry for each currently registered MN with MN-Identifier, the MN's HNP, a flag indicating the proxy registration and the interface identifier of the bidirectional tunnel between the LMA and MAG.

Mobile Access Gateway (MAG)
: Mobile Access Gateway is a function on an access router that manages the mobility-related signaling for a mobile node that is attached to its access link. It is responsible for tracking the mobile node's movements to and from the access link and for signaling the mobile node's local mobility anchor.

1.2.2 message exchanges

The execution of the message flow of the overall operations in PMIPv6 is show in the figure below:

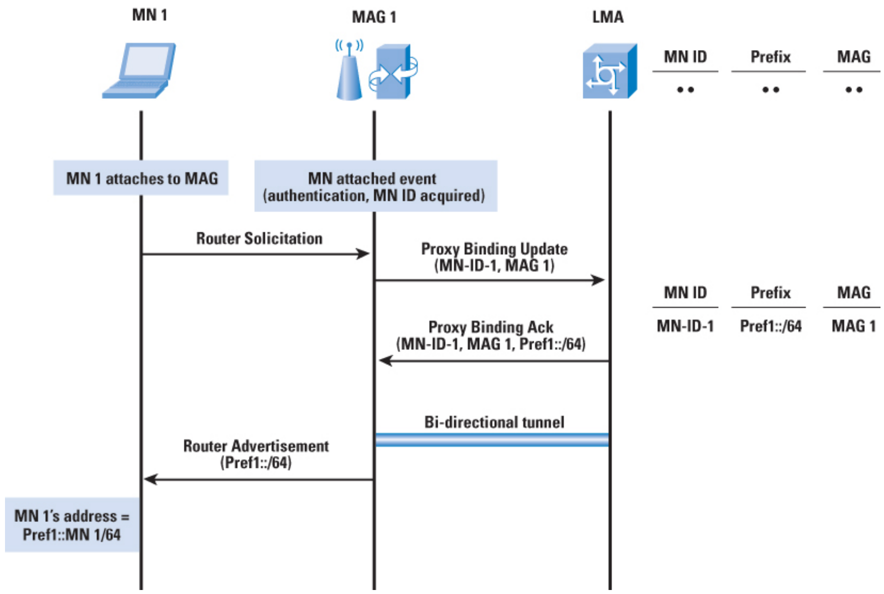


Figure 4: Tunneling messages under PMIPv6

The MN attaches to the MAG that performs an authentication procedure with a policy server using the MN's profile, which contains MN-Identifier, LMA address and other related configuration parameters before sending to the LMA a Proxy Binding Update (PBU) message on behalf of the MN including the MN-Identifier. the LMA by his turn replies with a Proxy Binding Acknowledgment (PBA) message including the MN's HNP.

With this procedure the LMA creates a Binding Cache Entry (BCE) for the MN and a bi-directional tunnel between the LMA and the MAG is set up Then the MAG sends Router Advertisement message to the MN on the access link advertising the MN's HNP as the hosted on-link-prefix. On receiving this message, the MN configures its interface either using stateful or stateless address configuration modes. Finally after obtaining the address configuration in the Proxy Mobile IPv6 domain, as the mobile node moves and changes its point of attachment from one mobile access gateway to the other, it can still continue to use the same address configuration. As long as the attached access link is in the scope of that Proxy Mobile IPv6 domain, the mobile node will always detect the same router advertising itself as default-router and advertising the mobile node's home network prefix(es) on each connected link.

1.3 Limitations of those Techniques

PMIPv6 and Mobile IPv6 was promising technologies but in the recent years user profile has changed , so that finding a solution for mobility of MN is one of the most critical criterion of selection in the operator perspective . Looking for an alternative resolution is due to these facts :

- Inter-domain handover is not supported .When the mobile node moves to another PMIPv6 domain the on-going sessions cannot be maintained.
- Centralized mobility management is simple to be implemented because the central anchor can follow the user movements by simply re-routing the packets over tunnels created with the access router where the mobile node is currently connected. But the mobility anchor represents a single point of failure, it poses scalability issues and can lead to non optimal routing policies.
- Handover latency problem : It is known that, compared to PMIPv6, MIPv6 has inferior performance in handover latency . The heaviest contribution to the handover latency of MIPv6 is made mainly by the binding signaling delay. Unlike PMIPv6 and MIPv6 the routing update procedure may cause a large delay.
- Hierarchical architecture of mobile and cellular networks forces the user traffic to go through all network parts up to the core where key entities are deployed to function as border IP gateways and mobility anchors.

To overcome these limitations many solutions where proposed thus Distributed mobility management DMM which aims to designing a flat mobile architecture that enables enhanced access to IP services and built-in support for mobility and heterogeneous radio access technologies. The DMM framework envisions an all-IP infrastructure where users data flows are routed through the optimal path, exploiting multiple anchors points and deployment of IP services closer to the users without requiring complex dedicated support from the mobile nodes. Moreover a wise assignment of IP addresses to the mobile nodes according to the available services for that user provides a mobile operator with the flexibility to handle users data traffic according to an extended set of policies. All of these advantages combined with an intelligent network architecture that distinguishes between the data plan and the control plan messages can result in quicker provisioning and configuration of network connections, high system performances, simplified networking as well as the deployment of new protocols and applications. This approach is called SDN-based DMM solution that we will introduce in the following chapter.

2 DMM Solutions

Introduction Software-defined networking (SDN) is an approach to computer networking that allows network administrators to manage network services through abstraction of lower-level functionality. This is done by decoupling the system that makes decisions about where traffic is sent (the control plan) from the underlying systems that forward traffic to the selected destination (the data plane). The inventors and vendors of these systems claim that this simplifies networking.

Let's see the architecture of the software defined network then we will explain the distributed mobility management combined with this solution.

2.1 SDN general idea and scheme

The figure below we can see the architecture of software defined network :

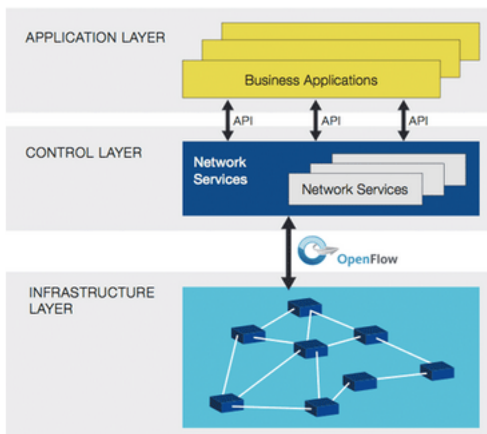


Figure 5: SDN architecture

SDN decouple the data and the control plan. Actually, in SDN there is three layers :

The infrastructure layer

SDN don't make restrictions on this layer. Transport of packets from the eNB to mobile core network takes place over so called mobile backhaul that makes use of all kinds of transmission and packet transport technologies such as Ethernet, Carrier Grade Ethernet, IP/MPLS and MPLS-TP. The physical layer in the backhaul networks uses Fiber, Radio, and copper based links. The physical links are either owned by the mobile operator or leased from another operator. An incumbent mobile operator may share its infrastructure with different types of mobile virtual operators. This approach helps to reduces the costs of the radio network to the mobile operator and adds capacity for the end user benefit.

Control layer

Mainly we speak here about the SDN controller which is the brain of the network . It contains a collection of pluggable modules that can perform different network tasks. Some of the basic tasks including inventorying what devices are within the network and the capabilities of each, gathering network statistics, etc. Extensions can be inserted that enhance the functionality and support more advanced capabilities, such as running algorithms to perform analytic and orchestrating new rules throughout the network.

Application layer

Mobile Backhaul Scaling Manage and optimize the provision of backhaul connections from the base stations to the Access App.

Mobility Management When a mobile device moves the rule in mOFS for the device needs to be modified and a new rule may need to be created in the new eOFS. If the new eNB is under the same eOFS as the previous one, then it is enough to modify an existing rule in the eOFS. We also need to take care of balancing the load across the alternative paths between an eNB and a particular mOFS. The Mobility Management App chooses the path for a device. For the load balancing decision it needs input from network Monitoring App.

Access App It aims to assign the IP address for the mobile device .

Secure Service Delivery App It helps to secure the process of service delivery and maximally benefiting from the economies of scale of cheap switches and generic hardware for control processing. The minimum goals of the service delivery network are to eliminate all source address spoofing and DDoS.

Software-Defined Networking (SDN) is an emerging architecture that is dynamic, manageable, cost-effective, and adaptable, making it ideal for the high-bandwidth, dynamic nature of today's applications. This architecture decouples the network control and forwarding functions enabling the network control to become directly programmable and the underlying infrastructure to be abstracted for applications and network services. SDN requires some method for the control plane to communicate with the data plane. One such mechanism, OpenFlow, is often misunderstood to be equivalent to SDN, but other mechanisms could also fit into the concept.

So finally SDN, network administrators can program the behavior of both the traffic and the network in a centralized way, without requiring independently accessing and configuring each of the networks hardware devices this can be helpful to cope with mobility issues. Distributed mobility management come as a new approach to concertize this in the context of IP mobility.

2.2 DMM protocol presentation

Introduction SDN allows allows for quicker provisioning and configuration of network connections. So, network administrators can program the behavior of both the traffic and the network in a centralized way, without requiring independently accessing and configuring each of the networks hardware devices. Also, this simplifies networking as well as the deployment of new protocols and applications. In addition, by enabling programmability on the traffic and the devices, an SDN network might be much more flexible and efficient than a traditional one. SDN-DMM based solution exploit these advantages to built a promising solution that:

Cope with mobile traffic increase. Distribute Mobility management functions to multiple locations. Serves Mobile node in any of these networks by a closest mobility function.

