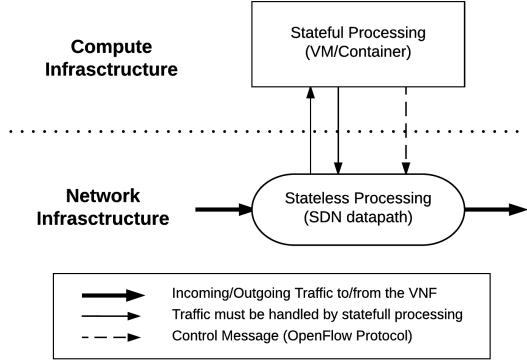


Fig. 1. Overview of network function



I. INTRODUCTION

THIS document is a template for Microsoft Word versions 6.0 or later. If you are reading a paper or PDF version of this doconference. (By Eric)

II. RELATED WORK

(By Eric)

III. vCPE SYSTEM OVERVIEW

A. Overview of Network Function

With the concept of SDN-enabled[1] VNFs, SDN technology work not only a for traffic steering but also as a part of network functions. In this idea, network function have been achieved by the synergies between compute and network infrastructures. The former is a VNF controller, mainly responsible for dealing with stateful processing. The latter is a SDN switch, used for stateless processing.

1) *Stateful Processing component (VNF controller in container)*: This component have to control the workflow, keep the state associated with the VNF, and provide interface for service providers or customers to configure and update the behavior of the stateless datapath processing component. We use SDN controller to implement the NFV controller and its worth noting that we use southbound APIs of SDN controller framework to handle the interface between the stateful and stateless component with OpenFlow protocol, which was originally designed for this.

2) *Stateless Processing component (SDN datapath)*: Stateless processing component, are implemented by SDN datapath resources, which is optimized for data plane traffic processing. Since SDN switch have decoupled the control plane and data plane, so it can accept the control message from the stateful processing component.

Using the advantages of this architecture, we can assign stateless or light-weight state work to the SDN switch, for example, packet filtering and packet counting, to load-off the computing resources. If we want to update our service, we just need to update the statful component, since the stateless component just follow the command from stateful components.

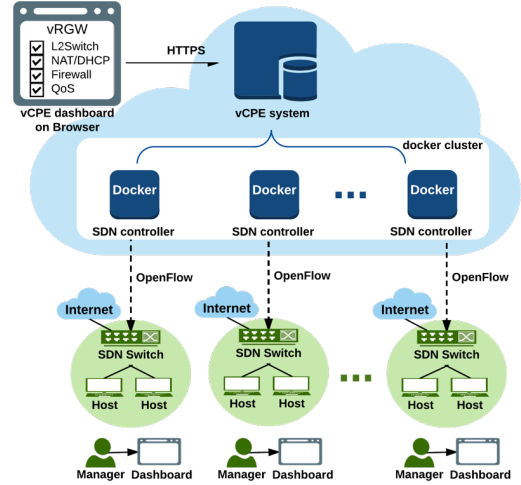


Fig. 2. Service Deployment Model

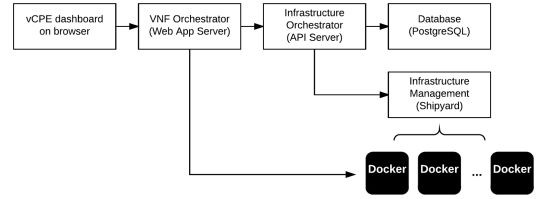


Fig. 3. Overview of vCPE framework

B. Service Deployment Model

With architecture mentioned in III-A, we come up with a network function service deployment model. Because computing infrastructures handles the algorithm and policies, and the generic network devices only do stateless processing, the customer just need to buy a general SDN switch at their home gateway and will have a different network function service by subscribing different NFV controller through our vCPE platform.

Figure 2 illustrates the service deployment model. Each green area is a local network domain of customer. At the gateway of this domain, theres a SDN-enabled switch. The customer can subscribe to our vCPE service through our dashboard. After subscribing, the vCPE system will create a new docker container, in which running a SDN controller we developed. The customer only need to setup the gateway SDN switch to connect the SDN controller by the OpenFlow protocol, then the switch will handle these service.

C. Architecture of the vCPE framework

1) *System Overview*: The architecture as shown in Fig 3 including of a Infrastructure Controller, Infrastructure Orchestrator, Cloud Database, VNF Controllers and VNF Orchestrator. The Infrastructure Orchestrator, VNF Orchestrator and Cloud Database are web servers Each component is introduced in the subsection below.

2) *Infrastructure Controller*: The infrastructure controller is a composed Docker management server with the ability to manage the Docker resources like containers and images. The infrastructure doesn't handle the customer authentication or maintaining the state of running service, it just follows the request from the infrastructure orchestrator to create, delete, start, stop and inspect containers.

3) *Infrastructure Orchestrator*: The infrastructure orchestrator plays the key role of our system. It connecting and automating of workflows when we deploy our services. When a customer subscribes, the infrastructure orchestrator authenticates the customer first, next it will call the infrastructure controller to create a container for this customer, and update information in database afterwards. It handle the entire lifecycle of our vCPE service.

