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# FENet: An SDN-Based Scheme for Virtual Network Management

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**Abstract**—Virtual networking is vital to efficient resource management in Clouds, and it is in fact one of the main services provided by many Cloud Computing platforms. Virtual network management needs to meet specific requirements, including tenant isolation and adaption to virtual machines' lifecycle. Most of the existing schemes for virtual network management are based on the use of overlay networks in order to achieve a desirable degree of flexibility. However, these schemes suffer from a common limit, i.e. relatively high performance penalty due to a complicated forwarding process. We address this performance concern by developing a new management scheme, FENet, which makes use of Software-Defined Networks (SDN) to create virtual networks and manage them via the SDN controller programs. We present the design of an SDN controller, with the definition of flow entry rules based on the OpenFlow protocol and the specification of a routing algorithm. The results from our experimental evaluation show that our SDN-based prototype can control virtual network interconnections and tenant isolation appropriately. FENet achieves about 30% better network performance than the management scheme based on OpenVPN and lower latency in comparison with the traditional bridging scheme.

**Keywords**—Cloud Computing; OpenFlow; SDN; tenant isolation; virtual networks;

## I. INTRODUCTION

Cloud Computing platforms provide services such as computing, storage, networking and security. As more and more distributed applications run on the Cloud Computing virtualization platforms, virtual networks become very important. The management of virtual networks differs from the physical networks in some aspects. Firstly, several virtual machines (VM) on the same host share the physical hardware including network interface cards (NIC), thus the management scheme needs to consider either transferring the virtual network packets via physical networks directly, or encapsulating them in the hosts' packets to forward. Secondly, tenant isolation should be supported as it is important to ensure security and eliminate impacts among tenants. Thirdly, The management scheme should flexibly adapt to the virtual network topology's changes that result from the VM operations like starting, migrating and deleting.

Nowadays, the common management schemes of virtual networks can be divided into two types. One is based on traditional bridging (taken by OpenStack [1]), which binds the VMs' NICs with the physical NICs on a

virtual bridge, and transfers the virtual network packets via the physical NICs. Though this transfer method achieves good network performance, the virtual network management lacks of flexibility, for example, lots of configuration work is needed and tenant isolation is constrained to limited number of tenants. The other type is based on overlay networks [2, 3], which encapsulates the virtual network packets into the hosts' packets, and forwards them by tunneling technique. This type of scheme achieves flexible virtual network management, however, the use of overlay networks leads to network performance loss because of the complicated forwarding process. It is hard to balance the trade-off between flexible management and network performance by traditional methods.

Over the past few years, Software-Defined Networks (SDN) [4] has become a research hot spot in the area of networking. SDN proposes separating the control plane and data plane of the switches, and concentrating the control planes into an uniform controller. The controller manages the whole network and instructs the switches to handle network packets. By leveraging the idea of SDN, it is possible to achieve flexible control and good network performance, because management logic in the devices can be accomplished conveniently. SDN has been used to develop improved solutions in areas like data center networks [5] and traffic engineering [6], however, research that aims at virtual network management is incomplete. For examples, [7] proposes an SDN-based method for tenant isolation, it enables communications among VMs only while Internet access is ignored. Besides, it does not consider how to handle broadcast packets.

This paper proposes FENet, which is an SDN-based scheme for virtual network management. FENet creates virtual networks upon the devices that support OpenFlow protocol [8], and develops SDN controller programs to manage them. The SDN controller responds to the VM operations and controls virtual network interconnections and tenant isolation. In addition, FENet provides packets validation and improved routing algorithm to achieve better network utilization. We develop a prototype of FENet, and conduct experiments to evaluate its effectiveness and performance. The experimental results show the prototype can accurately control virtual network interconnections and tenant isolation, besides, it achieves about 30% better network performance than the management scheme based on OpenVPN and lower latency than the scheme based on traditional bridging.

The remainder of this paper is organized as follows: Section II introduces the related work; Section III describes the details of design and implementation; Section IV presents the evaluation of the prototype with functional and performance experiments; Section V concludes the paper and describes the future work.

## II. RELATED WORK

### A. Management schemes based on traditional bridging

Management schemes based on traditional bridging leverage virtual Ethernet bridge (Linux Bridge, Open vSwitch [9]) to transfer the VMs' network packets via the host's NICs, then the packets are delivered to the physical networks. 802.1Q protocol is taken to achieve tenant isolation. Tenants are allocated with different VLAN identification numbers, and the network packets sent from VMs belonging to a tenant are tagged with a unique VLAN identification number, thus switches isolates the packets according to the VLAN tags. However, the VLAN tag in the Ethernet packets is only 12 bits long, which means the isolation units are no more than 4096. Methods like private VLAN [10] and VXLAN [11] are proposed to address this issue. Private VLAN configures the switches with two-level VLAN strategy and maintains a VLANs' mapping table, but its effect is not good as the packets forwarding become more complicated and the mapping table cannot be large enough. VXLAN is a kind of overlay networks actually. Schemes based on traditional bridging are not flexible enough as physical switches need lots of configuration like VLAN strategy, gateway and routing rules. Besides, VM migration is restricted within a layer-2 network in order to keep the network configuration of VMs unchanged.