2.2.1 Components of the architecture

The main component of the distributed mobility management are :

The network controller It is responsible to configure the nodes in the network via a common application programming interface (API), namely Southbound API which can be used by an external software application to program the forwarding plane of network devices. In our solution, it configures the forwarding rules on access routers (the DMM-GWs) using OpenFlow 1.3 API

DMM-GWs It's a simple device mainly to forward packets , redirect traffic and store some informations

the figure below shows the DMM -SDN based solution :

2.2.2 Description of message exchanges

Upon the MN's attachment to a cMAR, an IPv6 global prefix belonging to the MAR's prefix pool is reserved for it (Pref1). The prefix is sent in a PBU with the MN's Identifier (MN-ID) to the CMD, which, since the session is new, stores a Binding Cache Entry containing as main fields the MN-ID, the MN's prefix and MAR1's address as Proxy-CoA. The CMD replies to MAR1 with a PBA indicating that the MN's registration is fresh and no past status is available.MAR1 sends a Router Advertisement (RA) in unicast to the MN including the prefix reserved before, that can be used by the MN to configure an IPv6 address (e.g with stateless auto-configuration). The address is routable at the MAR, in the sense that it is on the path of packets addressed to the MN.

The figure below explains the whole procedure:

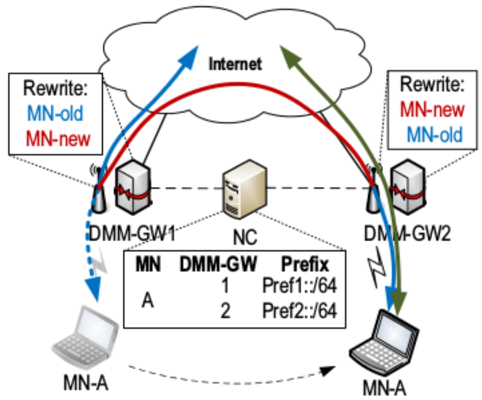


Figure 6: DMM component

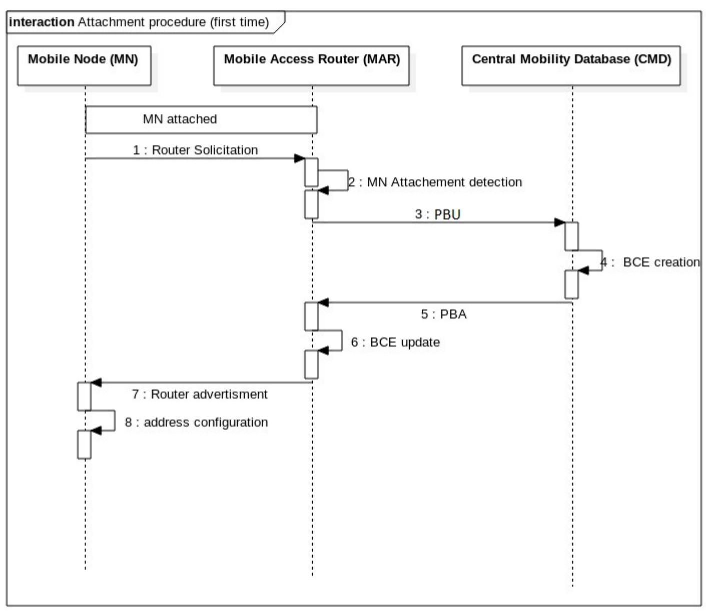


Figure 7: Attachment procedure

let's see now the component of each message :

MN attached After the Random Access procedure, if the MN is not already attached to the network it has to do so by initiating the attach procedure.

Router solicitation The mobile node, MN, attaches to MAR which is responsible for allocating the MN-HNP, the MAR contains data structure to store the association of a network prefix and a mobile interface identifier.

MN attachment detection MAR allocates and advertises HNP and updates MN's mobility session up to the database.

PBU A request message sent by the MAR to the CMD witch contains the MN-ID and the HNP prefix.

BCE creation Update the cache. It Allocate MN-HNP(s)

PBA A reply message sent by the CMD to a Proxy Binding Update message that it received from the MAR.

BCE update Setup BCE and Tunnel

Router advertisement The mobile node can initiate and maintain data transport sessions (with CN), using IP addresses derived from HNP, in a standard way while it remains attached to MAR.

When a MN is moving away from the area covered by one MAR node and entering a new area covered by another MAR, the handover process is performed as shown in Figure below and the on going session is transferred to the second MAR in order to avoid session termination when the MN gets out of the range of the first MAR.

When the MN enters the new MAR domain, initial attachment process is performed and the MN gets the new IPv6 address which will be used for new communication sessions to be started from now on. In the meantime, the on going session keeps using the old IPv6 address that was gotten from the previous MAR node that the MN visited when the session started.

After detecting the approach of the MN, the new MAR allocates a new HNP and creates a PBU message that includes the MN_ID and the allocated HNP and sends it to the CMD. When the CMD receives the PBU, it uses the MN_ID as a key to search the BCE table. The matched entry is updated and becomes the form of MN_ID : (old_HNP, old_MAR_ip) : (new_HNP, new_MAR_ip). After updating the BCE entry, the CMD replies to the new MAR with the PBA message that contains the information about old MARs, MN_ID : (old_HNP, old_MAR_ip). At the same time, The CMD sends to the old MAR the PBU message with the information of MN_ID : (old_HNP, new_MAR_ip).

When receiving the PBA message, the new MAR node inserts the information of MN_ID : (old_HNP, old_MAR_ip) into the BU(Binding Update) list and establishes a tunnel to the old MAR. In the meantime, the old MAR node that is receiving the PBU message from the CMD node updates the BCE table entry by using the information of MN_ID : (old_HNP, new_MAR_ip) and establishes a tunnel to the new MAR and replies to the CMD with the PBA message. This can be shown through the figure 8.

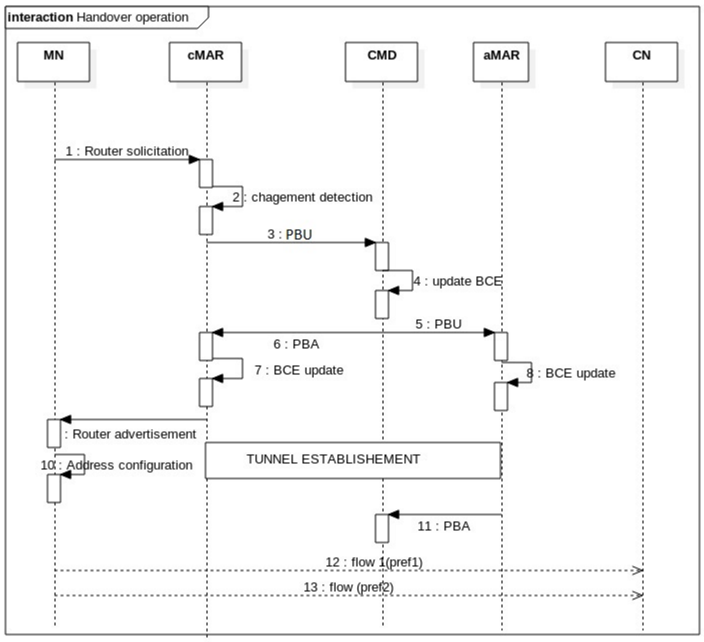


Figure 8: Tunneling under DMM

CMAR Correspondent Mobile Access Router

CMD Control Mobility Database

Router solicitation The mobile node MN attaches to MAR which is responsible for allocating the MN-HNP. By sending this message the mobile node declare its presence and asks for the network information to configure its parameter.

BCE creation delete the sentence It Allocate MN-HNP(s).

Part II
Project tools

In order to implement the Distributed Mobility Management SDN oriented previously described, several tools are required. We first need a SDN protocol implementation, then a way to emulate a SDN compatible network and finally a framework for the SDN controller.

3 OpenFlow

3.1 Presentation

OpenFlow is a communication protocol between the controller and the switches in a SDN oriented network. Switches use it to report the events they meet (e.g packet reception) to the controller, where all the network intelligence is centralized. Then using this protocol the controller sends to switches actions that have to be taken.

3.2 The concept of flows

OpenFlow formalizes the idea of orders pushed to switches by the controller in introducing the concept of flows, indeed a flow is composed by a set of fields set to certain values, those fields correspond to the ones that compose the structure of the packets exchanged between nodes, over the network. A elementary networking action is join along the field set, it can be for example 'forward to this interface'.

The controller as the brain of the network must have to tell to switches what to do and when, then that is now that the structure of flow is relevant : to transmit its order, the controller sends flows with a set of fields set to match a specific kind of packet, exactly like a firewall rule (for example type=ICMP, addr_dest=198.168.1.12) and with a action set to the action the controller wants the recipient of the flow to do whenever it receives this kind of packet.

With this approach switches get progressively autonomous, the more they are instructed by flows from the controller, the less they refer to it. Flows have a Lifetime and the controller can modify or even delete them after their submission. There are two ways of pushing flows to switches, the first one is proactive and consists in providing all the knowledge (i.e a complete set of flows) that switches need when the network initializes. The second method is reactive : when a packet reaches a switch and doesn't match any received flow, the switch asks the controller what to do with it, in response the controller sends a flow matching the packet.

3.3 Flow organization

Inside switches, flows are organized into tables and are affected with a priority level that defines the way they are ranked in the table. For every packet received the switch scans linearly the flow table, executes the action of the first matching flow and stops there.

If the switch reaches the end of the flow table without having found any matching flow it reports it to the controller, but moreover a default entry policy can be defined for the table, this is a way to define a default behaviour for switches.

It is important to have in mind that when a switch is waiting for a flow from the controller to know what to do with a packet just received, if no default behaviour is set, the pending packet and the similar next ones are lost until the flow is installed on the switch, buffering mechanisms can be set up to avoid those losses.

As flows may have different purposes and as the user may want to scan a first set of flows before a second one, multiples tables can be used. They are ranked according to their identifier and can be bound one after the other one so that different purposes flows are not mixed up. It is not possible for the flow scanning process to loop over the same table of to jump to a table with a lower identifier, it's a one way scan.

3.4 Punctual order

The advantage of pushing flows is that the controller is only solicited once by the switch to know it what to do with a specific kind of packet. But there are some cases for which the user wants the switch to keep the controller informed of the reception of the same kind packets. To do so the controller doesn't reply to the switch in providing him a flow but an individual elementary order, like a flow only with the action part. Therefore switch performs the order and its table doesn't change and then it will keep asking to the controller what to do with this kind of packet.