4) *Cloud Database*: The cloud database is used for restoring the of our vCPE services, which include each customers credential, customers container settings and virtual CPE service states. The cloud database is using PostgreSQL, which is a open source, easily customized and object-relational database system. Only Infrastructure Orchestrator has permissions to access cloud database.

5) *VNF Controllers*: VNF Controllers contains a SDN controller developed with ryu framework and a remote launcher module. The SDN controller does not have a remote launcher module to remotely execute a SDN controller. We built a lightweight server as a launcher module to resolve the remotely execution issue. The remote launcher module monitor the SDN controller process ID (PID) and properly kill the SDN controller process ID when on demand. When the infrastructure controller once create the container, the remote module will run up initially, waiting request from VNF Orchestrator. The details of SDN controller design will be presented at section IV.

6) *VNF Orchestrator*: The VNF Orchestrator is a Web application server hosting on Amazon Web server, being online for customer and provide a dashboard for virtual CPE and containers management and configuration.

Through the web UI provided by the VNF Orchestrator, the customers can subscribe to the desired service and without typing any command via the command line interface (CLI). After receiving the subscribing message, the VNF orchestrator will request the infrastructure orchestrator to create a new VNF controller, and then send the virtual CPE configuration to the new VNF controller. Based on configuration demands under different conditions, the network administrator is able to select any of the listed network functions on the dashboard such as Firewall, NAT, DHCP and QoS management.

D. Network Functions

1) *Firewall*: The firewall service could filter the packets based on packet header fields, including MAC address, IP, and layer4 protocols. The network manager can add new rules or remove rules to the access control list through our vCPE GUI.

2) *NAT*: The NAT service is a network function that can remap IP address to another one. The Source NAT (SNAT) is typically used by internal users (inside private network) to

access the Internet (outside network). The network function uses the action Set-Field, which defined by OpenFlow protocol for rewriting packet header fields. Via vCPE GUI interface, the network manager can set up the WAN port of SDN switch, public IP, default gateway, and local network address when using this function.

3) *DHCP*: DHCP service allocates IP addresses to hosts dynamically. To implement the function, the SDN controller cope with UDP packets which use port 67 and 68. It generates DHCP offer and DHCP acknowledge to reply DHCP discovery and DHCP request received from the hosts.

4) *Forwarding*: Forwarding Service is a basic service that forward traffic to its destination and we use the Mac address learning concept to implement our forwarding function.

5) *QoS*: Quality of Service (QoS) are always used to control the traffic flows of a network and prevent the traffic to exceed the network capacity and cause traffic congestion. Therefore we implement the bandwidth management using meter which is defined within OpenFlow protocol 1.3 to set the limitation of the bandwidth. Beside achieving network functions virtualization with SDN technology, we also make the network administrator manage and monitor a network more easily. As a result, we can offer the user the best network quality in the limited network resource without traffic congestion. In this paper, our QoS integrates with a flow classification engine and offers the three ways of bandwidth management:

- For a specific host.
- For a specific host.
- For a specific application from a host or a domain.

E. Application Identification

Application identification is to identify each flow as an application name to enable QoS management system to do bandwidth control or distribution at application level. A flow is defined by 5-tuple (source IP, source port, destination IP, destination port, and transport layer protocol). Applications include desktop applications, native mobile applications, and web applications, such as Facebook, Skype, YouTube, Instagram, Line and WeChat. We use supervised machine learning and a method based on inspecting domain name service (DNS) responses to do flow classification. After application identification system classifies a flow as an application name, it sends the classification result to a server with database. The server stores the classification result into database, and waits for query with 5-tuple from QoS management system. The detail will be described in section V.

IV. NETWORK FUNCTION WITH MULTIPLE TABLE MANAGEMENT MODEL

A. Multiple Flow Tables Strategy

In subsection III-A, the vCPE service design architecture have been introduced. The network functions are handled by the cooperation between SDN controller on cloud and SDN switch at the local network gateway. The controller transform the network functions to series of OpenFlow rules requests and send to SDN switch. Following the orders from controller, the

SDN switch inserts rules to its flow tables, checks incoming packets against the flow entry match fields, and execute the actions in matching rules. The flow table defines all matching and corresponding processing, thus playing an important role to executive network function.

Since the flow table is crucial component, and we find that single table binds us to implement our network functions. The [2] also mentioned two condition for single table is too restrictive. The first is a single packet need to perform independent actions based on matching different fields. The second is that the packet needs two-stage processing. Involves into both situation, our network functions implemented by multiple flow tables strategy.

In multiple flow tables strategy, the most important question is: which flow table should we insert rules into? We use the network function as a demarcation, that is, SDN applications which are responsible for specific network functions will only insert rules to one specific flow table, so we can focus on the design of the network function itself. In this way, however, the order of flow table become crucial. Should we put this network function at first, or the other? The answer is about the type of match and action in the rules generated by the network function

The network functions of our vCPE services including Forwarding, Firewall, NAT, DHCP and QoS. We have determined the order of each function, shown in IV-A. In the following subsections, we will introduce how to implement these network functions, which type of rules will be inserted to SDN switch, and how these rules affect our decision of the order of flow tables.