### B. Management schemes based on overlay networks

Overlay networks are logical networks that built upon physical networks. Management schemes based on overlay networks encapsulate the virtual network packets into the hosts' packets, and the encapsulation modules take charge of the management issues, such as network routing, tenant isolation and traffic measurement. The related projects includes VNET [2], IPOP [3] and OpenVPN [12]. In VNET, the virtual network packets are encapsulated and sent to a host acting as proxy. The proxy host will forward the packets to the host where the destination VM locates. IPOP creates a virtual device and binds it with the VMs' NICs, thus the hosts' programs could capture the virtual network packets by executing traditional read/write operations to the virtual device. OpenVPN is open-source implementation of VPN, which transfers network packets between different local area networks by IP tunneling. Usually, tunneling is used to extend the overlay networks across layer-3 networks. Nowadays, many Cloud Computing solutions take this type of scheme, such as VXLAN in VMware ESX, NVGRE [13] in Windows Azure and Amazon VPC [14].

In these schemes, tenant isolation is indicated by tunneling identification numbers, which is plenty enough to meet the demand of large amount of isolation units. Besides, these schemes have fewer constraints to VM migration because the network packets are encapsulated. However, the use of overlay networks suffers from higher

performance loss in comparison with schemes based on bridging, because the virtual network packets will be forwarded to the programs in the hosts firstly, and then sent out as data contents in the physical packets. So the total process takes twice copy operations between user space and kernel space. In addition, the routing of virtual network packets is handled by virtual routers on the hosts rather than physical network devices. The common virtual routers are acted by VMs with several NICs, which are less efficient compared with physical routers.

### C. Software-defined networks

Software-defined networks [4] could be used to address issues like the network management becomes too tough as the network scales up. The advantage of SDN is that developers could manage the networks much more flexibly and conveniently by designing the controller programs, which maintain the network topology and control the networks including routing, configuration and flow control. OpenFlow [8] is now a famous protocol in SDN that enables the communication between the controller and network devices. The main contents of OpenFlow protocol include the working process of OpenFlow switch, the structure of flow tables and message types between the controller and OpenFlow switches.

The research of SDN is focused on the controller design and improved methods of networking areas. Researchers pay high attentions to the SDN controller's performance [15, 16] as well as reliability [17], and advanced controllers likes Onix [18] are proposed to further improve the SDN network performance. Besides, SDN is applied to areas such as data center networks [5], QoS [19] and network virtualization [20].

Nicira Network Virtualization Platform (NVP) [21] proposes solutions aiming at virtual network management, it combines SDN and IP tunneling to achieve virtual network interconnections and isolation. However, IP tunneling makes the transfer process more complicated, which may result in performance loss. [7] proposes a method of tenant isolation based on SDN, but it only works when the hosts are in a layer-2 network, because it replaces the packets' destination MAC address with the host's MAC address while the destination IP address is still the VM's, so the packets cannot be routed across physical layer-2 networks. Besides, this method does not provide Internet access for the VMs. The OpenFlow protocol is flexible and it is possible to realize more management logic by flow entry rules.

## III. DESIGNS AND IMPLEMENTATION

Since OpenFlow protocol defines flexible rules for the network devices to handle packets, the virtual network management can be accomplished efficiently if virtual networks are created upon OpenFlow devices. On the one hand, physical devices forward the virtual network packets directly to achieve high network performance, on the other hand, the SDN controller takes charge of the virtual network management in a programmable way. In OpenFlow supported networks, the SDN controller instructs the network devices by sending OpenFlow flow entries, thus the management scheme of virtual networks

should design special flow entry rules to provide features like routing and tenant isolation. Besides, to adjust the flow entry rules accurately, the management scheme also needs to define interactive interfaces between the SDN controller and virtualization platforms. FENet is a kind of management scheme that designed according to above ideas.

The virtual network structure in FENet is as Fig.1 shows. Hosts are connected to virtual networks and the management network via two NICs, each host runs Open vSwitch (also supports OpenFlow protocol) to connect VMs. All the physical OpenFlow switches are connected with the controller via the management network. Besides, hosts are configured with NAT strategy for VMs' Internet access, and Open vSwitch acts as gateway for VMs.