When the switch requests the controller for an action to perform it joins in the OpenFlow message the message that has made it send the request. Then if the controller replies with a punctual order it also joins the packet in the response so that the provided action can be performed on the packet itself, and this way packet is not lost but just delayed.

4 Mininet

4.1 Presentation

Mininet is a network emulator, it allows to create realistic virtual network running switch and application code on a virtual machine.

Mininet makes easy to virtualize hosts, switches, links, and controllers and makes a single system looks like a complete network because the most part of their behavior is similar to discrete hardware elements. The figure below shows the hierarchy of the network building :

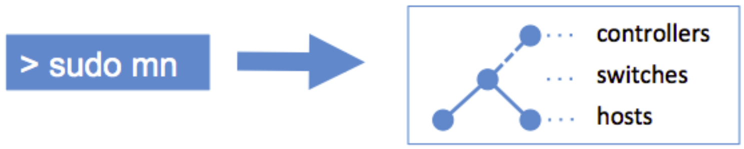


Figure 9: Mininet basic elements

4.2 Advantages and limitations

Mininet is simplified tool that get configured from a python script, then it is possible to design any kind of network with which the user can dynamically interact through a Command Line Interface and then can modify it at run-time.

Mininet suits particularly well SDN oriented networks as it provides the envelop for the controller application, then the controller code is just bound to it whatever its framework is. Messages between controller and Mininet go through the local loop and hopefully, Mininet is compatible with OpenFlow1.3.

The only problem met with Mininet is how complex it is to make the topology change at run-time through the command line interface.

5 Ryu

5.1 Presentation

Ryu is the SDN framework used for the implementation of our solution, it's python based, very flexible and embeds quite a lot of options published by an active developer community. Writing a SDN controller above Ryu is relatively easy as the framework abstracts all the configuration and the interaction with OpenFlow then user just has to tell what has to be done when a certain type of packet is received by a certain switch. Here is how it is located on a application stack:

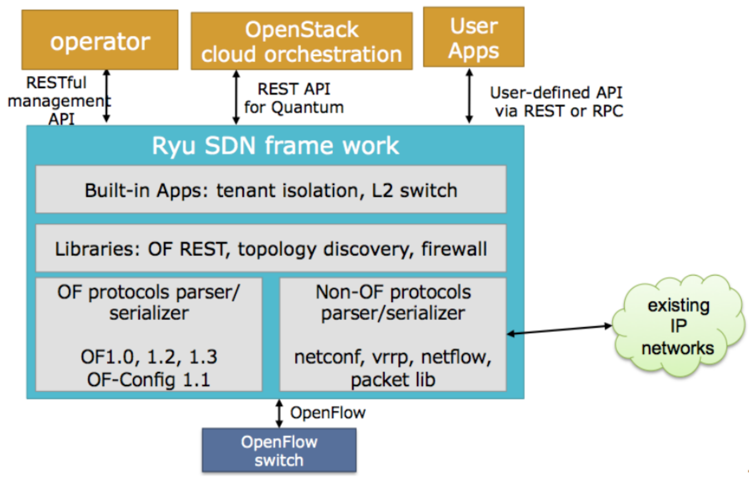


Figure 10: Ryu Architecture

5.2 Comparison with other frameworks

SDN controller frameworks are only a few and they are all very young, all written in different languages. The first one is Open DayLight comes from a consensus of several IT companies as it's running on a Java Virtual Machine, it allow user to use Java Libraries. The problem of this controller is that it's not handling IPv6 and is still stuck to IPv4 then it can't be use for our project. Another python based framework is POX but it also suffers from the same problem. Trema is a framework that handle IPv6 addresses but it is still very young and poorly documented.

This aim of this little part is mainly to say that SDN frameworks are evolving fast, we have chosen Ryu because at this time it seems to be the one that suits the most our project, but in few months it would be maybe better to migrate the controller implementation under Open DayLight framework to benefit its strong support.

5.3 Ryu available resources

A relatively big developer community works on Ryu project, then the user can find lot of help and examples at 'http://ryu.readthedocs.org' moreover there is a book called 'RYU SDN Framework' available on the internet. Then, for some more complex point the user may refer to the Ryu Mailing List.

Part III
Project Implementation

6 Enhance a simple switch in a real router

Introduction The implementation of the SDN controller, has been written from the code of simple_switch.py provided in the Virtual Machine distributed by SDNhub.com. The initial code is quite limited and allows a switch to handle message (only icmp echo reply and request) forwarding between hosts directely linked to it. Then to improve the code to get a controller able to achieve the previously described DMM solution the first step is to enable the controller with router capabilities which involves making it aware of the underlaying topology, making it handle icmpv6 control messages received by the switches and then making it request switches to forward packets across the network. Those steps are respectively described below.

6.1 Discovering network topology

6.1.1 Retrieving network backbone's topology

Ryu controller needs to access the underlaying network topology including nodes and the links between them, then it has to be launched with the "–observe-link" option. In order to build data structures where topology information are stored, the controller uses the LLDP messages exchanged between switches when the network is just created. That is why this option allows the controller to be aware of all the switches of the network and all the links between then but it can't retrieve any information about the hosts.

An important point is as we didn't find any way to notice when the discovery procedure was done, (ie detecting the instant when the topology data structures are fully completed by Ryu), our controller waits for the report of the reception of the first IPv6 message by one of the switches of the network to start reading into those data structures and build objects. Indeed we assume that IPv6 messages are exchanged long time after the whole network discovery has been done.

Our Ryu controller embeds a function called collectRoutingInfo() that has been created in the purpose of grabbing topology details and information given by mininet obtained during the discovery phase. It is then called once, when the first IPv6 message is submitted by a switch to the controller and uses the topology module of Ryu. Mininet information are collected this way:

```
#All the topology information are obtained from the
    app_manager
appManager = app_manager.RyuApp()
#Collecting switches and links information
```

```
self.switchList = ryu.topology.api.get_all_switch(
    appManager)
self.linkList = ryu.topology.api.get_all_link(appManager)
```

Two lists : self.switchList and self.linkList are filled up, with respectively switch and link objects. Those objects embed many attributes that turns out to be useful for the controller in the following parts that is why they are stored this way and not in only keeping their identifier or reference.

6.1.2 Setting up a virtual adressing plan

Mininet may assigns MAC and IP addresses to every node of the constructed network but since we want all the configuration decisions to be made by the controller, it redefines virtually all the IP and MAC addresses of the network. "Virtually" means that new given addresses are not written back on switchs interfaces to update the old ones but when the controller asks a node to send a packet it will also specify source and destination addresses the switch has to set on the packet and thoses addresses will be the ones the controller has defined itself.

Then, once every connection between every switch is registered, the collectRoutingInfo() function defines new IPv6 addresses and uses a dictionary called bindingList to store what is the new assigned IPv6 address to each interface of each switch (the key is the pair formed by the switch identifier and the interface identifier among the switch and the value is the assigned IPv6 address). New addresses depend on the identifiers of the switch itself, on the interface number and also on the identifier of the switch on the other side of the link.

Here is the code filling up the bindingList structure from the linkList and the switchList previously built.

```
for link in self.linkList:
    if (link.src.dpid,link.src.port_no) not in self.
        bindingList and (link.dst.dpid,link.dst.port_no)
        not in self.bindingList :
         self.bindingList[link.src.dpid,link.src.port_no]
            = '2000:'+str(link.src.dpid)+str(link.dst.dpid
            )+'::'+str(link.src.dpid)
         self.bindingList[link.dst.dpid,link.dst.port_no]
            = '2000:'+str(link.src.dpid)+str(link.dst.dpid
            )+'::'+str(link.dst.dpid)
```

Mac Addresses are also redefined the same way but as they all are generated the same way, they are not stored anywhere but computed on the fly every time they are needed. Here is the function that constructs them:

```
#return the MAC address associated to DATAPATH_id and
    port_id
```

```
def generateMAC(self, dpid, portid):
    addMAC = 'a6:0'+str(dpid)+':00:00:00:0'+str(portid)
    return addMAC
```

The way addresses are forged depends on the interfaces to which they are assigned, indeed interfaces domain can be divided in two partitions, the backbone interfaces and the local network interfaces. The first one corresponds to interfaces to which a link between two switches is plugged, and the second one corresponds to interfaces to which a link between a switch and a host is plugged. Backbone interfaces all share the same two bytes prefix : '2000:' and two backbone interfaces connected by a link share the same four bytes prefix : '2000:AB' where A and B are the identifiers of the switch to which interfaces belong (order of A and B depends on the link object from ryu.topology module). Then the last two bytes of the address is defined by the interface number among the switch. For example if we consider the third interface of switch number 2 through which the switch is linked to switch number 5, interface's address is 2000:25::3.

Then this addressing convention introduces a limit of the number of switch that can handle the controller, as the identifier of two switches must fit in two bytes for backbone addresses creation, and since identifiers are kept in decimal system (not hexadecimal) an identifier can't exceed the value of 99, therefore it is not possible to have more than 99 switches on the network.

Local network interfaces are not discovered yet by the controller as they are not registered on ryu.topology module's data structure, the controller can't assign them addresses right now.

Just after address assignment another data structure is built, it's called networkGraph, it's a dictionary binding each switch to its switch neighbor list. From this structure, routing algorithm is launched to resolve the detailed path, hop by hop, to reach one switch from another one.

6.2 Handling ICMPv6 configuration messages

Introduction This initialization job described in the previous part is done when the controller is solicited for the first time by a switch which has received an IPv6 packet. Once completed the received packet has to be handled, as well as the next incoming ones. Then when the controller is reported of the reception of a IPv6 packet by a switch, it firsts figures out the type of the packet and after run the appropriate instructions.
Our controller only works with ICMPv6 messages, other kinds of messages are filtered out.

