A West-East Bridge Based SDN Inter-Domain Testbed

Pingping Lin, Jun Bi, Stephen Wolff, Yangyang Wang, Anmin Xu, Ze Chen, Hongyu Hu, Yikai Lin

ABSTRACT

SDN [1] is considered to be a promising way to re-architect the Internet. However, the Internet is managed by owners of different administrative domains, so the centralized control model of SDN must be extended to account for inter-domain traffic. Thus, this article proposes a WE-Bridge mechanism to enable different SDN administrative domains to peer and cooperate. Based on WE-Bridge, we further designed two innovative inter-domain routing applications as use cases. To verify our design, we implemented the WE-Bridge and the two use cases by building an international testbed on which WE-Bridge, together with the two use cases, are deployed. The testbed is composed of four SDN networks: CERNET, Internet2 in USA, CSTNET, and SURFnet.

INTRODUCTION

Currently, the architecture of the network devices are closed systems. Closed systems do not favor network innovation, especially considering protocol development or network service evolution. SDN separates the network control plane from the network data plane, and moves it to a centralized software controller. In this article we treat a controller as network operating system (NOS) plus control applications above. The controller manages and controls the entire intra-domain information, including routes, bandwidth, and so on. Switches in the network are SDN switches that retain only the basic data forwarding function. Thus, SDN decouples the vertical and tightly coupled network architecture. At the same time, it standardizes forwarding technology in the data plane, and opens up the control plane and the associated protocols. Furthermore, the controller can run on a normal host or server to control data packet forwarding in SDN switches through a standardized protocol and an optional SSL (secure sockets layer) channel. In this way, all networking people, rather than only vendors, can contribute to SDN and promote the rapid innovation and the evolution of the network.

The idea of SDN is well received by academic researchers and industry researchers, network operators, and the networking industry. SDN is considered to be a promising way to re-architect networks. The Open Networking Foundation (ONF) is leading SDN standardization and has gained support from more than 100 companies who jointly accelerate the creation of standards, products, and applications, such as NEC, Google, IBM, and VMware.

PROBLEM STATEMENT

SDN works as a centralized control model. However, the Internet is managed by owners of different administrative domains, so the centralized control model of SDN must be extended to account for inter-domain traffic. An inter-domain protocol for SDN is necessary. Thus, this article proposes a West-East Bridge (WE-Bridge) mechanism to enable different SDN administrative domains to peer and cooperate. Beyond just achieving basic inter-domain routing, we leverage SDN to improve inter-domain routing by announcing domain-views containing rich/fine-granularity information/policies, to enable various inter-domain innovations based on network information.

SDN DOMAIN

The SDN domain in this article refers to the administrative SDN domain. One SDN domain may include multiple ASs (autonomous systems).

SDN already has some protocol implementations for the communication between the control plane and the data plane such as OpenFlow [2], NetOpen [3], and Grainflow [4]. OpenFlow is the most popular implementation; it has been deployed by many universities and research institutions around the world. To give readers a more concrete picture, we choose OpenFlow as an example to explain the whole article.

In the following sections this article rethinks inter-domain routing in SDN, describes the design of WE-Bridge, and the international SDN testbed infrastructure. Then we introduce two inter-domain applications — fine-granularity inter-domain routing and end-to-end QoS (Quality of Service) routing — to prove the feasibility of WE-Bridge. Finally, we conclude the article.

RETHINKING INTER-DOMAIN ROUTING IN SDN

SDN currently only changed how the intra-domain network works; it did not change the packet format but it changed intra-domain pack-

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et forwarding. In theory, BGP (Border Gateway Protocol Version 4, RFC4271) still can be used between inter-domains. We have already successfully applied BGP between SDN and IP domains or between SDN and SDN domains [5], which are feasible and verified by implementation and deployments. However, by further analyzing the characteristic of SDN, we found that we can do more revolutionary innovations for the SDN inter-domain beyond just applying BGP:

• Besides forwarding based on a destination IP address as in legacy IP networks, the OpenFlow protocol extended more fields (source IP address, source MAC address, destination MAC address, port, etc.) to be matched during packet forwarding, which is called flow-based forwarding. Inspired by this, the inter-domain can also apply such multi-fields matching forwarding to achieve inter-domain fine-grain routing.

• SDN is centralized control; the controller can control intra-domain packet routing, and adjust the traffic status in the data plane in real time. In this way, the controller also has the ability to control how packets from other domains transit its domain. Many newly proposed routing policies such as local transit policies [6], which are impossible to achieve in the current distributed routing network, become possible in SDN.

• On the other side, BGP still has much room for improvement. Some of its shortcomings are: lacking QoS routing; lacking support for multipath routing [7]; limited policy expressiveness; and lacking path diversity. Therefore, simply applying BGP to the SDN inter-domain is not an ideal solution.