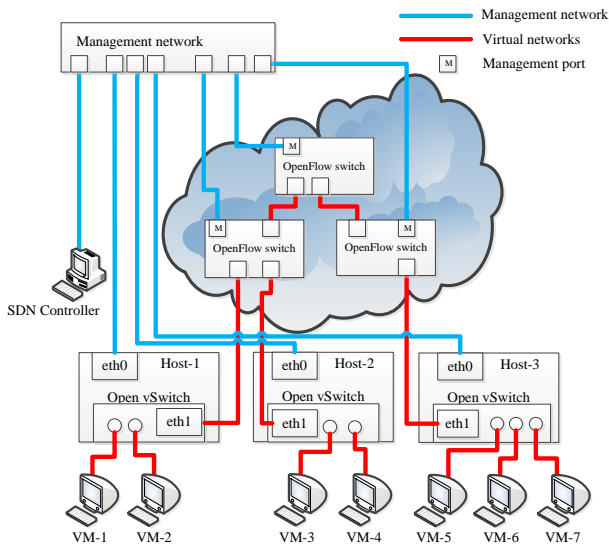


Fig.1. The structure of SDN-based virtual networks

The SDN controller maintains the global view of virtual networks. Once VM operations happen, the OpenFlow switches will send messages to the controller, which will handle the messages according to management

strategies. The general management strategies of virtual networks are as follows:

- Routing: VMs belonging to the same tenant could communicate with each other, no matter they are in the same subnet or not;
- Tenant isolation: VMs that belong to different tenants are isolated;
- Broadcast handling: ARP/DHCP requests from VMs are handled by the controller directly rather than broadcasting in the networks;
- Internet access: All the VMs can access the Internet via their gateways;

#### A. OpenFlow flow entry rules

OpenFlow switches handle the network packets according to the inside flow tables. To design reasonable and accurate flow entry rules, we need to classify and analyze the virtual network packets first. Network packets from VMs include data-link layer broadcast packets, IP layer broadcast packets, IP layer unicast packets, multicast packets and so on. At present, FENet has supported ARP broadcast packets, DHCP broadcast packets and regular IP unicast packets. Other network packets will be considered later. For example, multicast packets can be supported by maintaining multicast groups in the SDN controller. The classification of packets sent from/to VMs are shown in Table 1 and Table 2.

Open vSwitch acts as access switch for the VMs, thus the packets sent from VMs are firstly handled by Open vSwitch. For ARP requests, Open vSwitch permits them to transfer if the request's source VM belongs to the same tenant with the target VM/gateway, otherwise the request packets are discarded. After passing the validation, the ARP requests will be forwarded to the controller. As the controller stores the VMs' information, it can easily find out the requested destination MAC address and send back ARP reply packets to the Open vSwitch. By this way, ARP broadcast packets will not be transferred in virtual networks, which avoids network bandwidth occupied by large amount of broadcast packets as the network scales.

TABLE 1. PACKETS SENT FROM VM

Packet Type	Destination (address)	Flag	Permitted	Handling
ARP Request	Broadcast address	Out_1	Yes: within the same tenant	Forward to the controller
			No: other cases	Discard
DHCP Request	Broadcast address	Out_2	Yes	Forward to the controller
	VM (belongs to same tenant & same subnet)	Out_3	Yes	Forward to the VM
	VM (belongs to same tenant & different subnet)	Out_4	Yes	Route & forward to the VM
	Gateway (belongs to same tenant)	Out_5	Yes	Forward to the gateway
IP	Other internal IP addresses (Reserved IP) 10.0.0.0/8   172.16.0.0/16   192.168.0.0/24	Out_6	No	Discard
	Internet	Out_7	Yes	Forward to the gateway
	Others (such as multicast address)	Out_8	No (at present)	Discard

TABLE 2. PACKETS SENT TO VM

Packet Type	Source (address)	Flag	Permitted	Handling
ARP Reply	The controller	In_1	Yes	Forward to the VM or gateway
DHCP Reply	The controller	In_2	Yes	Forward to the VM
	VM belongs to the same tenant	In_3	Yes	Forward to the VM
IP	VM belongs to different tenants	In_4	No	Discard
	Gateway	In_5	Yes	Forward to the VM
	Internet	In_6	Yes	Forward to the VM
	Others(such as multicast address)	In_7	No (at present)	Discard

Besides, the packet validation filters spiteful ARP request packets, thus the controller can efficiently respond to the legal requests. The packet validation in Open vSwitch is applied to IP packets and DHCP request packets as well.

FENet takes OpenFlow version 1.3.0 specification. Switches supporting OpenFlow v1.3 handle the packets by several steps in a pipeline, and each step is instructed by a flow table. A special variable called metadata is transferred between adjacent steps to carry additional information. The flow table is a set of flow entries, and a flow entry is one record that consists of several fields including Match Fields, Priority, Counters and Instructions. The Match Fields is a set of several field types that refer to the outermost occurrence of the fields in the packet headers, for examples, Field `eth_dst` refers to the destination MAC address in the Ethernet packet headers. If a packet matches one flow entry's Match Fields, the corresponding Counters updates and the switch handles the packet as the Instructions indicates.

The OpenFlow flow entry rules in physical switches are different from Open vSwitch's, because Open vSwitch acts as access switch and plays an important role in validating the incoming packets, while the physical switches just forward the packets to the right destination. we select several match fields according to the OpenFlow protocol specifications: `eth_src` identifies the source MAC address, `eth_dst` identifies the destination MAC address, `ip_dst` identifies the source IP address, `arp_tpa` identifies the requested IP address in ARP request packets.