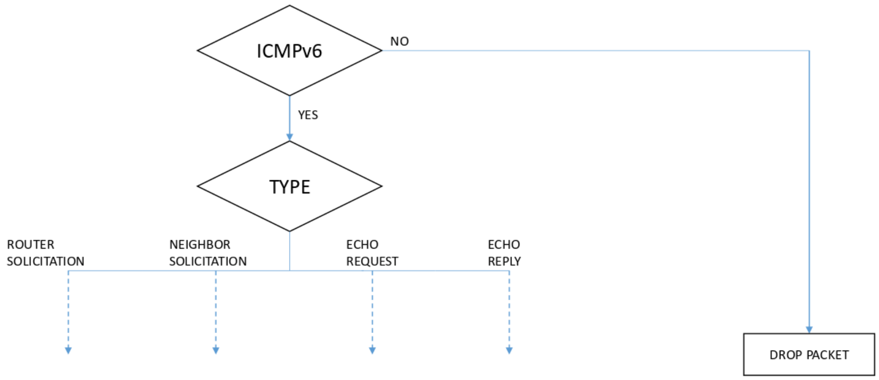


Figure 11: Global algorithmic scheme of the controler

6.2.1 Router Solicitation message

The first type of message of a switch can receive is ICMPv6 Router Solicitation message, this message is sent by hosts when they get their interface turned on or when they access a new network.

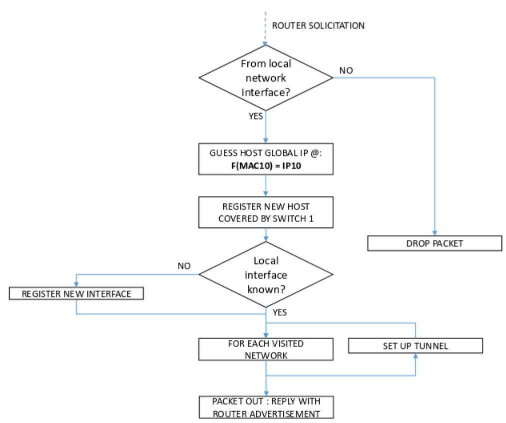


Figure 12: Controler algorithmic when handling router solicitation messages

What the controller does first in this case is checking if the input interface of the switch is not already registered as backbone interface, if it is the case, the controller does nothing. Otherwise handling keep going and as now controller is sure that the source is a host, it registers its MAC address (obtained from the source address field of the frame containing the Router Solicitation Message) in a data structure called coveredHosts. It stores hosts that have registered inside

the sub-network of each switch, in other words it stores for each switch the hosts that are supposed to be linked to it. This structure is a dictionary where keys are the couple: IPv6 addresses that the hosts has forged when joining the sub-network and the identifier of the joined switch. Values are the couple host's MAC address and the identifier of the switch's interface that is linked to the host to make things clear hear is an example:
dpid1 : host1IP:(host1MAC,intfLocal1),host2IP:(host2MAC,intfLocal2) , dpid2 : host3IP:(host3MAC,intfLocal1) .

An important point is, since the host doesn't have any IPv6 address yet, the one it generates from IPv6-autoconfiguration process is guessed by the controller from host's MAC address and from the switch's sub-domain in which the host is. It is important to have in mind that if the host uses a different way to forge its Global IPv6 address, the controller won't recognize it.

The bindingList is also extended, indeed if the Router Solicitation message is received on an interface never used before, as the controller just discovers it, it stores the new interface in the coveredList: now its knowledge of the network topology gets extended to local network interfaces and hosts to which they are linked.

Then as before an IPv6 address is assigned to this new discovered interface and the controller has also a convention for local network interfaces. The 2 bytes prefix of the address depends on the switch, indeed switches define sub-domain among the network, but the first half-byte of the prefix is always set to 2. Then the last two bytes of the address is like before, defined by the interface number among the switch. For example if the fourth interface of the switch number 7 through is linked to an host, interface's address is 2007::4. If the Router Advertisement reaches an already registered interface, nothing happens on the bindingList.

This is just after this step that the mobility management is done, the controller finds out if the host that has sent the Router Solicitation message comes from another sub-network and triggers or not mobility management procedure. For the moment we will skip this part, considering first a controller that makes the network behave normally, without any extra mechanism.

Last, the controller forges the ICMPv6 Router Advertisement to be sent by the solicited switch to the host that just contacted it, it first creates the core of the message this way:

```
icmp_v6 = icmpv6.icmpv6(type_=icmpv6.ND_ROUTER_ADVERT,
data=icmpv6.nd_router_advert(ch_l=64, rou_l=4,
options=[icmpv6.nd_option_pi(length=4, pl=64, res1=7,
    val_l=86400,
pre_l=14400, prefix=prefix)]))
```

with the variable 'prefix' set to the switch's local network interface IPv6 address to which the host is bound. This packet is then encapsulated in a IPv6 packet (with source address set to the local scope address of the interface, generated on the fly like MAC addresses) and in a Ethernet frame and is forwarded to the switch.

As we want every Router Solicitation messages to be reported by the switches to the controller in order to keep track of hosts moves across the network, no flow handling Router Solicitations messages are pushed down to the switch but only a punctual order asking to forward the provided Router Advertisement message on the specified interface.

Here is the associated code of a punctual order embedding a Router Advertisement message (under pck_generated name) sent by the controller to the switch (called datapath here):

```
actions = [parser.OFPActionOutput(out_port)]
out_ra = parser.OFPPacketOut(datapath=datapath,
buffer_id=ofproto.OFP_NO_BUFFER, in_port=0, actions=
    actions,
data=pkt_generated.data)
datapath.send_msg(out_ra)
```

The switch will execute the given order in forwarding to the host the Router Advertisement message and will keep reporting any Router Solicitation messages coming next to the controller.

6.2.2 Neighbor Solicitation message

A second kind of ICMPv6 message that can be reported by switches to the controller are ICMPv6 Neighbor Solicitation messages, there are two reasons for an host to send such a message to its local switch. The first one is in order to resolve the MAC address associated to a given IPv6 address : the target address. In this case the option field of the Router Solicitation message is not empty, and the controller checks if the target address is one of the virtually assigned addresses of the solicited switch's interfaces. If yes the controller forges the corresponding Neighbor Advertisement message that contains the IPv6 address of the spotted interface and transmits it back to the switch along a forwarding order for being relayed to the host, exactly as for Router Advertisement messages.

As several hosts can be connected to the same switch and then get configured with the same prefix even if they are linked to the switch through different interfaces, the controller also resolves inside domain requests : when a Neighbor Solicitation message received by a switch has a target address corresponding to one of the hosts of the local network. Then here, as every packet between hosts in the sub-network goes through the switch, the packet containing frame built

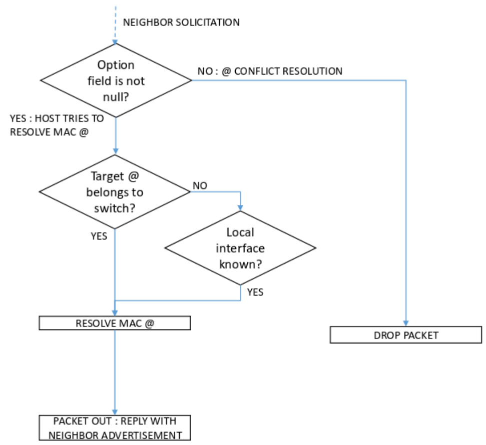


Figure 13: Controler algorithmic when handling neighbor solicitation messages

by the sender will have its destination MAC address set to the MAC address of the switch's interface it is linked to.

If the option field of the Neighbor Solicitation message is null that means that it has been sent by the host for address conflict resolution purposes, in this case, as address conflicts are not considered, the controller doesn't do anything : all the host registration process inside controller data structure is done at Router Solicitation message reception.

As address conflicts are not handled by the controller, if an host comes up with a new reconfigured IPv6 address it won't be recognized by the switch since this address is not obtained from the usual IPv6 auto-configuration process.

Router Solicitation and Neighbor Solicitation messages are the only two kinds of ICMPv6 control messages handled by the controller, as the controller redefines itself the whole backbone addressing plan and as address conflict is not managed there is no need to care about ICMPv6 Router Advertisement and Neighbor Advertisement Messages.

6.3 ICMPv6 Echo request & reply

The last kind of message we want to be handled by the controller are ICMPv6 Echo messages, they are representing data packets in the simulation.
When the reception of on ICMPv6 Echo message is reported by a switch to the controller, the controller first looks at packet's destination address and behaves according to it.

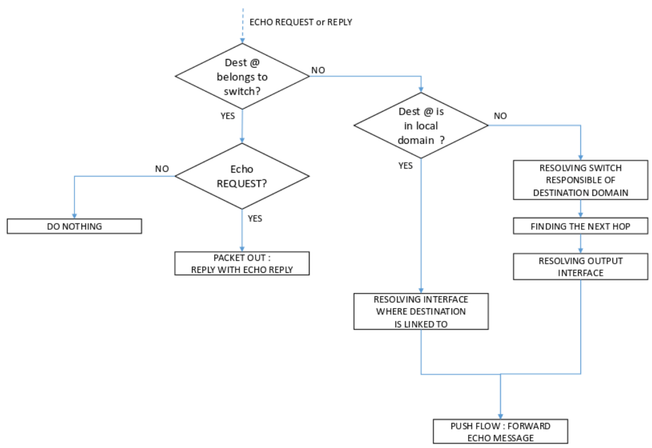


Figure 14: Controler algorithmic when handling echo messages

6.3.1 Answering to Echo messages

Once the controller gets packet's destination address it checks if this address belongs to one of the interfaces of the solicited switch using the bindingList, from which it retrieves switch's interfaces this way:

```
localAddressesList = [ self.bindingList[localPort] for
    localPort in self.bindingList.keys() if localPort[0]==
    dpid ]
```

If the destination address is indeed one belonging to the switch, there are two possible scenarios : if the message is an Echo Reply, nothing has to be sent back to the network and the controller doesn't do anything. If the message is an Echo Request, that means that someone is pinging the switch then it has to reply.

Exactly as when the controller was ordering the switch to send a Router Advertisement or a Neighbor Advertisement message, the controller first constructs the ICMPv6 Echo Reply message and the encapsulating packets, and pushes it to the switch along with a punctual forwarding order toward the interface the Echo Request was coming from.

Here we chose not to push flows to the switch since ICMPv6 Echo Reply message is constructed from the associated Echo Request message, it would have been necessary to push flows specific to each Echo Request's destination address that have their specific actions. Therefore flow table could have been over populated with Echo message related flows which are not the interesting ones.

