Software-Defined Networks and OpenFlow

by William Stallings

A network organizing technique that has come to recent prominence is the *Software-Defined Network* (SDN)[1]. In essence, an SDN separates the data and control functions of networking devices, such as routers, packet switches, and LAN switches, with a well-defined *Application Programming Interface* (API) between the two. In contrast, in most large enterprise networks, routers and other network devices encompass both data and control functions, making it difficult to adjust the network infrastructure and operation to large-scale addition of end systems, virtual machines, and virtual networks. In this article we examine the characteristics of an SDN, and then describe the *OpenFlow* specification, which is becoming the standard way of implementing an SDN.

Evolving Network Requirements

Before looking in more detail at SDNs, let us examine the evolving network requirements that lead to a demand for a flexible, response approach to controlling traffic flows within a network or the Internet.

One key leading factor is the increasingly widespread use of *Server Virtualization*. In essence, server virtualization masks server resources, including the number and identity of individual physical servers, processors, and operating systems, from server users. This masking makes it possible to partition a single machine into multiple, independent servers, conserving hardware resources. It also makes it possible to migrate a server quickly from one machine to another for load balancing or for dynamic switchover in the case of machine failure. Server virtualization has become a central element in dealing with "big data" applications and in implementing cloud computing infrastructures. But it creates problems with traditional network architectures (for example, refer to [2]). One problem is configuring *Virtual LANs* (VLANs). Network managers need to make sure the VLAN used by the *Virtual Machine* is assigned to the same switch port as the physical server running the virtual machine. But with the virtual machine being movable, it is necessary to reconfigure the VLAN every time that a virtual server is moved. In general terms, to match the flexibility of server virtualization, the network manager needs to be able to dynamically add, drop, and change network resources and profiles. This process is difficult to do with conventional network switches, in which the control logic for each switch is co-located with the switching logic.

Another effect of server virtualization is that traffic flows differ substantially from the traditional client-server model. Typically, there is a considerable amount of traffic among virtual servers, for such purposes as maintaining consistent images of the database and invoking security functions such as access control. These server-to-server flows change in location and intensity over time, demanding a flexible approach to managing network resources.

Another factor leading to the need for rapid response in allocating network resources is the increasing use by employees of mobile devices such as smartphones, tablets, and notebooks to access enterprise resources. Network managers must be able to respond to rapidly changing resource, *Quality of Service* (QoS), and security requirements.

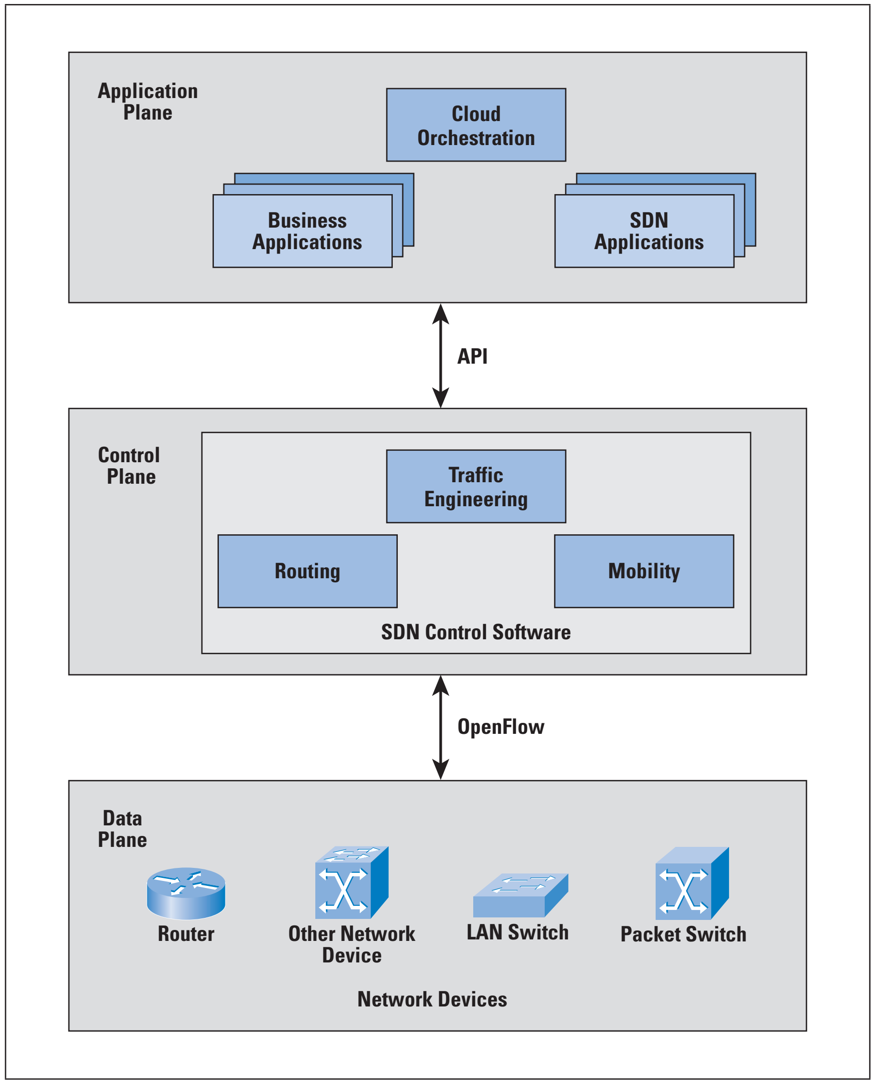
Existing network infrastructures can respond to changing requirements for the management of traffic flows, providing differentiated QoS levels and security levels for individual flows, but the process can be very time-consuming if the enterprise network is large and/or involves network devices from multiple vendors. The network manager must configure each vendor's equipment separately, and adjust performance and security parameters on a per-session, per-application basis. In a large enterprise, every time a new virtual machine is brought up, it can take hours or even days for network managers to do the necessary reconfiguration[3].