B. Service Control

Service control is used to enable or disable service. To enable a service, we need to modify the table-miss rule. We always put a packet-in rule in the table of the last active service as a table-miss in case that there isn't any corresponding rule. To make our service chain possible, the rules of each service except the last service contains an additional action, go to next table, so the packets can continue to pass through all active services.

To disable a service, we not only need to modify the table-miss rule but also have to add an enforce rule. Each enforce rules has maximum priority and the action is goto next table. It means that packets will still pass through the disabled service's table, and the only thing they do in this table is ignoring other rules and go to next table.

C. Firewall

Firewall service is able to block traffic dynamically, and in this service, the packets will not cause any packet-in event. On the dashboard, we can specify the blocking policies. There are 4 kinds of policies:

- Block any traffic from a certain source IP.
- Block all traffic to a certain destination IP.
- Block traffic based on known layer 4 protocols, such as SSH, HTTP, etc.
- Block traffic to any layer 4 ports of a host.

For different policies, the controller applies corresponding rules to the SDN switch. After the policies are set, the blocking rules will be installed immediately. Then any traffic that hit the blocking rules will be dropped. For normal traffic, they will not be affected.

As shown in Table IV-C, all the actions of flow entries are drop. The 1st rule illustrates that SSH connection with source IP address 192.168.2.1 would be blocked. The 2nd rule shows the flow entry would block the Telnet protocol.

In our multiple table model, the firewall service is located in the table 1, since once packets are caught by the blocking rules, they doesn't need to apply any other services. The packets which match the rules will be dropped immediately, and their journey in the flow table ends here. To other no-blocked packets, they pass all blocking rules and finally match the table-miss rule, which will let the packets go on the next table. The action of firewall is different from other services, since in other services, no matter what actions are taken to the packets, the packets have to go to the next table

D. DHCP

DHCP service implements DHCP protocol to dynamically assign IP addresses to hosts. DHCP operation uses UDP protocol. The clients use port 68 as the source port and 67 as the destination port. On the contrary, the server use port 67 as the source port and 68 as the destination port. Our system is able to handle these packets to realize DHCP service.

The service follows these steps:

- 1) The controller adds a DHCP rule for DHCP packets when the service is enabled.
- 2) All packets match this DHCP rule cause packet-in.
- 3) The controller checks if a packet is a DHCP discovery packet.
 - a) If so, the controller assigns an IP address, and generate a DHCP offer then do packet-out.
 - b) If not, the controller then checks whether it's a DHCP request. If the result is positive, the controller generate a DHCP acknowledge then do packet-out.

Our system support multitiable, but a specific table for DHCP service is not required. The reason is that only one rule will be installed for all hosts who request for DHCP service. When the service is disabled, the DHCP rule will be deleted, and the packets will continue to pass through our service chain. Following DHCP packets can reach other DHCP servers without entering our service chain since our controller will automatically flood out broadcast packets.

E. NAT

The NAT service could allow a lot of hosts to use one public IP address to connect the network. In order to achieve this thing, SDN controller have to set the packet header filed. Because the SDN switch would set the field, the first packet have to go to controller. And controller would add the flow to SDN switch, after that the packet would not go to controller. It can decrease the burdens of the controller.

Below is a examples to show how the NAT service modify the IP address and port number, as shown in Fig IV-E.

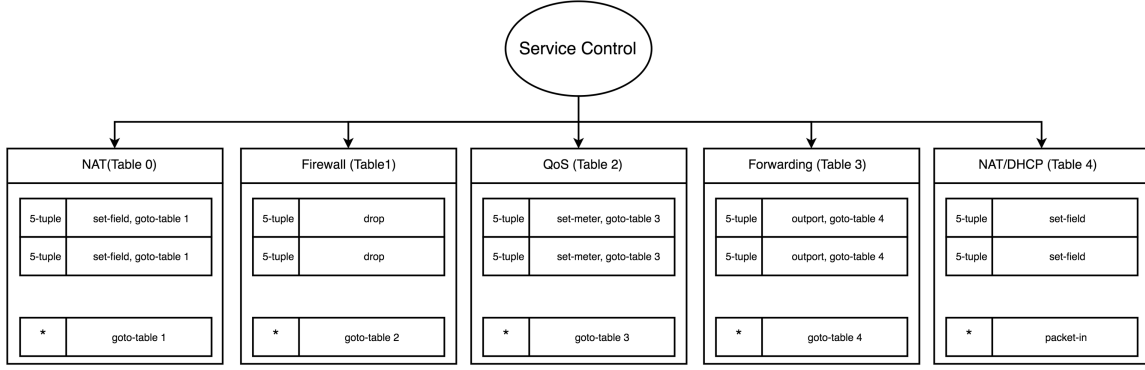


Fig. 4. The flow table order of our vCPE service

IP proto	IP Src	IP Dst	L4 sport	L4 dport	Action
TCP	192.168.2.1	*	*	22	Drop
TCP	*	*	*	23	Drop

Symbol * represents wildcard (match any value).