6.3.2 Forwarding Echo messages

When the destination address of the Echo packet is not one of the solicited switch's addresses, that means the switch is one intermediate node on the Echo message's path and have to forward it toward its destination, regardless if its an Echo request or an Echo reply.

The controller then figures out what is the local network to which the destination address belongs to: it extracts from the echo message's destination address the number contained on its first two bytes. From it, it gets the identifier of the switch the destination should be linked to unless if it is a backbone interface that is aimed and the result is null, in this case it extracts the last byte of the address where is written switch's identifier.

Then two cases are possible, either the destination node is an host directly linked to the solicited switch (in this case the extracted identifier is the one of the switch itself) and here the controller checks if there is an host registered in the coveredHosts list of the switch that own Echo message's destination address. If no host is found in the list the packet is dropped, but if one is found the controller fetches host's details from the coveredHosts list that are : host's MAC address and the switch's interface to which it's linked to. With all of this the controller has everything he needs to make the switch relay the echo message toward its destination.

If the extracted network identifier is not the one of the switch itself: another switch or an host located in a remote local network is aimed by the message. Here the controller finds out next hop switch toward the destination : for this purpose is uses the structure called networkGraph constructed during the initialization phase and runs on it the breadth-first algorithm to get the shortest path between the solicited switch and the destination switch. From the path, the controller learns which switch is the next one to reach the final one. The last step consists in, given a switch and one of its direct neighbour, finding the interface of the switch that is linked to this neighbor, the function routing() has been written for this purpose, the idea is a to scans all the links of the network until finding the one linking the two specified switches and look on which interface the link is plugged on the switch, here is the code:

```
def routing(self, source, dest):
    for l in self.linkList:
        if l.src.dpid==source and l.dst.dpid==dest:
            return l.src.port_no
```

Since this function uses the linkList structure it only works with interfaces linking one switch to another, that is why interfaces linked to hosts are stored in the coveredHost structure.

When we reach this point in every cases we have resolved the switch's interface on which the Echo message has to be forwarded. And as the message has to be encapsulated in a new MAC frame, new source MAC address and destination MAC address must be set. The source MAC address depends on the switch's interface and is computed on the fly as previously said, and the destination MAC address is fetched from the coveredHost structure if the next hop is an host. If the next hop is a switch the routing function is called on this switch in a symmetrical way in order to resolve identifiers of the interface located on the other side of the link. From it, the destination's MAC address can be generated.

Now in every cases all the elements needed for forwarding have been resolved (MAC addresses and Output interfaces) and here for the first time a flow is pushed to the switch from the controller instead of punctual order. This flow consists in matching every next Echo message reaching the switch with the same destination address and to forward them toward the interface that has just been resolved in changing MAC address with the ones provided, here is the associated code:

```
action =
[parser.OFPActionDecNwTtl(),parser.OFPActionSetField(
    eth_src=new_mac_src),
parser.OFPActionSetField(eth_dst=new_mac_dst),parser.
    OFPActionOutput(outputIntf)
]
match = parser.OFPMatch( eth_type=0x86dd, ip_proto=58,
    ipv6_dst=(ping_dst,'ffff:ffff:ffff:ffff:ffff:ffff:ffff
    :ffff'))
self.add_flow(datapath, 1, match, action,tblId=1)
```

Now the switch knows how to handle alone this specific kind of message and won't forward it anymore to the controller. This is how switches get progressively autonomous, by getting instructed at each reception of a new Echo message to forward.

Now the controller is able to handle switches over a normal network that is not requiring any extra services, but our purpose is to handle host mobility over the network, then we can imagine that other flows will be pushed down to switches so it is necessary to organize flows properly into switches order to avoid any conflict between flows of different purposes.

7 Handle host mobility across the network

7.1 Introduction

7.1.1 Flow organization inside switches

Once pushed to a switch, flows are grouped into ordered tables that can be bound together, our controller defines 3 tables insides switches : the first one (table number 0) and the last one (table number 2) are dedicated to flows related to mobility handling and their purpose will be explained later, for the moment the only thing to know about them is that the default entry policy of table number 0 is to forward message to the table number 1.

The table number 1 (the second one) is dedicated to flows related to classic message forwarding, like the flows pushed for relaying ICMPv6 Echo messages. At this point tables 0 and 2 are empty and the second one get progressively populated witch flow associated to Echo messages forwarding. For each switch, when a packet is received, it checks if it matches one of the entries of the first table, if not it checks if it matches one of the entries of the second table. If no match is found after having scanned the second table, the switch doesn't know how to handle it and asks the controller what to do with it (it's asking for an order or a new flow), that is what happens when a Echo message with a new destination reaches the switch.

7.1.2 Basic idea of how mobility management is done

Host mobility is ensured first in keeping track of them all around the network, by storing and updating the list of sub-networks each node has visited. So that when a host gets to a new network, all the old ones registered on the list are retrieved and involved in the mobility management procedure.

7.2 Retrieving Mobile Host history and enable local forwarding

7.2.1 Retrieving Mobile Host history

When a Router Solicitation is submited to the controller, after it has updated coveredHosts and bindinList data structures, the controller refers to the module called mobilityPackage to know if the host has visited sub-network before connecting to the solicited switch. This module is very simple consists in one dictionnary called trackingDict which stores the network history for each host and provides a unique function called getTraceAndUpdate(), that returns the list of previously visited networks by a specific host identified by its MAC address and appends to this list the identifier of the switch which notifies the Router Solicitation message to the controller.

The controller next build a tunnel between each previously visited returned by the module and the solicited switch which is now the one to which the mobile host is linked to, and therefore the one to which all the mobile host's on going communications has to be re-routed.

7.2.2 Enabling local forwarding of remote addresses

When a host gets connected to a switch, the controller computes the Global IPv6 address the host will generate and stores it into the coveredHost data structure so that when a ICMPv6 Echo message is aiming this particular address the controller can resolve the interface to witch the host is linked and the Echo message can be forwarded.

When now the host has visited other networks before connecting to a new switch, by setting up tunnels the controller makes all the active communications in which the host is involved, going through the new switch. Then, in this case the new switch receives packets coming from everywhere in the network and has to forward them on the interface the mobile host is now linked to. Since those communications have been started by the host other sub-networks, they are made of packets for which the host address is a previously generated one and the new switch doesn't have any ideas of them. Therefore to be able to achieve correctly the local forwarding, the switch has find out which are those previous addresses used by the host so that output interface can be resolved.

A simple solution to this issue consists in first resolving the previously IPv6 addresses used by the host and then pushing new flows from the controller to the new switch's table number 1 (the table for routing purposes) that would match packets whose destination address is the ones just resolved and forward them on the interface where the host registered. The problem now is that some packets that doesn't come from any tunnel may be forwarded to one of the new switch local interface instead of being routed normally, the switch associated to their destination address. Therefore those new flows would mess up the normal routing procedure and we want to keep this very particular local forwarding of remote addresses only for packets coming from tunnels and keep other packets out of it.

That is why a third flow table is set up inside switches, it contains all the flows related to local forwarding of remote address. The important point is that flow table can only be accessed by messages coming from a tunnel. As host's previous network are known as well as host's MAC address, the controller computes the global IPv6 addresses the host has generated when it was in those networks, and then pushes flows that match packets having those addresses as destination address and make the new switch forward them on the interface on which the Router Solicitation message has been received.

7.3 Setting up tunnels

7.3.1 General scheme

Tunnels are established between the switch just joined by the Mobile Host and the ones it was connected to before. In this way all the messages aiming an address that the host has forged in a old sub-network reach the associated router that forwards them in the tunnel just set up to the new switch that extract them out of the tunnel and relays them to the host.

In the reverse direction, when the host sends a message with a old generated IP address as source address, this message is tunneled from the new switch to the one covering the sub-network where this old address has been built (no route optimization mechanisms are set up). The old switch then extract packets out of the tunnel and forwards them toward their final destination.

7.3.2 Tunnel properties

Tunnels are materialized with Vlan tags, as it only deals with the layer 2 of switches' stacks, the handling is lighter and faster for them.

Moreover for a given direction, only one tunnel exists between two switches and it is shared between hosts, this makes the number of flows to push for mobility purposes lower, indeed, the first host that goes from a network A to a network B will trigger the establishment of a tunnel between the associated switches and every next host that do the same crossing from A to B will have its message going conveyed through this same tunnel.

Tunnels are unidirectional on the way hosts move, in the sense that they convey messages (in both directions) to ensure host mobility from a network A to another network B but if the host goes back to A from B another tunnel will be used. Indeed it is not possible to merge two opposite tunnels into one as switch's job is not the same when the switch is on the new or on the old side of the tunnel.

7.3.3 Tunnel related flows

A tunnel between a previously visited switch A and the currently visited switch B is set up by the controller first in pushing two flows to both switches A and B. This time flows are related to host mobility, they are then store in the first table (table 0) of each switch.

Two flows are pushed to the first table of switch A:

The first one matches packets coming from the network whose destination address is the one that the Mobile Host forged when it was in the sub-network of switch A (let's call this address "host's old address"), and its action consists in pushing a VLAN tag on those packets, and forwarding them toward router B, in changing MAC addresses. Here the VLAN tag is the concatenation of switch A and switch B's identifiers (let call this value "V"). To avoid any undesirable tunnel binding effect the flow matches only packets without VLAN tag.

The second flow matches packets whose source address is the host's old address and which include a VLAN tag set to V. The associated action consists in first getting rid of the VLAN tag and then in relaying the new packet to the flow table number 1 of the switch so that it will be passed through the table like a normal packet from the local network and be forwarded as usual to the external network.

Two other flows are pushed to the first table of switch B:

The first one matches all the received packets whose source address is the host's old address. The associated action is to push a VLAN tag with the value V and then to forward packets toward router A, in changing MAC addresses. As IPv6 addresses are unique there is no risk that this flow matches packets received on a backbone interface of switch B and forwards them into the tunnel because the mobile Host is the only entity of the network that sends packets with this precise source address. Here again, to avoid any undesirable tunnel binding effect the flow match only packet without VLAN tag.