Assume that VM<sub>a</sub> (IP address is ip, MAC address is mac, gateway is gw and belongs to tenant T<sub>1</sub>) is connected to the Open vSwitch S on port P, the flow entry installation for virtual networks is as follows:

- 1) To handle the packets sent out from VM<sub>a</sub>, install one flow entry to the flow-table 0 (used in the first step of the process pipeline) in all switches, the Match Fields is 'eth\_src=mac', the Priority is 2 and the Instructions is 'set metadata=T<sub>1</sub> and go to flow table 1 (used in the second step of the pipeline)'.
- 2) To handle the packets sent to VM<sub>a</sub>, install two flow entries in Open vSwitch S: one to flow-table 0 with the Match Fields is 'eth\_src=mac', the Priority is 1 and the Instructions is 'Forward packets to port P'; the other one to flow-table 1 with the Match Fields is 'eth\_src=mac, metadata=T<sub>1</sub>', the Priority is 4 and the Instructions is 'Forward packets to port P';
- 3) To handle the packets sent to VM<sub>a</sub> in other switches except from S, the controller computes each switch S<sub>i</sub>'s routing path to VM<sub>a</sub> and gets the next hop port number P<sub>i</sub>, after that it installs one flow entry to flow-table 1 in switch S<sub>i</sub>, the Match Fields is 'eth\_src=mac, metadata=T<sub>1</sub>', the Priority is 1 and the Instructions is 'Forward packets to port P<sub>i</sub>';

Combining the rule 1 to 3 together enables VMs to communicate with the ones belonging to the same tenant.

For example, as Fig.2 shows, when VM<sub>1</sub> sends packets to VM<sub>2</sub>, the packets firstly match No.1 flow entry of switch S<sub>1</sub>'s flow-table 0, and then match No.3 flow entry in flow-table 1, so the packets are sent to switch S<sub>2</sub>. In switch S<sub>2</sub>, the packets match No.1 flow entry of flow-table 0 firstly and then match No.4 flow entry of flow-table1, and eventually get to VM<sub>2</sub>.

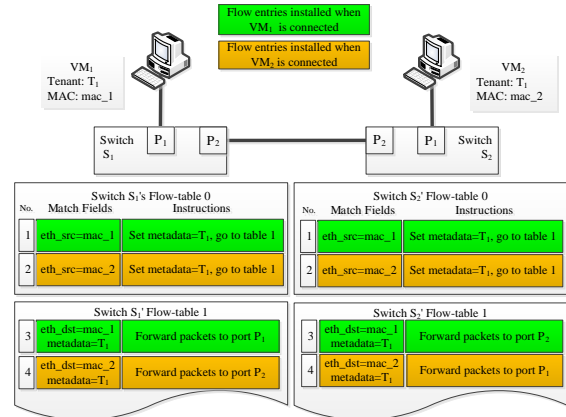


Fig.2. An example of communication between VMs

- 4) Install default flow entry (Priority=1) for ARP request packets with Instructions is 'Drop'. And for ARP request packets that request for VM<sub>a</sub>'s MAC address, install a flow entry to flow table-1 in each switch, the Match Fields is 'Packet type is ARP request, arp\_tpa=ip and metadata=T<sub>1</sub>', the Priority is 2 and the Instructions is 'Forward packets to the controller'. The controller will handle the requests and send the ARP reply packets back to the access switch. The flow entry rule for VM<sub>a</sub>'s DHCP requests is similar.
- 5) To handle the packets sent from VM<sub>a</sub> to Internet, the controller computes the routing path for VM<sub>a</sub> to access its gateway, and install a flow entry to switches along the path. The flow entry's Match Fields is 'metadata=T<sub>1</sub>, eth\_src=mac and eth\_dst=gw', the Priority is 1 and the Instructions is 'Forward to the next hop port'.
- 6) When VMs that locate in other different subnets send packets to VM<sub>a</sub>, the packets' destination IP address is ip but destination MAC address is their gateways' address, so the controller install a flow entry rewriting the destination's MAC address to mac into the Open vSwitch. The flow entry's Match Fields is 'metadata=T<sub>1</sub>, ip\_dst=ip and eth\_dst=gw', the Priority is 3 and the Instructions is 'Write eth\_dst=mac and forward the packets to the next hop port'. This method achieves efficient routing process.
- 7) To achieve tenant isolation, we appoint all the VMs are configured with internal IP addresses (marked as Reserved IP) [22]. A default flow entry is installed to flow table-1 in each switch, the Match Fields is 'ip\_dst=Reserved IP and eth\_dst=gw', the Priority is 2 and the Instructions is 'Drop'.