TABLE I

FIREWALL RULES IN FLOW ENTRY

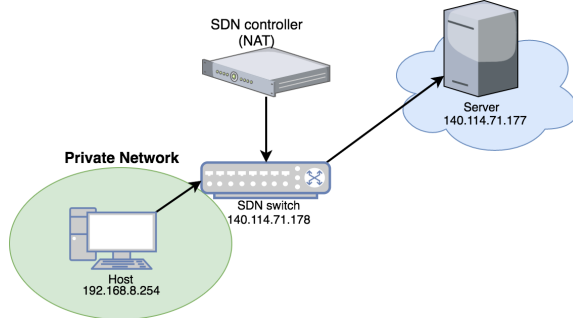


Fig. 5. Illustration of NAT service

For outgoing packet, SDN switch doesn't have any flow entry in flow table, so the Packet-in event will be triggered at the beginning. The packet that is sent by private network host will be sent to SDN controller, and the packet header fields are modified by Set-Field action. The source IP address and source port number of outgoing packet will be modified to public IP address and remapped a new port number for NAT. For incoming packet, the destination IP and destination port number are modified to fit private IP and port number. And then SDN controller adds these flow entries to SDN switch, it can't avoid that all the packets sent to controller. Fig. IV-E shows the public IP address of NAT is 140.114.71.178 and a host private IP is 192.168.8.254 and port number 7878. The client sent the packet to a server with IP address 140.114.71.177 and port number 9898.

As shown in Table IV-E, when host sent the packet to server (outgoing), the Packet-in will be triggered, and then packet to controller. The Set-Field action would modify the Source IP to public IP address of NAT is 140.114.71.178 and source port to 2000. When the server sends back to the client (incoming), the packet header field would be modified. The destination IP address and destination port number would be modified to 192.168.8.254 and 7788.

In the single table framework, we have to add the two rules to SDN switch to match the outgoing and incoming situation. At the first, we predict the NAT service to be put one the last table in the multiple table framework. Because the NAT service needs to set the packet header fields and play a role of connection to the outside network. And the most important thing is that the SDN switch is according to order of table to match. We have to consider the outgoing and incoming situations. As a result of all the above factors combined, the NAT service is located at the first and the last table in our multiple table framework.

F. QoS

QoS service is mainly for traffic control and we provide three management functions for QoS service. We will introduce these three strategies first and then discuss the table order of QoS service in multiple table model.

1) *Rate limitation of hosts*: When some hosts take up a lot of bandwidth of network, it will make other hosts in slow speed or make traffic congestion. To prevent this, rate limiting is used to control the rate of traffic from a host. For implementing the host rate limitation, we create a meter for desired bandwidth first and then add a flow, of which matches hosts' MAC address and action is the meter we just created.

The concept of this option is shown in Fig. 6 and Table III. In T0, host 1 and host 2 are not limited yet. Since host 2 takes up a lot of bandwidth from network in T0 T1, the network administrator sets host 2 rate-limited under 400 Kbps. When controller receives this request, marked as (a), it will create a new meter with meter id = 1 and bandwidth = 400 Kbps, and set the rule in the flow table with destination MAC address = HOST1 MAC and meter = 1. According to our flow table, it will limit the rate of the target host. Then the traffic from Host 2 will reduce and be limited with 400Kbps immediately. The similar situation also occurs to Host 1 in T2. The administrator chooses to set Host1 under 600 Kbps, marked as (b), and then traffic from Host 1 will be limited with 600Kbps.

	IP Src	IP Dst	L4 src port	L4 dst port	Action
1. outgoing	192.168.8.254	140.114.71.177	7878	9898	IP Src \rightarrow 140.114.71.178; L4 src port \rightarrow 2000
2. ingoing	140.114.71.177	140.114.71.178	9898	2000	IP Dst \rightarrow 192.168.8.254; L4 dst port \rightarrow 7878

TABLE II
FLOW ENTRY FOR MODIFYING THE PACKET HEADER FIELDS OF PACKETS

Request	Match	Action
(a)	Destination MAC Address = MAC address of Host 1	Goto Meter 1 (400Kbps), Next Table
(b)	Destination MAC Address = MAC address of Host 2	Goto Meter 2 (600Kbps), Next Table

TABLE III
FLOW ENTRY FOR MODIFYING THE PACKET HEADER FIELDS OF PACKETS

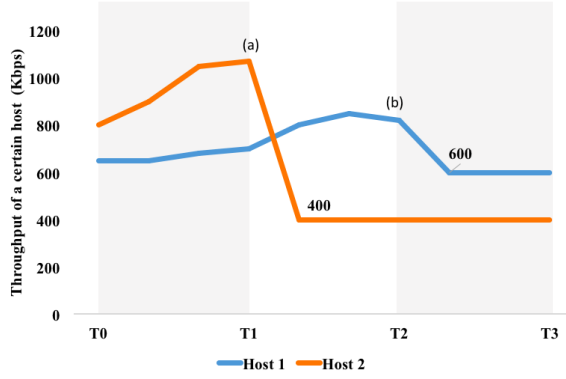


Fig. 6. Illustration of rate-limiting for a certain host

2) *Rate limitation of applications:* There are more and more networks applications used such as online games, video streaming, conference call, etc. Therefore, there are massive traffic working in the network. Consequently, we integrate with a flow classification engine to identify the flow belongs to which application is. However, an application may have many connections, we will equally distribute the bandwidth to each connection.