The second flow matches packets from router A that include a VLAN tag set to V, then the associated action consists in first stripping the VLAN tag out of packets. Second, as those packets have their destination address set to the host's old address they are then relayed to the flow table number 2 of switch B so that the local output interface will be resolved based on the destination address of the packets.

Now that flows are pushed to the entry point and to the exit point of the tunnel, the controller has now to tell switches of the network this tunnel crosses to relay packets going through the tunnel. In applying the breadth-first algorithm over the networkGraph data structure, the controller gets the list of the intermediate switches to instruct, and push to each of them two flows :

The first one matches packets that include a VLAN tag set to V and whose source address is host's old address, the associated action is forwarding them in keeping them unchanged (except their MAC addresses) to the next hop on the path to reach B.

The second one matches packets going in the reverse direction, those ones include a VLAN tag set to V and their destination address is host's old address, the associated action is forwarding them in keeping them unchanged (except their MAC addresses) to the next hop on the path to reach A.

With this set of flow host mobility is ensured all over the network but there is currently one configuration that makes the program not working : when the tunnel entry point has to forward encapsulated packet on the same interface on which it has received them just before, it doesn't forward anything out on the interface and nothing is send inside the tunnel. This problem is not fixed today!

7.4 Advanced mobility

It's important to keep in mind that the mobile host may not only go from one network to another but may roam across many different ones and also go back to previously visited networks. Therefore the tunnel establishment algorithm described before is a trade between having a simple sequence of operations to be done by the controller and try not to make switches flow table soaring after host have roamed for a while, that is why shared tunnel solution has be selected.

7.4.1 Subsequent Handover

When the mobile host, after having left its home network A to go to network B, changes again of network and goes to network C, there are now two address for which mobility have to be ensured : the one acquired in network A and the one acquired in B, that means that two tunnels have to be set up : one between switch A and switch C and another between switch B and switch C, moreover the previously tunnel from A to B must not be used anymore for the considered host.

Once installed into a switch, a flow can be updated when a new flow with the same matching criteria is pushed to this switch, this is what happens when the host gets to network C. Before the host joins switch C, two tunnel flows are installed into switch A : one ensures that every packet aiming the mobile host's old address is forwarded in a Vlan tunnel toward B, let's call this flow FA1. The other one ensures that every packets going from the Vlan tunnel is piped to the routing table, let's call it FA2.

When the mobile node reaches network C, a new Vlan tunnel is set up between switches A and C, FA1 is then updated because a new flow matching every packets aiming mobile host's old address forged in network A is pushed, and this new flow makes switch A forwards them into the new Vlan-tunnel toward C. From now switch A doesn't forward anymore packets related to the considered mobile host in the tunnel it shares with switch B (but it still can forward into it packets related to other mobile hosts). The second new pushed flow matches packets based on a new Vlan tag, then it doesn't update FA2 as tunnels between A and B and between A and C use different tags.

Then switch A has now 3 flows in its flow table number 0 : two of them handle host mobility toward network C and the last one is now useless for the considered host but still important to handle mobility of other mobile nodes that have moved from network A to network B.

The two new flows pushed to switch B when the mobile node gets in network C are exactly analog to the ones pushed to switch A when the host moved from network A to network B, but they are associated with the new Vlan tunnel between switch B and switch C. One of the two already existing flows related to the Vlan tunnel established with switch A, was in charge of forwarding packets coming from the tunnel to switch B's flow table number 2, let's call it FB1. The other one was matching packets with the mobile host's old address as source address and was sending them into the tunnel, let's call it FB2. As the mobile node is not anymore in network B, FB2 becomes completely useless as the mobile host is no more emitting directly toward switch B, but FB1 is still used for other mobile nodes that have moved from network A to network B.

Two pairs of flow are then pushed to switch C they are analog to the pair pushed to switch B when the mobile node reached network B from network A, but one pair is related to the tunnel between switch A and switch C and the other to the tunnel between switch B and switch C.

7.4.2 Subsequent Handover Complexity

In this scenario of subsequent handover, when the node gets to network C, 8 flows are pushed by the controller, and every time a mobile node moves to a new network, n time 4 flows will be pushed with n the number of visited networks. Indeed the fact of having simple flow pushing algorithm makes the number of OpenFlow messages quite important. However, our method doesn't present a great space complexity regarding to switches flow tables, and especially for the first flow table. Indeed as tunnel are shared, among the four flows pushed during the first handover between network A and network B, one (FA1) is updated, two are still useful for other mobile hosts (FA2 and FB2), and only one becomes unused (FB1) until the mobile node goes back to network B.

7.4.3 Back to a visited network

If the mobile host, after having visited network C, keeps roaming and goes back to network B, the mobility of the the address acquired in network A and of the one acquired in network C have to be ensured, moreover packets going to the address that the mobile node has forged in network B doesn't have to be transferred in a tunnel anymore.

First, two flows are pushed to switch A and two others are pushed to switch B and as they are exactly the same as the one pushed when the host moved first from network A to network B (the Vlan tag is still the same), there won't have new flows in switch A and switch B's flow table but the flow FA1 will be once again updated and incoming packets aiming the host's old address forged in network A will be forwarded to the tunnel toward B.

Two other pairs of flow are pushed to switch C and switch B again, indeed as we said tunnel are unidirectional in the sense that one tunnel ensure mobility between two switches for a given direction, then two more entries are written in both switch B and switch C's flow table.

Packets going to the address that the mobile node forged into network B when it got there for the first time were matched by a flow entry that sent them into the tunnel between switch B and switch C. Now this flow entry is updated by the controller that pushes a last flow to B with the same matching criteria and that forwards packets on the second flow table of switch B, so that packets going to this specific address are forwarded normally by B toward the local interface the mobile Host just connects to.

When the mobile nodes goes back to a previously visited network, old flow entries are used again, and then flow table size doesn't become very high. As each mobile node is associated to the list of the networks that he visited, if it goes back to previous networks, the same network indentifier can occur multiple time on the list, then in order to avoid to push multiple times flows related to the same tunnel during the same handover procedure, the controller keeps in memory which tunnel it has already updated in order not to send new flows related to an already updated tunnel.

8 Observations and results

Introduction This part is following the steps of what is supposed to be presented during the final presentation, its role is to illustrate and make clearer the concepts presented in the previous section.

8.1 Network topology and simple ping

8.1.1 Topology

Let's consider a network composed by five switches and six hosts, organized according to the following scheme :

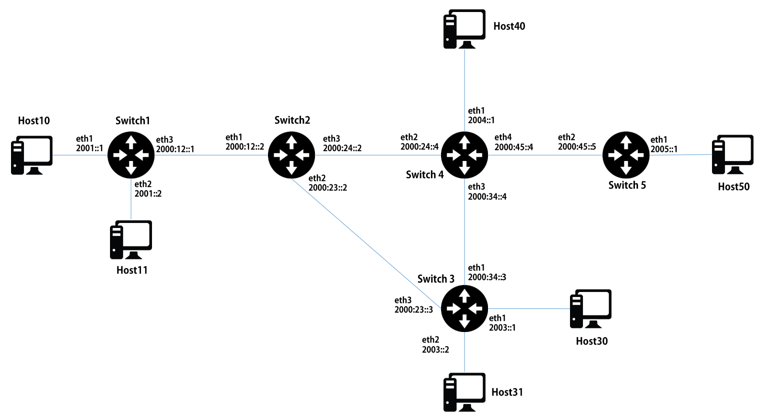
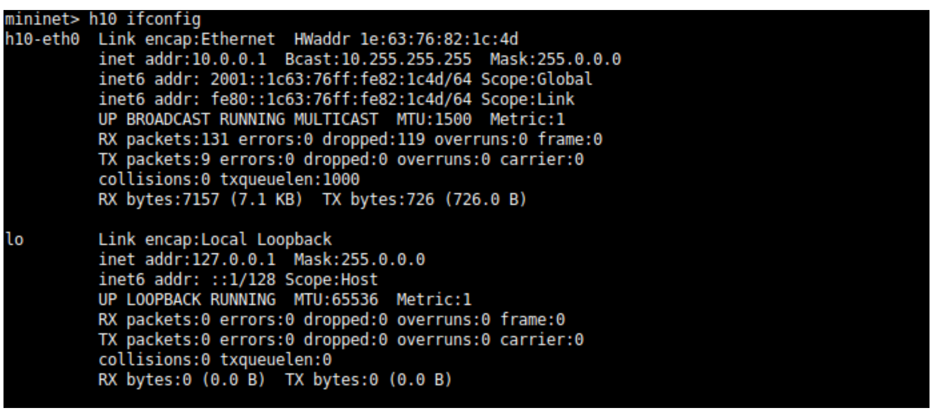


Figure 15: Network topology and addressing

A mininet script has been written to reproduce this topology, to make things clearer the script assignes to each switch address that will be virtually generated by the controller. It also makes the default route configuration on hosts easier.

Once both mininet and the controller are launched, after few seconds hosts get configured with global IPv6 addresses, here is a view of h10's interface configuration:



```
mininet> h10 ifconfig
h10-eth0  Link encap:Ethernet  HWaddr 1e:63:76:82:1c:4d
          inet addr:10.0.0.1  Bcast:10.255.255.255  Mask:255.0.0.0
          inet6 addr: 2001::1c63:76ff:fe82:1c4d/64 Scope:Global
          inet6 addr: fe80::1c63:76ff:fe82:1c4d/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:131 errors:0 dropped:119 overruns:0 frame:0
          TX packets:9 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:7157 (7.1 KB)  TX bytes:726 (726.0 B)

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: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)
```

Figure 16: Interface configuration of h10

8.1.2 Simple Ping

To enable hosts to send messages, they have to be given a default route, here the local router is the default route.