Inspired by the analysis above, we designed a new inter-domain mechanism named West-East Bridge (WE-Bridge) for inter-domain SDN, which is used for different SDN administrative domains to peer. WE-Bridge itself is not an inter-domain routing protocol, but a platform to exchange basic network information between different domains, and enable the third party to carry out SDN inter-domain innovations.

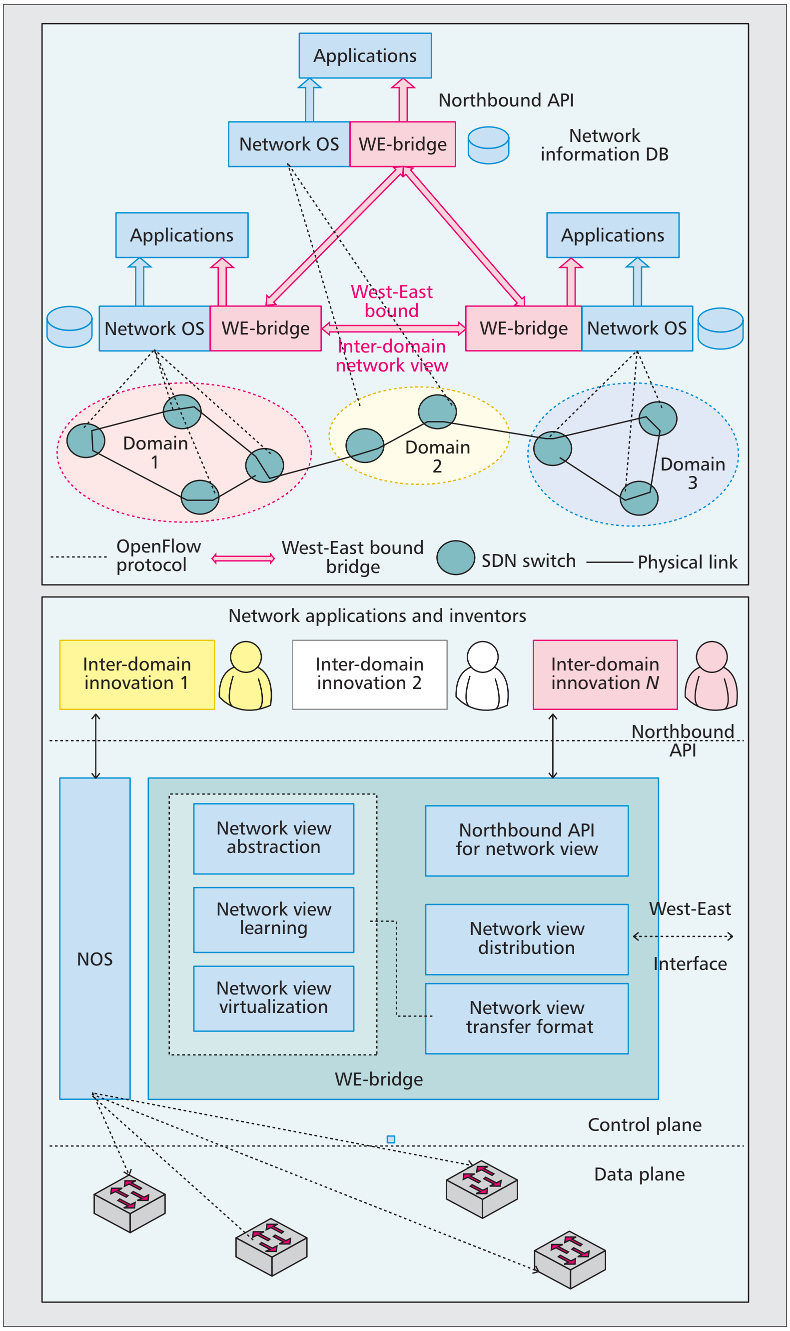

Figure 1. West-East Bridge for SDN inter-domain communication (top); overview of WE-Bridge (bottom).

WE-Bridge

By providing the intra-domain network view to applications above the NOS, SDN promoted the intra-domain network protocol innovations. Similarly, to enable inter-domain innovations, WE-Bridge needs to exchange the basic inter-domain network information, and provide it to the applications above the NOS through a north bound API (application programming interface) as shown in Fig. 1. We design what information should be exchanged among domains, how to exchange such information in high performance, and the north bound interface for providing such information to the applications above.

We call the information that is needed to be shared among different domains a "virtual network view." WE-Bridge is designed to be compatible with different third-party NOSs and network view storage systems. In the following section we will give definitions to the network view, network view abstraction, and network view learning. Considering the network privacy and policy, each SDN domain may only want to expose part of its domain information to its peers, which urges us to further design the network view virtualization. Then we describe the data expression format for virtual network view during transfer among different SDN domains. After that we introduce the network view distribution, and the north bound API.