For instance, if there is an application and we can find out which flows belong to this application through the flow classification engine. If we want to limit this application to 1000Kbps. As Figure. 7 and Table IV, in T0, we know there are 3 connections belong this application and we will set the bandwidth of meter to each link with $1000/3 = 333$ Kbps. In T2, there are more two connections added to this application and we will reset the bandwidth of meter to each links with $1000/5 = 200$ Kbps. In T2, there is a connection ended by this application, we will reset the bandwidth of meter to each links with $1000/4 = 250$ Kbps, therefore. Whereas, the sum of bandwidth from this application is always being 1000Kbps. That is, the bandwidth will dynamically adjust basic on the algorithm 1 if we want to set the bandwidth of application to B Kbps and there are N connections from the application. The algorithm is shown as Algorithm 1.

3) *Rate limitation for a certain application of certain host:* By way of flow classification, we can know the 5 tuple (IP protocol, source IP, destination IP, source port, destination port) from each connection between an application and a host. Consequently, the network administrator can use those 5-tuple

Function UpdateMeterBandwidth(app,B,N):

```

if there is no exclusive meter for the application then
    Assign a free meter to this application
end
if there are new connections added or ended then
    Reset the meter's bandwidth to B/N
end
return

```

Algorithm 1: Updating the bandwidth to application

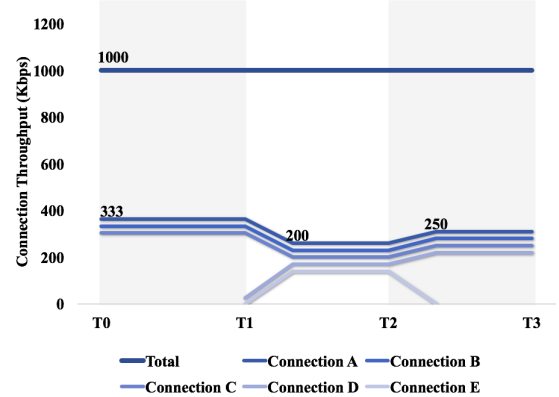


Fig. 7. Illustration of rate-limiting for a certain host

and dynamically adjust the bandwidth of meter, according the algorithm mentioned in above, to limit the bandwidth of each application from a host. As shown in figure. 8. and Table. V. In T0, we want to limit the application B to the Host with 600 Kbps and we will add the rules matching each 5 tuples from application A and set Meter 1 to those rule. In the meantime, the bandwidth of Meter 1 is set to $600/N$ Kbps if there are N connections built from application B of the host. In T1, marked as (a), If we want to limit the application A to the Host with 300 Kbps, we will add the rules matching each 5 tuples from application A and set Meter 2 to those rule. Then in T2, marked as (b), application B has already been limited since T0 and we want to change the bandwidth of application B from 600Kbps to 1000 Kbps. However, We would not change the rule in flow table, we only change the bandwidth of the correspond meter in the meter table. That is, the bandwidth of

Condition	Meter Bandwidth
At T0, there are three connection initially.	$1000 / 3 = 333$ Kbps.
At T1, Two new connection (D, E) come up.	$1000 / 5 = 200$ Kbps.
At T2, A connection (E) is closed.	$1000 / 4 = 250$ Kbps.

TABLE IV
METER BANDWIDTH CHANGING BASED ON THE NUMBER OF APPLICATION CONNECTIONS

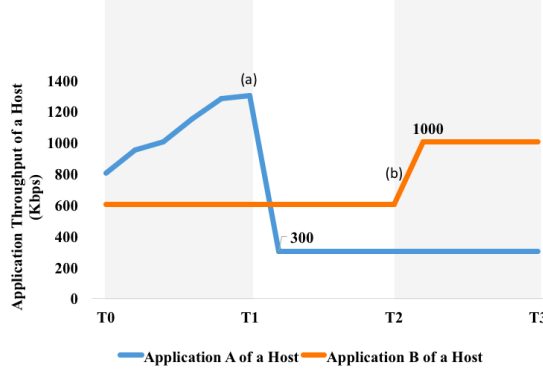


Fig. 8. Illustration of rate-limiting for a certain application of certain host

Meter 1 will be set from $600/N$ to $1000/N$. Therefore, there only have a little overhead between switch and controller. That is, if there are N_i connections in time T_i , then the bandwidth will be set as shown as following. Similarly, we can use the same way to limit the whole network while not only to the specific host.

4) *The table order of QoS service:* QoS service is located at table 2, because the location of NAT/DHCP, firewall are determined. Here we only need to decide the arrangement of QoS and forwarding. Let's consider the scenario that we put the QoS table after the forwarding table. Plus, we have only two services enabled, forwarding and QoS, then suppose a host is not limited by QoS policies. The very first packet will not be affected in both arrangement. For the following packets, the difference can be observed. The packets which has matched the rules of the forwarding table will still cause packet-ins when they go to QoS table. This is not supposed to happen, since the host is not restrained by QoS policies and any packet-in increase the controller's load. To reduce the burden of the controller, we put QoS table ahead of forwarding table. In this scenario, all packets that pass through QoS table will continue to go to forwarding table without matching any QoS rules. Then the packets except the very first packet will just be forwarded by forwarding service instead of causing packet-ins. Hence the controller's load will decrease. To use our system, the forwarding service is necessary, so there is no such scenario that users enable QoS and disable forwarding.