To conclude above rules, there are two steps in the process pipeline of Open vSwitch, and flow entries in Open vSwitch will cover all the types of network packets listed in Table 1 and Table 2. Assume that the number of VMs is  $N$ , then the total number of flow entries in flow table-0 is about  $2N$ , thus FENet supports more than 32,000 VMs under the size limitation of flow table (in our environment, 65535), and the tenant isolation units can be as many as the number of VMs.

## B. Routing algorithm in FENet

When a new VM is connected to the network, the controller computes the routing path for every switch to access the VM. The common method is the shortest path algorithm that just takes the hop counts between switches into consideration. Since the controller stores the network topology, computing the routing path only once is very efficient for the controller to respond to the flow entry installation requests. However, the location of VMs usually depends on the loads of the hosts, such as CPU and memory, which means hop count-based routing may lead to low network utilization and load unbalanced. To address this problem, we choose to execute the routing algorithm each time a new VM is connected, and the routing algorithm will do its best to allocate loads evenly within the entire network. Prediction of the network traffic is a tough issue, so we identify a network link's load by the count of VMs that will send packets through it.

In FENet, we design several dictionary variables for Switch objects. The variable nextHop refers to the links established between switches, variable nextHopCount refers to the count of VMs that send packets through network links in nextHop, variable local\_vm refers to the VMs directly connected to the switch, and variable remote\_vm refers to the VMs that send packets through the switch. The data structures of these variables are shown in Table 3.

TABLE 3. DATA STRUCTURES OF DICTIONARY VARIABLES

Attributes	Format
nextHop	{'port_num': 'switch_addr'}
nextHopCount	{'port_num': 'count'}
local_vm	{'tenant_id': {'vm_mac': 'port_num'}}
remote_vm	{'tenant_id': {'vm_mac': 'port_num'}}

FENet executes the routing algorithm by two stages. The first stage is updating the load of each link because the new VM may have access to VMs belonging to the same tenant. Assume that all the Switch objects are stored in array switch, a new VM<sub>a</sub> (belongs to tenant  $t_1$ , MAC address is mac) is connected to switch  $S_A$  (stored in switch[i]) at port  $P_0$ . Algorithm 1 describes the procedure of the first stage:

Algorithm 1 Updating the load of links when a new VM added

```

1. switch[i].local_vm[t1][mac] = P0
2. for mac, port in switch[i].remote_vm[t1].items():
3.   sw = switch[i]
4.   while sw.remote_vm[t1].has_key(mac):
5.     port_num = remote_vm[t1][mac]
6.     // update the load of network link from one vertex:
7.     sw.nextHopCount[port_num] += 1
8.     sw = sw.switch[nextHop[port_num]]
9.     // update the other vertex's nextHopCount
10.  end while
11. end for

```

The second stage of the algorithm selects the routing path for every switch to access VM<sub>a</sub>, the selection process is based on greedy strategy. We define the maximum load of all the network links in one path as the path's load. Switches that to be routed are marked as unvisited, and the algorithm maintains several variables for each unvisited switch  $S_i$ , including variable  $P_{opt}(i)$  that stores the optimal path for  $S_i$  to VM<sub>a</sub>,  $load\_count(i)$  that stores the load of  $P_{opt}(i)$ . Besides, the load of link between  $S_i$  and its previous switch along  $P_{opt}(i)$  is stored in  $previous\_count(i)$ , and the hop count of  $P_{opt}(i)$  is stored in  $distance(i)$ , all these three variables related to  $P_{opt}(i)$  are the smaller the better. Each round the algorithm selects the optimal  $P_{opt}$  from  $P_{opt}(i)$  at a priority order of  $load\_count > previous\_count > distance$ , and marks the corresponding switch  $S_i$  as visited  $S_{new}$ , which means the routing path for  $S_{new}$  to access VM<sub>a</sub> is found. If  $S_{new}$  connects VMs that belong to the same tenant as VM<sub>a</sub>, the algorithm needs to update the  $previous\_count$  of the switches on  $P_{opt}$  and the  $load\_count$  of other affected  $P_{opt}(i)$ . The pseudo codes of updating operations are as Algorithm 2 shows.

Algorithm 2 Updating affected load\_count and previous\_count

```

1. vm_count = Snew.local_vm[t1].count()
2. if vm_count > 0:
3.   sw = Snew
4.   // update the previous_count of switches till SA
5.   // variable previous stores the previous switches on the path to SA:
6.   while not sw == SA:
7.     previous_count[sw] += vm_count
8.     root_sw = sw
9.     sw = previous[sw]
10.  end while
11. // update the affected switches' load_count
12. queue.push(root_sw)
13. while not queue.empty():
14.   sw = queue.pop()
15.   load_count[sw] += vm_count
16.   // AFFECTED_SET is the set of switches whose Popt(i) contains
17.   // sw and load_count(i) < load_count[sw]:
18.   for switch in AFFECTED_SET:
19.     queue.push(switch)
20.   end for
21. end while
22. end if

```

At the end of each selection round, the algorithm traverses  $S_{new}$ 's unvisited neighbor switches to check whether there is any improvement of  $P_{opt}(i)$  through  $S_{new}$ . Assume that the number of switches is  $N$ , then the time complexity of the total routing algorithm is  $O(N^3)$ .