Benefits from WE-Bridge:

- For network innovators: by providing the global basic network information to the applications above, WE-Bridge provides a platform for network researchers to innovate SDN inter-domain protocols;
- For the SDN network: WE-Bridge provides a way to enable multiple SDN inter-domain protocols to coexist, which is verified by the two use cases shown later. Multiple inter-

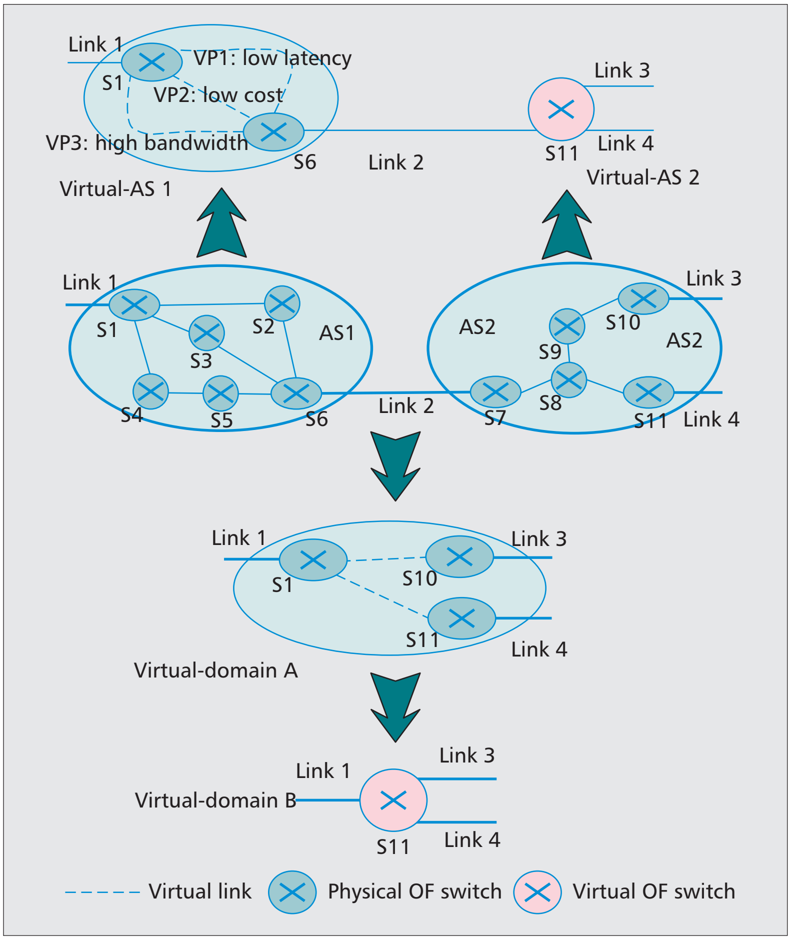

Figure 2. Network view virtualization (VP: virtual path; OF: OpenFlow; S: switch).

domain protocols can form a complementary or competitive relationship and promote the SDN inter-domain evolution.

Network View Abstraction

For the inter-domain circumstance, controlling the flow of data packets in a global network requires each controller to have a relative global network view to determine the next controller hop. Hence, NOSs are required to exchange reachability and topology information between inter-domain networks. We describe all the network entities with a network view and further divide it into two types: physical network view and virtual network view.

Network View — Both physical network view and virtual network view include two aspects: the network static information aspect and the dynamic information aspect. The network static aspect includes the following information:

- Reachability: IP addresses.
- Topology: nodes (e.g. switches, servers, hosts, controllers, firewalls, balancers, others), links, link attributes, port throughput, link connections.
- Network service capabilities, such as SLA (service level agreement), GRE (generic routing encapsulation), SSL (secure sockets layer), OpenFlow version, numbers of FlowTables in each switch, and how many flow entries each FlowTable supports.
- Forwarding capability parameters, such as latency, reliability, packet loss rate, availability, maximum throughput, time delay variation, and cost.

The network dynamic information mainly includes the network status, such as FlowTable entries information in each switch, real-time bandwidth utilization in the topology, and all the flow paths in the network.

Physical Network View Learning — Currently, LLDP (Link Layer Discovery Protocol) is used by controllers to discover the network topology. Usually, the controller in each SDN domain instructs each of the connected OpenFlow switches to send LLDP packets out from all the ports (the LLDP packet carries the source switch identity, out-port, and other capabilities). Once the neighbor switches receive the LLDP packets, they will send it directly to the controller. Then the controller abstracts and analyzes the information from the LLDP packet to determine if the source switch identity belongs to its domain and the LLDP packet received by a neighbor is the same as the one sent out from the source OpenFlow switch. If this is true, the controller will then create a direct intra-domain link between the source switch and this neighbor. For the inter-domain link, we extended LLDP in the NOS by adding a network view driver: if the source switch identity does not belong to its domain, then the controller can infer that this packet is from another domain, and will create an inter-domain link like (S6, S7) in Fig. 2 according to the source switch identity, source switch out-port, and the destination switch (who received the LLDP packet in its SDN domain) identity with the in-port. The inter-domain links should be stored in both the neighbor domains' local network views.