This state of affairs has been compared to the mainframe era of computing[4]. In the era of the mainframe, applications, the operating system, and the hardware were vertically integrated and provided by a single vendor. All of these ingredients were proprietary and closed, leading to slow innovation. Today, most computer platforms use the x86 instruction set, and a variety of operating systems (Windows, Linux, or Mac OS) run on top of the hardware. The OS provides APIs that enable outside providers to develop applications, leading to rapid innovation and deployment. In a similar fashion, commercial networking devices have proprietary features and specialized control planes and hardware, all vertically integrated on the switch. As will be seen, the SDN architecture and the OpenFlow standard provide an open architecture in which control functions are separated from the network device and placed in accessible control servers. This setup enables the underlying infrastructure to be abstracted for applications and network services, enabling the network to be treated as a logical entity.

SDN Architecture

Figure 1 illustrates the logical structure of an SDN. A central controller performs all complex functions, including routing, naming, policy declaration, and security checks. This plane constitutes the *SDN Control Plane,* and consists of one or more SDN servers.

Figure 1: SDN Logical Structure



The *SDN Controller* defines the data flows that occur in the *SDN Data Plane*. Each flow through the network must first get permission from the controller, which verifies that the communication is permissible by the network policy. If the controller allows a flow, it computes a route for the flow to take, and adds an entry for that flow in each of the switches along the path. With all complex functions subsumed by the controller, switches simply manage flow tables whose entries can be populated only by the controller. Communication between the controller and the switches uses a standardized protocol and API. Most commonly this interface is the OpenFlow specification, discussed subsequently.

The SDN architecture is remarkably flexible; it can operate with different types of switches and at different protocol layers. SDN controllers and switches can be implemented for Ethernet switches (Layer 2), Internet routers (Layer 3), transport (Layer 4) switching, or application layer switching and routing. SDN relies on the common functions found on networking devices, which essentially involve forwarding packets based on some form of flow definition.

In an SDN architecture, a switch performs the following functions:

- The switch encapsulates and forwards the first packet of a flow to an SDN controller, enabling the controller to decide whether the flow should be added to the switch flow table.
- The switch forwards incoming packets out the appropriate port based on the flow table. The flow table may include priority information dictated by the controller.
- The switch can drop packets on a particular flow, temporarily or permanently, as dictated by the controller. Packet dropping can be used for security purposes, curbing *Denial-of-Service* (DoS) attacks or traffic management requirements.