## C. VM operations handling processes

The SDN controller maintains the virtual network topology, including the information of all the VMs and switches. To ensure the consistency of relations between VMs' status and the switches' flow entry rules, FENet takes a series of VM operations handling processes between the SDN controller and virtualization platforms. By this way, FENet accurately adjusts the flow entry rules and achieves flexible management. Usually virtualization platforms provide a web interface (marked as portal) for the users to access, thus we use portal to represent virtualization platforms in the following description.

### 1) VM deploying

The portal sends the new VM's information (network configuration and tenant ID) to the SDN controller, after

that the controller inserts a record of this VM into the database, and sets the VM's status to deployed.

### 2) VM starting

When the VM starts, its access switch will report to the controller about an OpenFlow message that a port turns to UP status, and this message contains the access device's MAC address. The controller queries the database to get the VM record and checks the status of the VM. If the status is deployed or migrated, then the controller will install new flow entries to the related switches.

### 3) VM migrating

The portal sends the migrating operation details to the controller, including information of the migrating VM and the target host. Then the controller updates the migrating VMs' status to migrated and sets its access\_switch to the target switch. Once the VM starts on the target host, the next handling process is similar with 2).

### 4) VM stopping

The portal sends the stopping operation details to the controller, and the controller updates the target VM's status to stopped.

### 5) VM deleting

The portal sends the deleting operation details to the controller, and then the controller updates the target VM's status to deleted. When the target VM shuts down, the controller will receive an OpenFlow message from the access switch that a port turns to DOWN status, and it queries the database to get the VM record that matches the MAC address contained in the OpenFlow message. If the VM's status is deleted, then the controller instructs all the switches to delete flow entries related to the deleted VM, and updates the load of network links.

## IV. EXPERIMENTAL EVALUATIONS

The prototype of FENet is developed upon RYU [23], which provides OpenFlow interfaces for developing SDN controller programs. We conduct functional experiments to validate the effectiveness of the prototype. Besides, performance experiments are conducted to evaluate the prototype, including the virtual network performance and the scalability of virtual networks.

### A. Virtual network interconnections and isolation

We build a virtual network as Fig. 4 shows. 2 hosts are connected to an H3C S5820 OpenFlow switch, and each host runs 4 VMs. The VMs are tagged with several tenants' ID, and some of them are configured with IP addresses belonging to different subnets. Various experiment conditions makes accurate validation of virtual network interconnections and isolation.

Firstly, we take ping tests among the 8 VMs. The partial results are shown in Table 4. As we expected, the VMs belonging to the same tenant could communicate each other, no matter their IP addresses are in the same subnet or not. And the VMs belonging to different tenants are isolated. The results verify that virtual network interconnections and isolation are controlled accurately. Secondly, we test the VMs to access the Internet. The virtual network has 5 subnets, but there are only two true

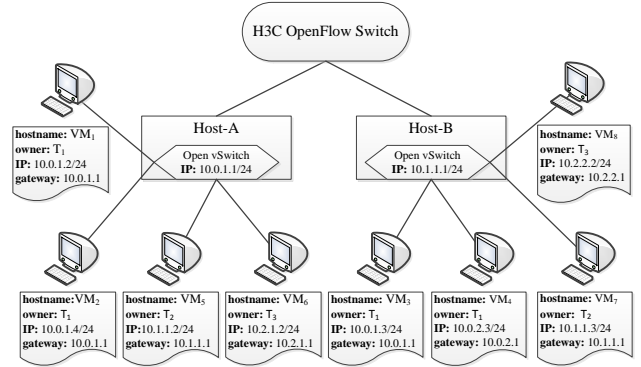


Fig.4. Network topology of functional experiments

gateway devices, thus VMs belonging to tenant T<sub>1</sub> and tenant T<sub>3</sub> are mapped to gateway on host-A, while those belonging to tenant T<sub>2</sub> are mapped to gateway on host-B. The results show all the VMs could communicate with public IP addresses. This test verifies that different subnets could share a gateway for accessing the Internet. That's valuable as in production environment the number of virtual subnets increases dynamically while the hosts' is usually fixed.