To learn more network view information such as OpenFlow version and number of the FlowTables on each node, link utilities, and flow entries, we extended the LLDP by adding an LLDP extension module. By counting the total number of packets related to a certain port in all the FlowTables in an OpenFlow switch, the LLDP extension can learn the link utilities. By the flow stats APIs defined in OpenFlow, the LLDP extension can learn the OpenFlow version, number of FlowTables, and flow entries in each switch.

Network View Virtualization

Each SDN domain may be willing to expose only a part of its domain information to its peers, rather than the entire network view, due to policy concerns. We can abstract a physical network view to a virtual network view in such situations. As shown in Fig. 2, we design three kinds of virtual network views:

- Abstract a physical network view into a virtual network view with only the edge switches, like AS 1 to virtual AS 1. Route path segments (like VP 1, VP 2, VP 3) from the ingress switch to the egress switch in the virtual network can have SLA (service level agreement)-level path attributes such as time latency, reliability, bandwidth, and packet loss rate.

- Abstract a physical network view into a virtual node, like AS 2 to virtual AS 2. The virtual node only retains three physical inter-domain (cross-domain) links: link2, link3, link4. After network virtualization, each NOS should store a mapping table between the physical network view and the virtual network view.
- In addition, one administrative domain may include several ASs. Assume AS1 and AS2 in Fig. 2 belong to the same administrative domain. We design to virtualize multiple ASs in one administrative domain to the same virtual domain like virtual domain A, or virtual domain B.

To compute an end-to-end or global routing path with QoS, the path computing application on the NOS needs the network views in other domains, or should at least know the abstracted virtual network views of other domains as shown in Fig. 2. After WE-Bridge exchanges the local virtual network views, each NOS can construct the global network view based on all the local virtual network views plus the inter-domain links and their attributes, and provide it to network applications above. Then the path computing application can compute an end-to-end path, cooperate with other peer networks to set up an end-to-end path, and send the cross-domain packet directly to the edge switch output port along the routing path.

Virtual Network View Transfer Format and Distribution

Different domains sharing network view (including the reachability information) requires the network view to be expressed in a manner WE-Bridges from all domains can understand. Thus, an application-independent language to enable peering between heterogeneous NOSs is needed such as JSON (JavaScript Object Notation), XML (eXtensible Markup Language), and YAML (YAML Ain't Markup Language). We chose JSON in our design since JSON is more light-weight.

After defining and expressing the network view, WE-Bridge needs to set up peer connections and to deliver the network view data. All SDN network controllers/peers are equivalent to each other, and they construct a peer-to-peer control plane. We design the network view distribution mechanism with the following principles. On one side, since the more connections each peer sets up, the more stable the peer control plane will be, each peer should set up as many connections as its resources can support (Principle 1). On the other side, the shorter the average hops in the peer control plane, the shorter the convergence time will be for network view update message delivery (Principle 2). Based on these two principles, we propose a maximum connection degree based connection algorithm [8].

By now the entire work-flow of WE-Bridge is as follows: WE-Bridge in each SDN domain collects and virtualizes the local physical network view. The reachability information of the domain can be configured by network operators, which is similar to the situation when network operators configure BGP routers with routes in the current IP network. Then all WE-Bridges from different SDN domains exchange the basic reachability (route) and virtual network information in JSON format, construct the relative global network view, and provide such information to the applications above. Then inter-domain routing applications in different domains translate all the routes into OpenFlow flow paths and cooperate with each other to set up cross-domain routing paths.

North Bound API

To promote SDN inter-domain innovation such as new inter-domain routing, we need to provide as many types of inter-domain information as we can to applications above the NOS/WE-Bridge in an easy-to-use manner. The north bound API is designed for such a purpose. After exchanging virtual network views by WE-Bridge, WE-Bridge in each network can construct a relative global network view and provide it to network applications above. However, to better serve the application above, WE-Bridge provides various types of network views, which mainly fell into two categories:

Original global network view: This includes local network view and virtual network views learned from all other domains.

Specific network view: after data processing to the original global network view, which is valuable for particular applications, such as the virtual network view data of a specific SDN domain or a set of SDN domains, the routes information of a specific SDN domain or a set of SDN domains, the topology information of a specific SDN domain or a set of SDN domains.