G. Forwarding

In this service, when the first packet in a new connection incoming, it will cause a packet-in event because there is no corresponding rule. When controller receives the packet, it will record IP-layer information, including source IP, destination IP, input port number, source mac address and destination mac address. With the recorded information, the controller is able

to install a 5-tuple forwarding rule for this connection and following packets don't need to packet-in again. The 5-tuple is source IP, destination IP, network layer protocol, source layer 4 port, and destination layer 4 port.

In order to gather per-session statistics information, 5-tuple rules are needed. This is why we don't add rules based on mac address. The controller installs a pair of dummy rules for every connection, and then request the switch to get current flow statistics every second. In this way, we can get the real-time bandwidth statistics of each connection by just subtracting the byte count from byte count of last second.

V. APPLICATION IDENTIFIER METHOD

In order to let QoS management system be able to control or distribute bandwidth at application level, we designed and implemented an application identification system (also called flow classification system) to judge each flow is established by what application. In other words, the system can classify each flow as an application name in real time, rather than a rough category or a transport layer protocol. We use supervised machine learning (ML) and a method based on inspecting domain name service (DNS) responses to do flow classification. Except for DNS responses, the system only analyzes transport layer information of packets without inspecting their payload

A. Architecture of our application identification system

There are training phase (also called preparation phase) and classifying phase, their architectures are shown in Fig 9 and Fig 10 respectively. These architectures can be integrated, and do training and classifying in the same time. The detail will be mentioned in the following paragraph

B. Overall procedure of application identification

In training phase, we generate some data needed by ML and the method based on inspecting DNS responses. In classifying phase, if a flow meet some requirement, we use the method based on inspecting DNS response to classify; otherwise, we use ML to classify.

C. Procedure of Supervised ML in our system

In training phase, the architecture is show in Fig I. Flow classification engine is to build classification model by training data from Trainer, and update the model when new training data comes. Trainer is to analyze traffic from mirror port to get flow attributes. After Trainer finishes calculating flow attributes of a flow, it gets ground truth of the flow from Scanner or App Meta Server to generate training data, and sends training data to flow classification engine. App Meta Server is to store mappings of 5-tuple and ground truth

Request	Match	Action
Initial	5 tuples from an application B connection of the Host	Goto Meter 1 (600 Kbps), Next Table
(a)	5 tuples from an application A connection of the Host	Goto Meter 1 (300 Kbps), Next Table
(b)	5 tuples from an application B connection of the Host	Goto Meter 2 (1000 Kbps), Next Table

TABLE V

FLOW ENTRY OF RATE-LIMITING FOR A CERTAIN APPLICATION OF CERTAIN HOST

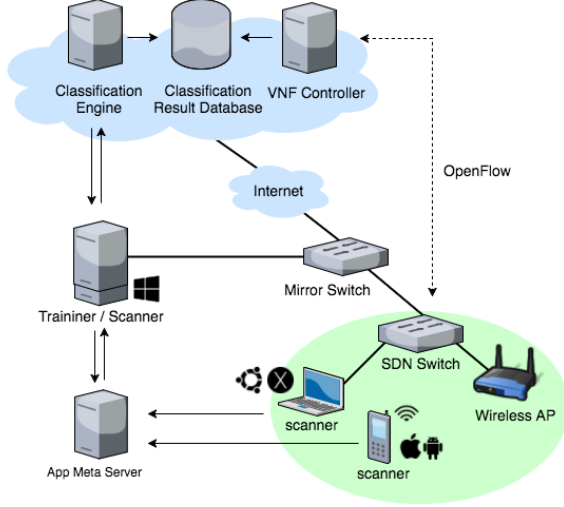


Fig. 9. Architecture of our application identification system in training phase

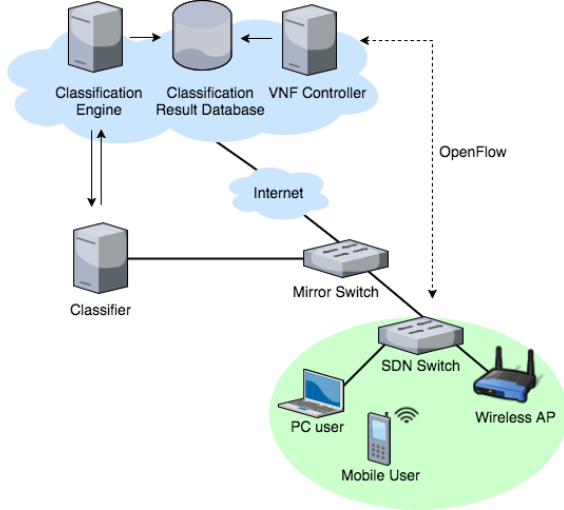


Fig. 10. Architecture of our application identification system in classifying phase

from Scanner, and accept queries from Trainer. Scanner is to get mappings of 5-tuple and ground truth from OS. In classifying phase, the architecture is shown in Fig. Flow classification engine is to use flow attributes from Classifier and classification model to get a classification result, and sends classification result to Classifier. Classifier is to analyze traffic from mirror port to get flow attributes. After Classifier finishes calculating flow attributes of a flow, it use flow attributes to ask flow classification engine for classification result if needed.