TABLE 4. PING TESTS RESULTS

Use Case	Conditions			Expected Result	Test Result
	Same tenant	Within subnet	Same Host		
VM <sub>1</sub> →VM <sub>2</sub>	Yes	Yes	Yes	enabled	enabled
VM <sub>1</sub> →VM <sub>3</sub>	Yes	Yes	No	enabled	enabled
VM <sub>3</sub> →VM <sub>4</sub>	Yes	No	Yes	enabled	enabled
VM <sub>2</sub> →VM <sub>4</sub>	Yes	No	No	enabled	enabled
VM <sub>2</sub> →VM <sub>5</sub>	No	No	Yes	rejected	rejected
VM <sub>6</sub> →VM <sub>7</sub>	No	No	No	rejected	rejected

### B. Virtual network performance

We realize the control of a 4 VMs' virtual network by 3 types of schemes respectively, including scheme based on OpenVPN, scheme based on traditional bridging and FENet. All the three schemes use Open vSwitch-2.0.0 as the VMs' access switch. VM<sub>1</sub> and VM<sub>2</sub> run on the host-A, and their IP addresses are configured in a same subnet. VM<sub>3</sub> and VM<sub>4</sub> run the host-B, VM<sub>3</sub> is in the same subnet with VM<sub>1</sub>/VM<sub>2</sub> while VM<sub>4</sub> is in another subnet. These 4 VMs belong to the same tenant, thus they are able to communicate with each other.

We measure the network performance between VMs by Iperf and ping. The results are shown in Fig. 5 and Fig. 6. We use openvpn to identify the OpenVPN scheme, and use bridging to identify the traditional bridging scheme.

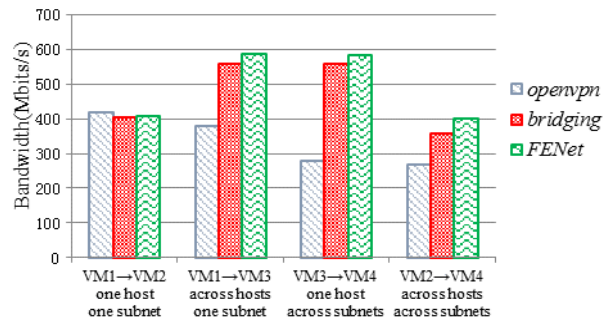


Fig.5. Bandwidth of communication between VMs

VM<sub>1</sub> and VM<sub>2</sub> communicate with each other via a layer-2 network because they are connected with the same Open vSwitch and their IP addresses are configured in the same subnet, so the packet forwarding process of these three schemes are similar, the result shows the bandwidth of communication between VM<sub>1</sub> and VM<sub>2</sub> are about 400Mbps/s. Though VM<sub>3</sub> and VM<sub>4</sub> run on the same host, they are configured into different subnets, thus the packets forwarding between them needs layer-3 routing, bridging leverages physical layer-3 switches to accomplish routing, the packets are sent out from host-B firstly and then sent back to host-B after routing. FENet makes use of packet headers rewriting to accomplish routing and the packets are forwarded within host-B. openvpn runs a VM as virtual router. The results show FENet and bridging provide better bandwidth of communication between VM<sub>3</sub> and VM<sub>4</sub> than openvpn. FENet improves the bandwidth further by a special routing method.

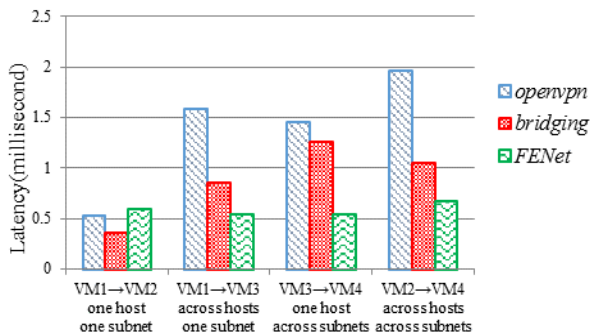


Fig. 6. Latency of communication between VMs

When VMs that locate different hosts communicate with each other, the network performance in FENet is about 30% higher than openvpn. Because in openvpn, the packets are encapsulated and sent to the VPN server for transferring. Besides, the routing process handled by virtual router also pays a cost of performance loss.

Packets transfer process of FENet is essentially based on bridging, so the bandwidth performance of FENet and bridging are similar. However, the results show FENet achieves lower latency. On the one hand, bridging takes VLAN field as the tenant isolation identification tag, thus the operations of adding/removing VLAN tags are additional in compared with FENet, on the other hand, FENet accomplishes routing efficiently by packet headers rewriting.

### C. The scalability of virtual networks

As we described in sector II, the flow entry rules in FENet support more than 32,000 VMs, and FENet is faced with challenges of virtual networks' scalability in two aspects, one is responding to the ARP requests, and the other is responding to VM startup and installing flow entries to the switches. We run Cbench [24] to measure the responding ability of the controller. The controller application is running on a host that has 8 cores of Intel(R) Core(TM) i7 CPU 860 @2.80GHz and 8 GB memory.

Firstly, we measure the controller's throughput of ARP replies when different amounts of switches are connected to the controller, we assume that each switch

has a fixed number of hosts of 100, which is above the common case of today's commercial products. The results are shown in Fig.7. As the number of switches increases, the throughput of the controller keeps improving till an upper bound is reached. Finally, the throughput holds steady at more than 18,000 responses per seconds, because the CPU usage reaches 100%.