We design the following two approaches to pass the network views including both original global network view and specific network view from WE-Bridge to applications above the NOS:

Information subscribe/publication: applications above the NOS can register themselves with WE-Bridge for certain information requirements. Each time a WE-Bridge module receives a corresponding information event, it will notify all the applications who subscribed before.

North bound API: WE-Bridge provides all kinds of network information and provides it to the applications above by north bound REST (representational state transfer) API.

Testbed for Inter-Domain Innovation

We implemented the WE-Bridge, and for deployment, we built an international federal SDN testbed in July 2013, and deployed WE-Bridge to this testbed as shown in Fig. 3. The testbed includes four SDN networks: Internet2 (United States open national research and education network), CERNET (China Education and Research Network), CSTNET (China Science and Technology Network), and SURFnet (the national research and education network of the Netherlands). WE-Bridge successfully connected those four SDN networks. The testbed

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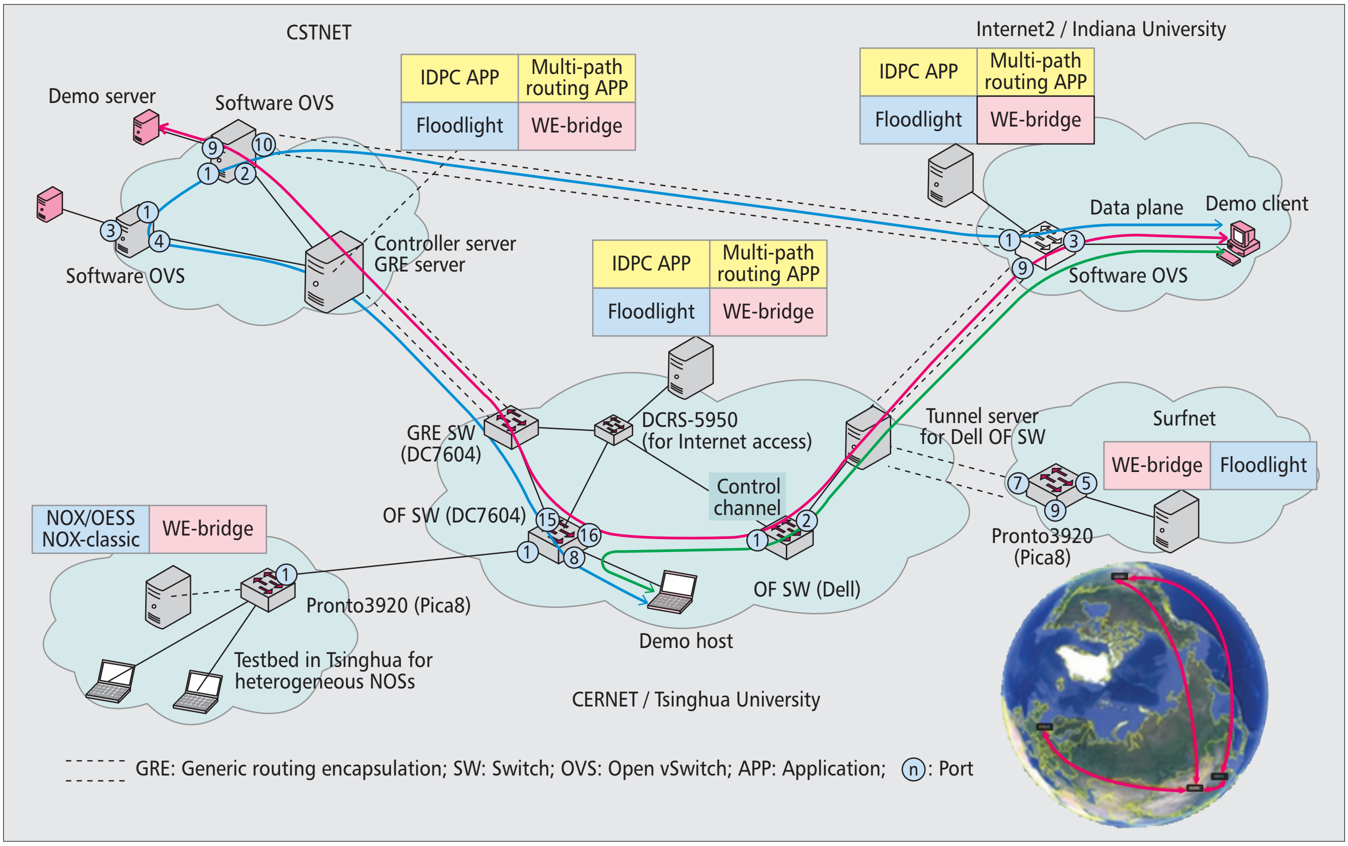

Figure 3. Global SDN Federated Testbed: Internet2 (United States open national research and education network), CERNET (China education and research network), CSTNET (China science and technology network), and SURFnet (the national research and education network of the Netherlands).

has been running since last summer as an international collaboration project and users in CSTNET and CERNET have kept using it as a production network for trans-Pacific genomic data transfer.