D. Flow attributes we adopted in ML

In ML, when system calculates flow attributes, we only use transport layer information of packets which have payload. We use Application Round (APPR) proposed by [] to analyze flow behavior. We use number of packets, packet sizes, transmission time, transmission direction, throughput, and APPR to define flow attributes. There are 69 attributes in total, as defined in our previous work [].

E. Algorithms we adopted in ML

We use algorithms implemented by Weka, a famous open source ML tool developed at the University of Waikato. We call Weka Java API to build classification model. We use three algorithms, namely RandomSupSpace with RandomTree [], FilterClassifier with discretization and RandomTree [], and RandomCommittee with RandomTree [].

F. Procedure of a method based on inspecting DNS response in our system

In training phase, we collect the mappings of server IP and application name. A mapping of server IP and application name means the application has ever establish connection with the server whose IP is the server IP, and the server IP has ever occurred in any DNS response we have captured. In classifying phase, we only use those mappings which have been used by one application to classify. When system detect a flow, we check whether source IP or destination IP of the flow match any server IP of those mappings. If it matches any server IP, we regard corresponding application name as classification result; otherwise, we use flow attributes of the flow and classification model to classify.

VI. PERFORMANCE EVALUATION

A. Multiple Table Performance

The single table framework implementation is easier than multiple table framework, but the multiple table framework is more flexible. To verify the efficacy of multiple table vCPE framework, this experiment use the NAT service to compare the throughput between single table vCPE and multiple table vCPE. ;We use the iPerf to generate the UDP packets and send to server from client, and set the fixed value to bandwidth at 100Mbps. These experiments would use diffrent payload sizes to inspect their performances. As shown in Fig. 12, the throughput value show that the performances of large packets such as 1024 bytes and 1470 bytes is better than small packets. Because the NAT service need to set the packet header field and small payload size would send more packets to server at the same time, the performance of larger packets is well. We can see that the throughput value of multiple table framework

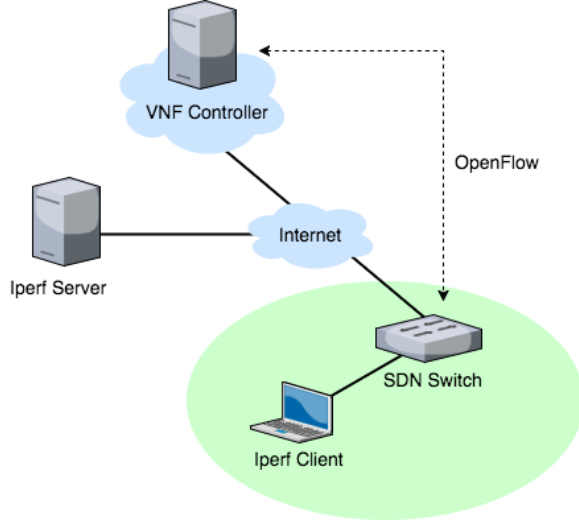


Fig. 11. Multiple Table Performance Evaluation Scenario

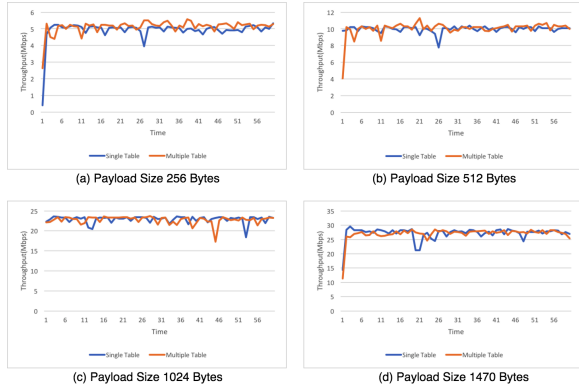


Fig. 12. Result of Multiple Table Performance Evaluation

is close to single table framework. So we can realize the multiple table framework is more flexible than single table framework, and the performance is close to each other.

B. Accuracy of Application Identification

1) *Testing data set*: Testing data set are mappings of flow attributes and ground truth (also called rules). This testing data set were generated by our system in our lab in National Tsing Hua University in Taiwan in 2016. We manually operated applications to generate traffic. After the system generated rules, it exported them into a file, because we wanted to do 10-fold cross validation on the testing data set. There are 14659 rules in total, and there are 137 applications if we view each platform version of an application as one application. (fig 1)

2) *Validation method*: Although the system can do online training and classifying, we do offline training and classifying. More specifically, when we did online training to analyze traffic, get ground truth, and export the rules into a file. We do 10-fold cross validation on the rules. There are 10 rounds in 10-fold cross validation. Each round, we split testing data set into training dataset and classifying dataset.