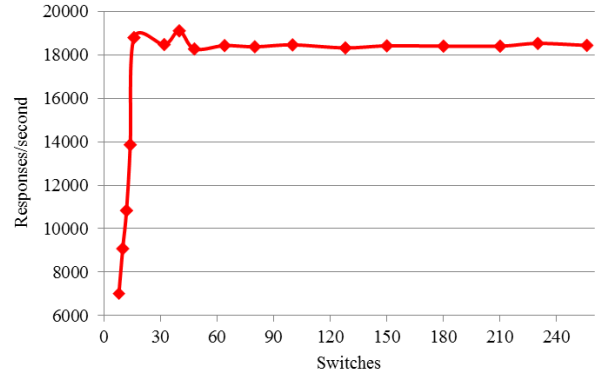


Fig. 7. The throughput of controller with different number of switches

Besides, we measure the elapsed time of OpenFlow flow entry installation when a VM is connected to virtual networks of different scale. The virtual network scale is determined by the amount of physical switches, each physical switch is connected with 20 Open vSwitch. When the controller manages a virtual network of 64 physical switches, it will install flow entries for 1280 switches (including software based Open vSwitch), the elapsed time of flow entry installation for one VM is 1.185 seconds, and the results of other cases are shown in Fig. 8. As RYU is single-threaded the controller has to take serial processing for flow entry installation when plenty of VMs concurrently start. In a virtual network of 4 physical switches, when 1000 VMs start at the same time, the total elapsed time of flow entry installation is about 81 seconds.

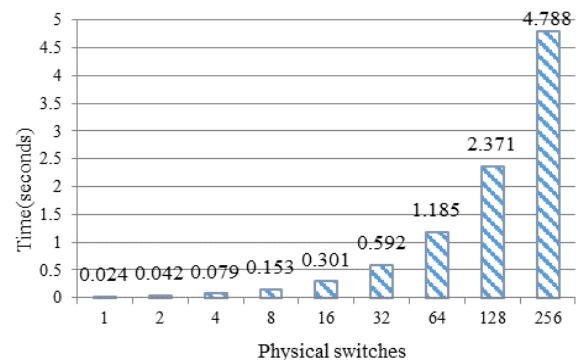


Fig. 8. Elapsed time of flow entry installation for one VM

### D. Network utilization of routing algorithm

In this test we run twelve VMs on six hosts. These VMs are allocated to different tenants, VM<sub>1,2,3</sub> belong to tenant-1, VM<sub>4,5,6,9,10</sub> belong to tenant-2 and VM<sub>7,8,11,12</sub> belong to tenant-3. After that the SDN controller respectively takes the FENet's routing algorithm and the routing algorithm based on the shortest path algorithm to compute routing paths for the 12 VMs. The network utilizations under these two algorithms are shown in Fig. 9.



The shortest path routing algorithm only considers the hop counts between the packets' source and destination, while in FENet, the controller chooses routing paths based on several metrics, such as the links' loads and the hop counts of paths, therefore FENet achieves higher virtual network utilization, and the network links are relatively load balanced, which may help to relieve network congestion.

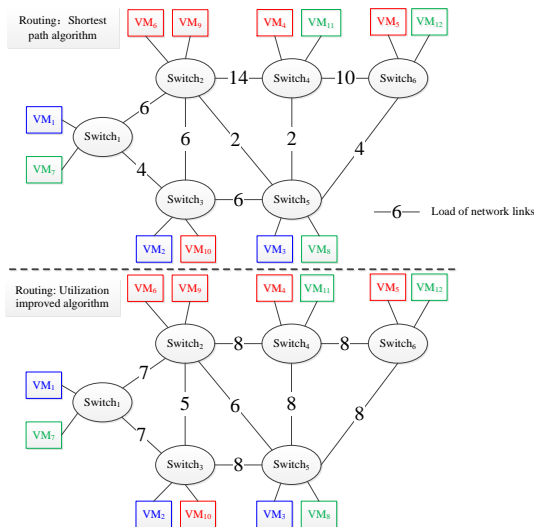


Fig.9. The network loads of different routing algorithms

## V. CONCLUSIONS

This paper proposes FENet, a flexible and efficient management scheme for virtual networks. FENet creates virtual networks based on SDN, and develops an SDN controller to guarantee tenant isolation and flexibly manage the virtual network interconnections even though the VMs are added or removed constantly. In addition, FENet takes several effective methods, such as packets validation and improved routing algorithm, to improve the network utilization and performance. The contributions of this paper include designing the OpenFlow flow entry rules to achieve virtual network management, proposing a network utilization concerned routing algorithm and the handling processes of VM operations between the SDN controller and virtualization platforms.

The functional experiments validate the prototype's effectiveness of virtual network interconnections and tenant isolation. Besides, FENet achieves about 30% better network performance than the management scheme based on OpenVPN and it improves the network latency in comparison with the management scheme based on traditional bridging.

As the virtual networks scale up, FENet may need a distributed controllers deployment to improve management efficiency. And the tunneling technique may be used to enable virtual network communications across data centers. We leave these topics as our future works.

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