Hardware Configuration

We deployed three hardware OpenFlow switches (DC7604 from Digital China, Pronoto3920 from Pica8, one Dell OpenFlow switch) in CERNET, one hardware GRE (generic routing encapsulation) switch (DC7604 from Digital China), and one aggregation switch (DCRS-5950 from Digital China). There are two Open vSwitches (software switch) [9], one GRE server, two demo servers in CSTNET. Internet2 also has an Open vSwitch, one server running the controller, and one host for the traffic test. SURFnet used one hardware switch Pronoto3920 form Pica8.

Software Configuration

The controller used in this implementation is Floodlight [10], and the software switch used is Open vSwitch [9]. Each network deployed a WE-Bridge. The NOX/NOX-Classic/OESS [11, 12] in Tsinghua are used for trying out heterogeneous NOS peering with WE-Bridge. Currently, the four SDN testbeds in CERNET, CSTNET, Internet2, and SURFnet are not neighbors in layer 2. Therefore, we connected those four OpenFlow testbeds by GRE tunnels shown in Fig. 3. Then from the viewpoint of each SDN network, all four testbeds are neighbors.

Two Use Cases

Based on such a testbed and to verify the feasibility of the WE-Bridge platform, we further designed and carried out two innovative inter-domain routing applications as two use cases to the SDN inter-domain routing:

- Source-address based multi-path routing. Based on a path vector algorithm like BGP, we apply the flow based routing into SDN inter-domain by adding more fields (such as Ether type, source IP address) to the route announcement message to achieve fine-granularity inter-domain routing.
- Inter-domain path computation (IDPC). Considering the path attributes such as bandwidth and time latency, we let different domains negotiate the path attributes to achieve end-to-end QoS routing. Both of them are implemented as network applications running on NOS.

We also implemented those two applications, and deployed them to the testbed. The first use case (fine-granularity multi-path routing) achieves the global infrastructure connection. Then WE-Bridge in each network exchanges the reachability and topology information with its peers, and the global network view is constructed. Then, inter-domain path computation applications in each domain cooperate together and set up end-to-end paths. Such deployment to the real SDN network proves the feasibility of WE-Bridge and its ability to enable inter-domain innovations.

Use Case 1: Source-Address Based Multi-Path Routing — This use case presents a new fine granularity inter-domain routing, which supports multipath inter-domain routing to the same destination based on different source IP addresses.

As shown in Fig. 3, each network works as an AS. CERNET at Tsinghua university sets host IP addresses 101.6.30.100 and 101.6.30.101, CSTNET has a block of IP addresses denoted as 159.226.61.*, and Internet2 has a host with IP address 149.165.130.212.

AS4 (Internet2) announces three routes with the same destination IP address with different source addresses, while Tsinghua announces two routes as shown in Fig. 4 (a). All the routes are propagated along AS paths indicated respectively by the green, red, and yellow arrows. Thus, the flow matching (src: 101.6.30.100, dst: 149.165.130.212) will traverse AS path (AS1, AS3, AS4), and the flow matching (src: 101.6.30.101, dst: 149.165.130.212) will be forwarded along AS path (AS1, AS4). All other flows matching (dst: 149.165.130.212) take the AS path (AS1, AS4). We used the ping command to ping the demo client address 149.165.130.212 in Internet2 from different source addresses 101.6.30.100 and 101.6.30.101 on the demo host in Tsinghua. Then the two traffic flows are routed along two different AS-level paths shown with the blue and green color lines in Fig. 3. Figure 4b presents a similar case with one more SDN network, SURFnet. The routes that traverse AS path (AS4, AS1) in Fig. 4a change to traverse AS path (AS4, AS2, AS1) in Fig. 4b.