From now hosts are able to ping each other, the first ping messages won't be conveyed to their destination as flows are getting pushed to switches but once they received all the information from the controller, messages are well relayed. Here is an example with h10 pinging h31's IPv6 address :

```
mininet> h10 /sbin/route -A inet6 add default gw 2001::1
mininet> h31 /sbin/route -A inet6 add default gw 2003::2
mininet> h31 ifconfig h31-eth0
h31-eth0  Link encap:Ethernet  HWaddr fa:92:1f:25:a3:7f
          inet addr:10.0.0.4  Bcast:10.255.255.255  Mask:255.0.0.0
          inet6 addr: fe80::f892:1fff:fe25:a37f/64 Scope:Link
          inet6 addr: 2003::f892:1fff:fe25:a37f/64 Scope:Global
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:78 errors:0 dropped:66 overruns:0 frame:0
          TX packets:8 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:4454 (4.4 KB)  TX bytes:656 (656.0 B)

mininet> h10 ping6 2003::f892:1fff:fe25:a37f
PING 2003::f892:1fff:fe25:a37f(2003::f892:1fff:fe25:a37f) 56 data bytes
64 bytes from 2003::f892:1fff:fe25:a37f: icmp_seq=7 ttl=61 time=0.829 ms
64 bytes from 2003::f892:1fff:fe25:a37f: icmp_seq=8 ttl=61 time=1.15 ms
64 bytes from 2003::f892:1fff:fe25:a37f: icmp_seq=9 ttl=61 time=0.812 ms
64 bytes from 2003::f892:1fff:fe25:a37f: icmp_seq=10 ttl=61 time=0.822 ms
64 bytes from 2003::f892:1fff:fe25:a37f: icmp_seq=11 ttl=61 time=0.844 ms
64 bytes from 2003::f892:1fff:fe25:a37f: icmp_seq=12 ttl=61 time=1.23 ms
^C
--- 2003::f892:1fff:fe25:a37f ping statistics ---
12 packets transmitted, 6 received, 50% packet loss, time 11039ms
rtt min/avg/max/mdev = 0.812/0.949/1.231/0.175 ms
```

Figure 17: Ping messages between h10 and h31

The first message of this series of ping has triggered flow pushing to the second flow table of switches on the path from h10 and to h31, at the beginning those tables were empty and now they get populated with the occurrence of new ping messages, here is the content of the flow tables of s1.

```
*** s1 ----------------------------------------------------------------------
NXST_FLOW reply (xid=0x4):
 cookie=0x0, duration=142.540s, table=0, n_packets=158, n_bytes=8058, idle_age=0, priority=6553
5,dl_dst=01:80:c2:00:00:0e,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=142.540s, table=0, n_packets=28, n_bytes=2936, idle_age=59, priority=1 ac
tions=resubmit(,1)
 cookie=0x0, duration=70.136s, table=1, n_packets=11, n_bytes=1298, idle_age=59, priority=1,icm
p6,ipv6_dst=2003::f892:1fff:fe25:a37f actions=dec_ttl,mod_dl_src:a6:01:00:00:00:03,mod_dl_dst:a
6:02:00:00:00:01,output:3
 cookie=0x0, duration=65.108s, table=1, n_packets=6, n_bytes=708, idle_age=59, priority=1,icmp6
,ipv6_dst=2001::d441:bbff:fef4:f93 actions=dec_ttl,mod_dl_src:a6:01:00:00:00:01,mod_dl_dst:d6:4
1:bb:f4:0f:93,output:1
 cookie=0x0, duration=142.540s, table=1, n_packets=11, n_bytes=930, idle_age=65, priority=0 act
ions=CONTROLLER:65535
 cookie=0x0, duration=142.540s, table=2, n_packets=0, n_bytes=0, idle_age=142, priority=0 actio
ns=CONTROLLER:65535
```

Figure 18: Flow tables of s1

At this moment the two other tables are still empty.

8.1.3 Simulating one hop mobility

As making hosts move from one router to another with mininet looks possible to implement in a python script, but not with command line instruction. The idea to overcome this issue is to use IP and MAC spoofing inside the network. Indeed let's configure h50 with the same addresses as h31 while h31 is turned off, as h50 presents h31 identifiers the controller will treat it as if it was h31. Here are the spoofing instructions:

```
mininet> h31 ifconfig h31-eth0
h31-eth0  Link encap:Ethernet  HWaddr fa:92:1f:25:a3:7f
          inet addr:10.0.0.4  Bcast:10.255.255.255  Mask:255.0.0.0
          inet6 addr: fe80::f892:1fff:fe25:a37f/64 Scope:Link
          inet6 addr: 2003::f892:1fff:fe25:a37f/64 Scope:Global
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:359 errors:0 dropped:336 overruns:0 frame:0
          TX packets:19 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:19458 (19.4 KB)  TX bytes:1890 (1.8 KB)

mininet> h31 ifconfig h31-eth0 down
mininet> h50 ifconfig h50-eth0 down hw ether fa:92:1f:25:a3:7f
mininet> h50 ifconfig h50-eth0 inet6 add 2003::f892:1fff:fe25:a37f
mininet> h50 ifconfig h50-eth0 up
mininet> h50 /sbin/route -A inet6 add default gw 2005::1
```

Figure 19: Spoofing instructions

Now, if h10 pings again h31's address, ping messages are still well exchanged but now the TTL of the ping response is equal to 59 whereas it was equal to 61 before, that means that there is two more hops now on the path from h10 to h31's address. With a packet sniffer it is possible to see ping messages going from s1 to s3 and then being relayed in VLAN tagged packet to s5, h31's address mobility is then provided.

```
mininet> h10 ping6 2003::f892:1fff:fe25:a37f
PING 2003::f892:1fff:fe25:a37f(2003::f892:1fff:fe25:a37f) 56 data bytes
64 bytes from 2003::f892:1fff:fe25:a37f: icmp_seq=1 ttl=59 time=14.6 ms
64 bytes from 2003::f892:1fff:fe25:a37f: icmp_seq=2 ttl=59 time=0.932 ms
64 bytes from 2003::f892:1fff:fe25:a37f: icmp_seq=3 ttl=59 time=2.06 ms
64 bytes from 2003::f892:1fff:fe25:a37f: icmp_seq=4 ttl=59 time=1.05 ms
64 bytes from 2003::f892:1fff:fe25:a37f: icmp_seq=5 ttl=59 time=1.18 ms
^C
--- 2003::f892:1fff:fe25:a37f ping statistics ---
5 packets transmitted, 5 received, 0% packet loss, time 4005ms
rtt min/avg/max/mdev = 0.932/3.987/14.692/5.367 ms
```

Figure 20: ping message between h10 and h50 spoofing h31

Ping messages are now received and treated by h50 that now plays the role of h31 as we can see from a packet capture on h50's interface:

Flow tables have been updated, the first flow table of s3 is now containing two flows that transfer packets going to h31's address in the tunnel toward s5. The first and third flow table of s5 have also been populated as we can see:

```
root@sdnhubvm:~/git/EURECOM_SDN_assistance_DMM/SDN_Controler/Topologies[13:04] (master)$ tcpdump -nni h50-eth0 ip6
tcpdump: verbose output suppressed, use -v or -vv for full protocol decode
listening on h50-eth0, link-type EN10MB (Ethernet), capture size 65535 bytes
13:04:33.560272 IP6 2001::d441:bbff:fef4:f93 > 2003::f892:1fff:fe25:a37f: ICMP6, echo request, seq 1, length 64
13:04:33.560298 IP6 2003::f892:1fff:fe25:a37f > 2001::d441:bbff:fef4:f93: ICMP6, echo reply, seq 1, length 64
13:04:34.561715 IP6 2001::d441:bbff:fef4:f93 > 2003::f892:1fff:fe25:a37f: ICMP6, echo request, seq 2, length 64
13:04:34.561749 IP6 2003::f892:1fff:fe25:a37f > 2001::d441:bbff:fef4:f93: ICMP6, echo reply, seq 2, length 64
13:04:35.563274 IP6 2001::d441:bbff:fef4:f93 > 2003::f892:1fff:fe25:a37f: ICMP6, echo request, seq 3, length 64
13:04:35.563307 IP6 2003::f892:1fff:fe25:a37f > 2001::d441:bbff:fef4:f93: ICMP6, echo reply, seq 3, length 64
13:04:36.564374 IP6 2001::d441:bbff:fef4:f93 > 2003::f892:1fff:fe25:a37f: ICMP6, echo request, seq 4, length 64
13:04:36.564408 IP6 2003::f892:1fff:fe25:a37f > 2001::d441:bbff:fef4:f93: ICMP6, echo reply, seq 4, length 64
13:04:37.565767 IP6 2001::d441:bbff:fef4:f93 > 2003::f892:1fff:fe25:a37f: ICMP6, echo request, seq 5, length 64
13:04:37.565798 IP6 2003::f892:1fff:fe25:a37f > 2001::d441:bbff:fef4:f93: ICMP6, echo reply, seq 5, length 64
13:04:38.564677 IP6 fe80::f892:1fff:fe25:a37f > 2005::1: ICMP6, neighbor solicitation, who has 2005::1, length 32
13:04:38.570240 IP6 2001::d441:bbff:fef4:f93 > 2003::f892:1fff:fe25:a37f: ICMP6, echo request, seq 6, length 64
13:04:38.570273 IP6 2003::f892:1fff:fe25:a37f > 2001::d441:bbff:fef4:f93: ICMP6, echo reply, seq 6, length 64
13:04:38.582545 IP6 2005::1 > fe80::f892:1fff:fe25:a37f: ICMP6, neighbor advertisement, tgt is 2005::1, length 32
13:04:39.571996 IP6 2001::d441:bbff:fef4:f93 > 2003::f892:1fff:fe25:a37f: ICMP6, echo request, seq 7, length 64
13:04:39.572030 IP6 2003::f892:1fff:fe25:a37f > 2001::d441:bbff:fef4:f93: ICMP6, echo reply, seq 7, length 64
^C
16 packets captured
16 packets received by filter
0 packets dropped by kernel
```