3) *Mapping of category names*: We do name mapping on training dataset before we use training data set to build

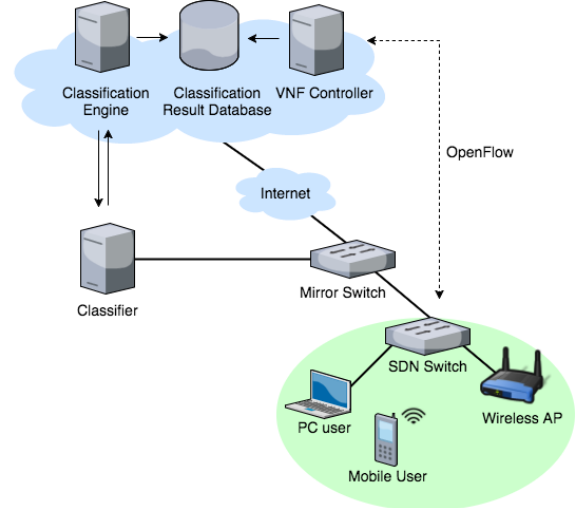
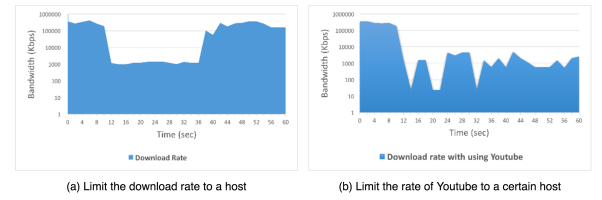


Fig. 13. Architecture of our application identification system in classifying phase



classification model, and do name mapping on classifying data set before we use classifying data set to calculate accuracy. The main reason is that some application have different ground truth in different operating system.

4) *Accuracy matrices*: To evaluate accuracy, we used precision, recall and F-measure (also called F1 score), as shown in Eq. (1), Eq. (2), and Eq. (3) []. In each round in 10-fold cross validation, we calculate precision and recall of each category to calculate F1 score of each category. After ten rounds, we calculate average

VII. LIMIT HOST BANDWIDTH

We choose a way to verify our function is downloading the file in that it is a situation always takes up the network recourse in real world. We decide to download the image of Ubuntu 14.04 which is about 1GB size. As Figure VI-B4(a), We used a desktop computer to be the experimental host and record the bandwidth in every 2 seconds. In the beginning, we start downloading the file without limiting and the rate is between 190000 Kbps to 410000 Kbps. At 10th seconds, we wanted to limit this hosts bandwidth to 1024Kbps and we added the rule the destination MAC address is matching this desktop computer with a meter of 1024Kbps. Then we can find out the bandwidth from this host is decrease and be limited to about 1024Kbps immediately. At 36th seconds, we cancel the limit to this host. That is, removing the meter field from the rule in the flow table. Obviously, we also observed the bandwidth of download from this host is rising rapidly and without limiting.

Time	Bandwidth of the meter to each connection from Youtube (Kbps)	Total Bandwidth from Youtube (Kbps)
0	Unlimited	358896
4	Unlimited	292512
8	Unlimited	290464
12	8192	1544
16	4096	1544
20	4096	24
24	8192	4584
28	8192	4552
32	2730	24
36	4096	584
40	4096	576
44	8192	2096
48	4096	576
52	4096	584
56	2730	536
60	4096	2616

TABLE VI

LIMIT THE THROUGHPUT OF SKYPE TO ALL HOSTS FROM A NETWORK DOMAIN.

VIII. LIMIT APPLICATION BANDWIDTH

There are a lot of people using the streaming applications nowadays and those applications always take up an amount of networks source. We integrated with application identification to classify each flow belongs what the application is, consequently. As Figure VI-B4(b), Then we choose YouTube to verify our limitation function of applications. In the beginning without limitation, the bandwidth is between 190000 Kbps and 360000 Kbps. At 10th seconds, we limited the Youtube to 8192 Kbps by adding the rule of 5 tuples to flow table. Therefore, we can find out the traffic of Youtube from this host is reducing immediately and the total traffic will not exceed the limited bandwidth since then. The relationship between total traffic from Youtube and bandwidth of meter to each connection with time diagram is show as following Table VI. The bandwidth of meter will change dynamically according the number of connection at that time.

As we known from the above, when we want to limit the application from a host, we used the 5 tuple from application to a host. Now we can use the similar concept to extend this limitation from a whole network domain instead of a host. That is, we didnt just limit the application from a host, we were limiting the 5 tuples of each hosts from this network domain. The bandwidth dynamically adjust is also basic on the algorithm 1. But the number of connections of the application should include the whole hosts from this network domain instead of a host. As the figure VIII, there are 3 hosts in the same network domain and we choose Skype to do the experiment. In the beginning without limitation, the bandwidths are almost 900000 Kbps to 1200000 Kbps in whole network. At 10th seconds, we limited the Skype to 16384 Kbps by adding the rule of 5 tuples from all hosts to flow table. Therefore, we can find out the traffic of Skype from this network domain is reducing immediately and the total traffic will not exceed the limited bandwidth since then.



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