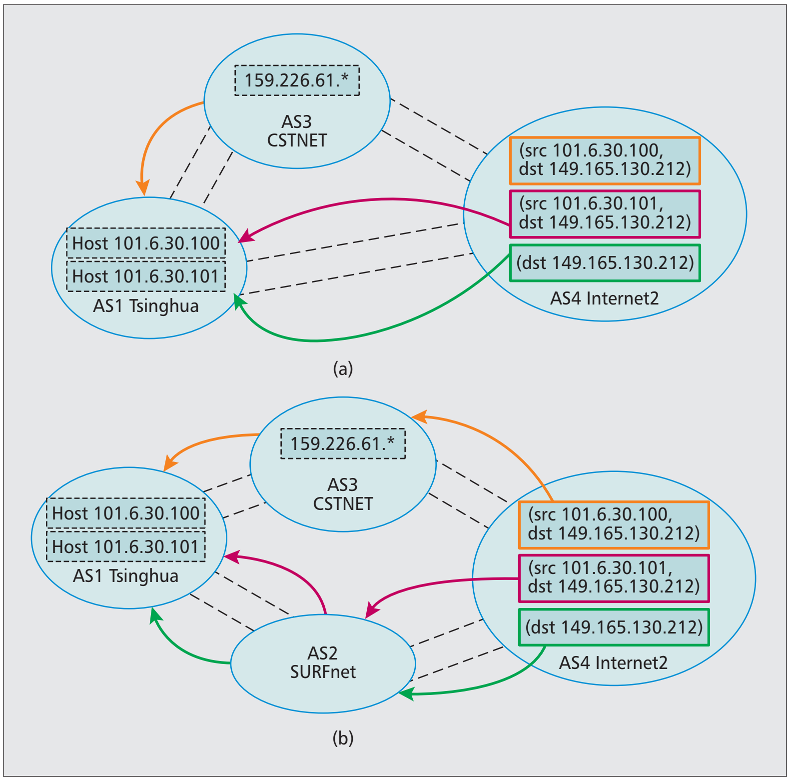

Figure 4. A concept illustration of source address based multipath routing.

Use Case 2: Inter-Domain Path Computation — Inter-domain path computation (IDPC) application is also developed and installed as an application. The purpose of IDPC is to achieve end-to-end QoS routing. After WE-Bridge modules in all the domains exchange local virtual network views including the bandwidth information, each domain can construct a relative global network view.

According to the specification of OpenFlow, each time there is a new packet coming and if there is no rule for this packet in the switch, this packet will be transferred to the controller. Then the IDPC application reads the global virtual view information provided by WE-Bridge and judges the location of the destination IP: whether the destination IP of an incoming data flow is located in the intra-domain or in other domains. If the destination IP is in the intra-domain, it will carry out re-active flow calculation and installation. If the destination IP is in other domains, it will compute an end-to-end path according to the global network view, and negotiate with other IDPC applications along the path with path segment request (ingress switch and port, egress switch and port, matching fields, path attributes) to set up an end-to-end path with QoS attribute. Then each IDPC application translates the corresponding path segment request into flow entries and installs them to the OpenFlow switches. Then an end-to-end path (satisfying the QoS requirement of user traffic) is set up. In this use case the QoS requirement is simplified as the minimal bandwidth requirement of user traffic.

The bandwidths of the GRE tunnel link between Tsinghua and Internet2 and between CSTNET and Tsinghua are larger than that between CSTNET and Internet2. Therefore, the flow tables in each switch for the traffic will be set up automatically by IDPC applications as follows: CSTNET->Tsinghua->Internet2.

At last, we delivered one Terabyte of trans-Pacific genomic data (FTP: File Transfer Protocol) from the server in CSTNET to the client in Internet2. We monitored the traffic on each interface of the OpenFlow switches along the routing path by SNMP (Simple Network Management Protocol). As shown in Fig. 5, we can see the average speed of the traffic is 20 MB/s.

The sizes of the virtual network views of CSTNET, CERNET, and Internet2 are 452 bytes, 486 bytes, and 319 bytes. Compared with the traffic data, the bandwidth occupied by the control plane data is very small. So we are able to conclude that WE-Bridge is a lightweight solution to enable different SDN domains to cooperate.

Related Work

To enable incremental deployment of SDN, a research study of SDN-IP network peering [5] was conducted by us in 2013. This work focuses on the interaction between BGP-based SDN domain and legacy IP domain. This solution applies BGP between the SDN and IP domains or between SDN and SDN domains without improving the inter-domain routing.