Figure 21: Capture of ping messages on h50 interface

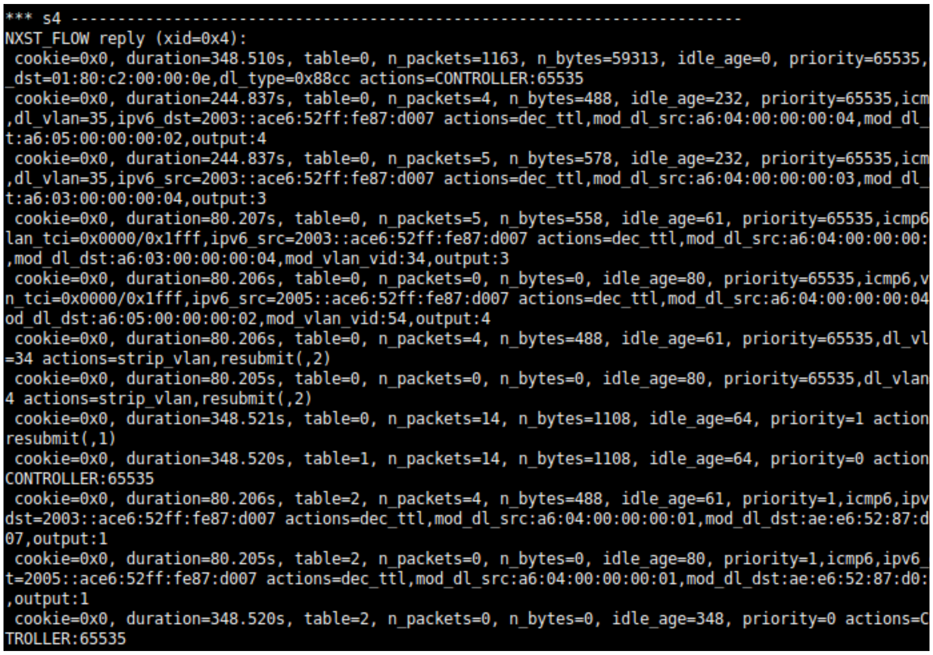
```
*** s5 ----------------------------------------------------------------------
NXST_FLOW reply (xid=0x4):
 cookie=0x0, duration=1094.274s, table=0, n_packets=1215, n_bytes=61965, idle_age=0, priority=6
5535,dl_dst=01:80:c2:00:00:0e,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=648.940s, table=0, n_packets=13, n_bytes=1502, idle_age=220, priority=655
35,icmp6,vlan_tci=0x0000/0x1fff,ipv6_src=2003::f892:1fff:fe25:a37f actions=dec_ttl,mod_dl_src:a
6:05:00:00:00:02,mod_dl_dst:a6:04:00:00:00:03,mod_vlan_vid:35,output:2
 cookie=0x0, duration=648.940s, table=0, n_packets=12, n_bytes=1464, idle_age=220, priority=655
35,dl_vlan=35 actions=strip_vlan,resubmit(,2)
 cookie=0x0, duration=1094.284s, table=0, n_packets=14, n_bytes=1124, idle_age=221, priority=1
actions=resubmit(,1)
 cookie=0x0, duration=1094.284s, table=1, n_packets=14, n_bytes=1124, idle_age=221, priority=0
actions=CONTROLLER:65535
 cookie=0x0, duration=648.939s, table=2, n_packets=12, n_bytes=1464, idle_age=220, priority=1,i
cmp6,ipv6_dst=2003::f892:1fff:fe25:a37f actions=dec_ttl,mod_dl_src:a6:05:00:00:00:01,mod_dl_dst
:fa:92:1f:25:a3:7f,output:1
 cookie=0x0, duration=1094.284s, table=2, n_packets=0, n_bytes=0, idle_age=1094, priority=0 act
ions=CONTROLLER:65535
```

Figure 22: Flow tables of s5

8.1.4 Simulating advanced mobility

Let's now turn h50 off and make h40 impersonate h31 exactly as the same way we did before with h50, the controller will then believe that h31 has now moved from s5 coverage to s4 coverage. Then ping messages go now through a new tunnel between s3 and s4, and second tunnel is set up between s5 and s4, we can retrieve them with the dump of s4 flow table:

When the mobile node moves back under s3 coverage after having visited s4 network, flow tables are updates and ping messages are now routed again to s3 and s3 now forwards packets going to h1'address not anymore on a tunnel but on its local interface where is now plugged h31.



```
*** s4 ---------------------------------------------------------------------
NXST_FLOW reply (xid=0x4):
 cookie=0x0, duration=348.510s, table=0, n_packets=1163, n_bytes=59313, idle_age=0, priority=65535,
_dst=01:80:c2:00:00:0e,dl_type=0x88cc actions=CONTROLLER:65535
 cookie=0x0, duration=244.837s, table=0, n_packets=4, n_bytes=488, idle_age=232, priority=65535,icm
,dl_vlan=35,ipv6_dst=2003::ace6:52ff:fe87:d007 actions=dec_ttl,mod_dl_src:a6:04:00:00:00:04,mod_dl_
t:a6:05:00:00:00:02,output:4
 cookie=0x0, duration=244.837s, table=0, n_packets=5, n_bytes=578, idle_age=232, priority=65535,icm
,dl_vlan=35,ipv6_src=2003::ace6:52ff:fe87:d007 actions=dec_ttl,mod_dl_src:a6:04:00:00:00:03,mod_dl_
t:a6:03:00:00:00:04,output:3
 cookie=0x0, duration=80.207s, table=0, n_packets=5, n_bytes=558, idle_age=61, priority=65535,icmp6
lan_tci=0x0000/0x1fff,ipv6_src=2003::ace6:52ff:fe87:d007 actions=dec_ttl,mod_dl_src:a6:04:00:00:00:
,mod_dl_dst:a6:03:00:00:00:04,mod_vlan_vid:34,output:3
 cookie=0x0, duration=80.206s, table=0, n_packets=0, n_bytes=0, idle_age=80, priority=65535,icmp6,v
n_tci=0x0000/0x1fff,ipv6_src=2005::ace6:52ff:fe87:d007 actions=dec_ttl,mod_dl_src:a6:04:00:00:00:04
od_dl_dst:a6:05:00:00:00:02,mod_vlan_vid:54,output:4
 cookie=0x0, duration=80.206s, table=0, n_packets=4, n_bytes=488, idle_age=61, priority=65535,dl_vl
=34 actions=strip_vlan,resubmit(,2)
 cookie=0x0, duration=80.205s, table=0, n_packets=0, n_bytes=0, idle_age=80, priority=65535,dl_vlan
4 actions=strip_vlan,resubmit(,2)
 cookie=0x0, duration=348.521s, table=0, n_packets=14, n_bytes=1108, idle_age=64, priority=1 action
resubmit(,1)
 cookie=0x0, duration=348.520s, table=1, n_packets=14, n_bytes=1108, idle_age=64, priority=0 action
CONTROLLER:65535
 cookie=0x0, duration=80.206s, table=2, n_packets=4, n_bytes=488, idle_age=61, priority=1,icmp6,ipv
dst=2003::ace6:52ff:fe87:d007 actions=dec_ttl,mod_dl_src:a6:04:00:00:00:01,mod_dl_dst:ae:e6:52:87:d
07,output:1
 cookie=0x0, duration=80.205s, table=2, n_packets=0, n_bytes=0, idle_age=80, priority=1,icmp6,ipv6_
t=2005::ace6:52ff:fe87:d007 actions=dec_ttl,mod_dl_src:a6:04:00:00:00:01,mod_dl_dst:ae:e6:52:87:d0:
,output:1
 cookie=0x0, duration=348.520s, table=2, n_packets=0, n_bytes=0, idle_age=348, priority=0 actions=C
TROLLER:65535
```

Figure 23: Flow tables of s4

Part IV
Conclusion & Futur Enhancements

9 Conclusion

We have finally managed to implement a controller working regardless the underlying network topology and built for IPv6. Simulation shows that host mobility is well handled then now controller code can be tested on a physical network. This controller can be also used only for managing classic IPv6 network without host mobility needs.

This project has been a great opportunity to work with Software Defined Networking tools and to understand deeply the concept. It has also been a great mean to discover the latest frameworks built for SDN and the details of OpenFlow.

10 Enhancements

10.1 Controller algorithms

10.1.1 Having less flow to push

We already said that each time a node moves to a new network after having visited n networks, 4 time n flows have to be pushed down by the controller, then after a while it can turns out to be lot of flow to send. In order to limit this number a new way to handle mobility would be only to set up a tunnel between the switch of the network just left by the host and the one of the network just reached, then mobility would be ensured with this series of tunnel bound one after the other one among which switches would forward packets going to the address the mobile node has forged under their coverage but also packets going to the address the mobile has forged in the network visited before : coming from the sequence of tunnel.

10.1.2 Handling the first packets of flow

As routing flows are pushed re-actively the first packets of a sequence that triggers a flow pushing are lost. This can be avoided in implementing a buffering mechanism inside the controller or in making it tell switches to forward those packets to their destination while flows are being set up.

10.1.3 Handling other types than ICMPv6

Flows pushed to both the first or the second flow table of each switch match IPv6 echo messages, this has to be changed in the future to allow other types of message to be treated. The question then is gather all the network traffic type in one general matching flows or assign specific flows for each supported protocol.

10.1.4 Handle address conflict within the same sub network

In our implementation, we suppose that hosts compute their local and global IPv6 addresses following an unique method implemented in the controller. Address conflicts between hosts leading to a different manner to forge them are then not considered by the controller.

10.1.5 Introducing access control to mobility service

As mobility management is presented as a service it would be nice to control which user can use it. Then the implementation of a policy decision an enforcement entity could be done which would be consulted when a new user shows up in the network. The authentication can be first based on the mac address, and then on more advanced criteria.

10.2 Interaction with Mininet

10.2.1 Make hosts move for real

Yet a way to make host moves from one switch to another within the Mininet virtual network hasn't been found, that is why our way was to trick the SDN controller with addresses spoofing. But as hosts doesn't properly move in our simulation we do not really know how the system really reacts and may be the messages exchanged between the mobile node and the switch are not exactly the same.

10.2.2 From command line to a batch program

Our demonstration has been done in typing one by one all the Mininet instructions that turns out to be quite the same, it would make the interaction with Mininet easier and faster especially during the test phases to load once an instruction file instead of writing them all every single time.

10.3 fixing the bug

When a ICMPv6 Echo message has to be forwarded by a switch on the same interface that it has been received, nothing happen : the flow that tell the switch to forward the packet is matched but the output packet is not detected by packet sniffer. This problem even occurs when packets to forward are modified in getting inserted a Vlan tag in their structure. Then tunnel establishment is strongly impacted by this bug whose origin is still not known.