RouteFlow [13] is one of the first implemen-

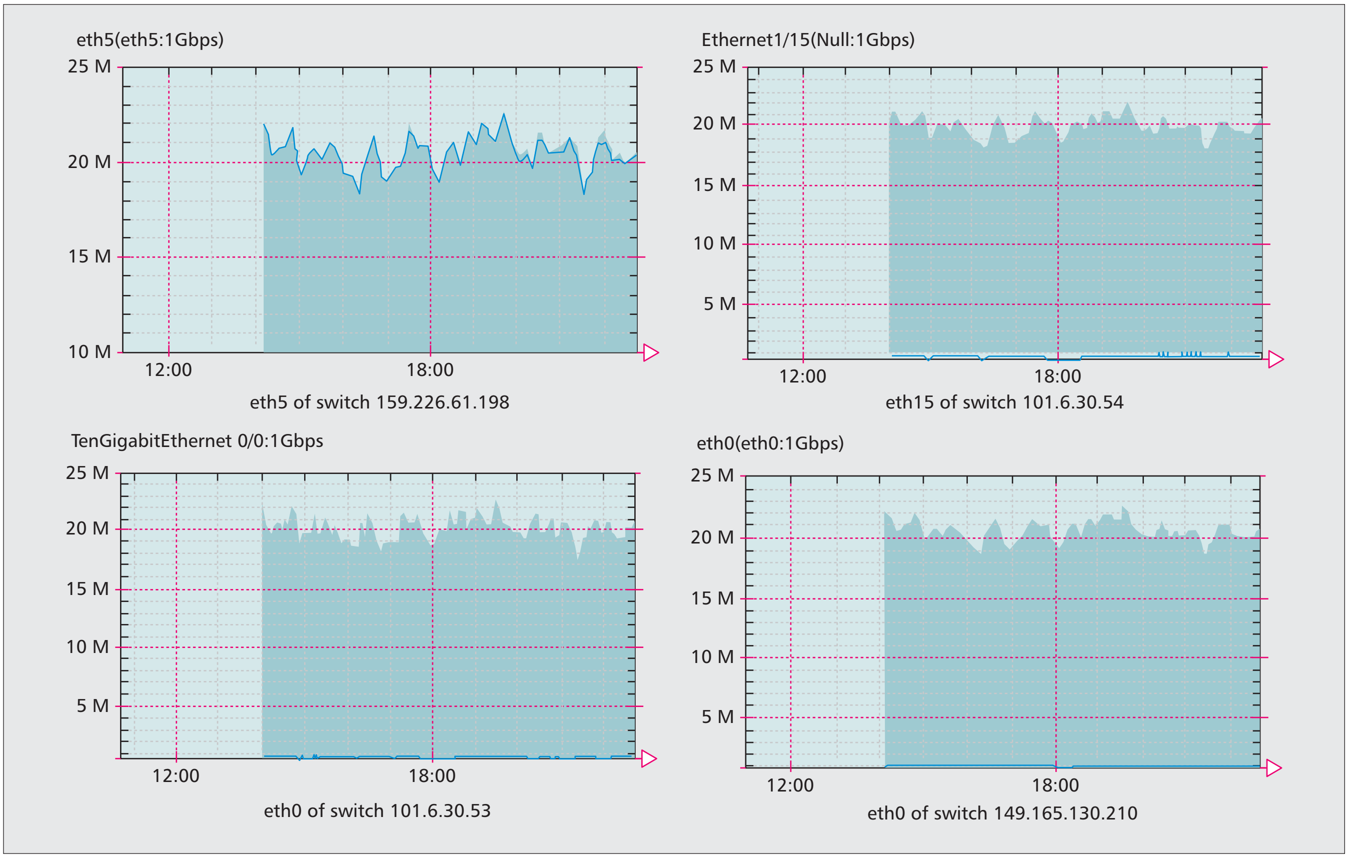

Figure 5. Traffic at interfaces of OpenFlow switches along the routing path.

tations of IP routing on OpenFlow switches. RouteFlow instantiates a VM for each OpenFlow switch with as many virtual network interfaces as there are active ports in the corresponding device, and runs a stack of open-source routing protocols on the virtual topology. All control messages are exchanged between VMs as if they are running as a distributed control plane. The routing engine is still based on traditional open source software like Quagga [14]. Inter-domain routing is still standard BGP. Such a solution incurs the overhead of distribution without the benefits of scale.

Feamster *et al*. [15] presented a software defined Internet exchange (SDX) to bring SDN enabled features to today's BGP inter-domain routing. This article aims to take advantage of Internet exchange points (IXPs) and to enable more expressive policies than conventional destination IP address based forwarding with BGP. However, domains that are not connected to IXPs cannot benefit from this.

SDN inter-domain peering is currently still a challenge. No single solution has been successfully deployed in large scale yet.

Conclusion

This article designs a West-East Bridge for SDN inter-domain peering. We first defined what network information can be exchanged and how such information is efficiently exchanged among inter-domain SDN peers. With this technology, we built an international SDN testbed with four SDN networks: CERNET, CSTNET, Internet2, and SURFnet. To verify the WE-Bridge platform, we further designed, implemented, and deployed two SDN inter-domain routing innovations. From the two innovations, we proved it is easy to do innovations and implementations on WE-Bridge. Some new features of inter-domain that cannot be achieved on current networks can be achieved in the SDN environments with the WE-Bridge platform, such as fine-granularity inter-domain routing and end-to-end QoS routing, as shown in the two use cases. WE-Bridge has great potential to enable SDN inter-domain innovations.

In the future, we plan to expand our SDN testbed by connecting more SDN networks with WE-Bridge and attracting more real inter-domain traffic.

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Some new features of inter-domain that cannot be achieved on current networks can be achieved in the SDN environments with the WE-Bridge platform, such as fine-granularity inter-domain routing and end-to-end QoS routing, as shown in the two use cases. WE-Bridge has great potential to enable SDN inter-domain innovations.