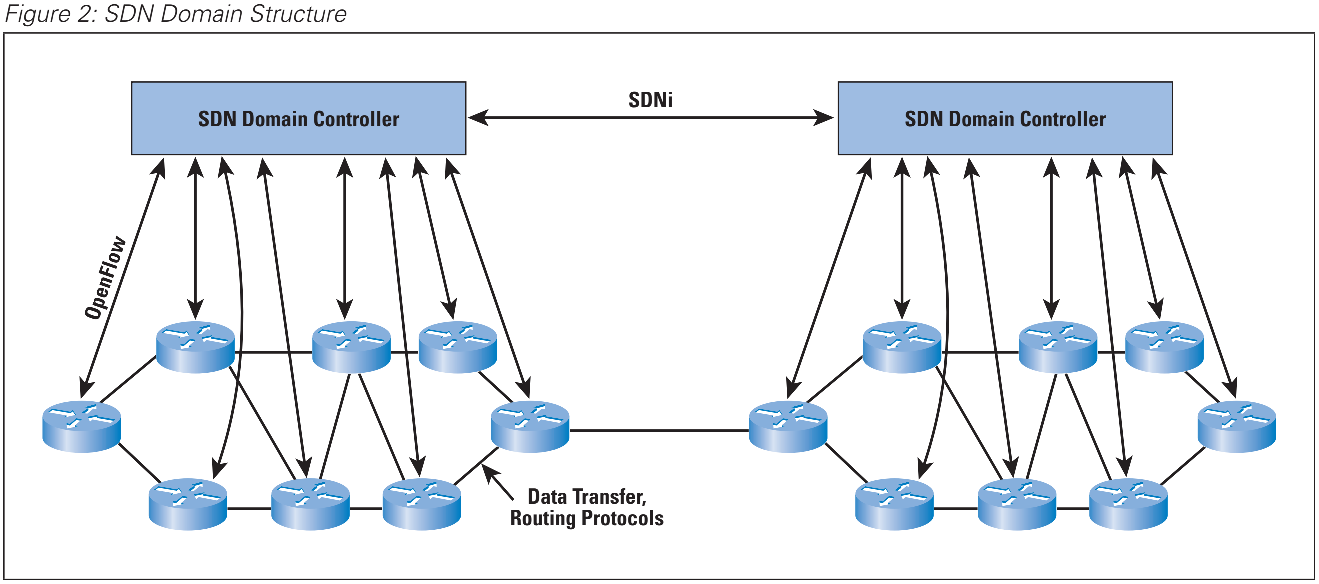
In simple terms, the SDN controller manages the forwarding state of the switches in the SDN. This management is done through a vendor-neutral API that allows the controller to address a wide variety of operator requirements without changing any of the lower-level aspects of the network, including topology.

With the decoupling of the control and data planes, SDN enables applications to deal with a single abstracted network device without concern for the details of how the device operates. Network applications see a single API to the controller. Thus it is possible to quickly create and deploy new applications to orchestrate network traffic flow to meet specific enterprise requirements for performance or security.

SDN Domains

In a large enterprise network, the deployment of a single controller to manage all network devices would prove unwieldy or undesirable. A more likely scenario is that the operator of a large enterprise or carrier network divides the whole network into numerous nonoverlapping SDN domains as shown in Figure 2.

Figure 2: SDN Domain Structure



Reasons for using SDN domains include the following:

- *Scalability:* The number of devices an SDN controller can feasibly manage is limited. Thus, a reasonably large network may need to deploy multiple SDN controllers.
- *Privacy:* A carrier may choose to implement different privacy policies in different SDN domains. For example, an SDN domain may be dedicated to a set of customers who implement their own highly customized privacy policies, requiring that some networking information in this domain (for example, network topology) not be disclosed to an external entity.
- *Incremental deployment:* A carrier's network may consist of portions of traditional and newer infrastructure. Dividing the network into multiple, individually manageable SDN domains allows for flexible incremental deployment.

The existence of multiple domains creates a requirement for individual controllers to communicate with each other via a standardized protocol to exchange routing information. The IETF is currently working on developing a protocol, called *SDNi,* for "interfacing SDN Domain Controllers"[5]. SDNi functions include:

- Coordinate flow setup originated by applications containing information such as path requirement, QoS, and service-level agreements across multiple SDN domains.
- Exchange reachability information to facilitate inter-SDN routing. This information exchange will allow a single flow to traverse multiple SDNs and have each controller select the most appropriate path when multiple such paths are available.

The message types for SDNi tentatively include the following:

- Reachability update
- Flow setup/tear-down/update request (including application capability requirements such as QoS, data rate, latency etc.)
- Capability update (including network-related capabilities such as data rate and QoS, and system and software capabilities available inside the domain)

OpenFlow

To turn the concept of SND into practical implementation, two requirements must be met. First, there must be a common logical architecture in all switches, routers, and other network devices to be managed by an SDN controller. This logical architecture may be implemented in different ways on different vendor equipment and in different types of network devices, so long as the SDN controller sees a uniform logical switch function. Second, a standard, secure protocol is needed between the SDN controller and the network device.

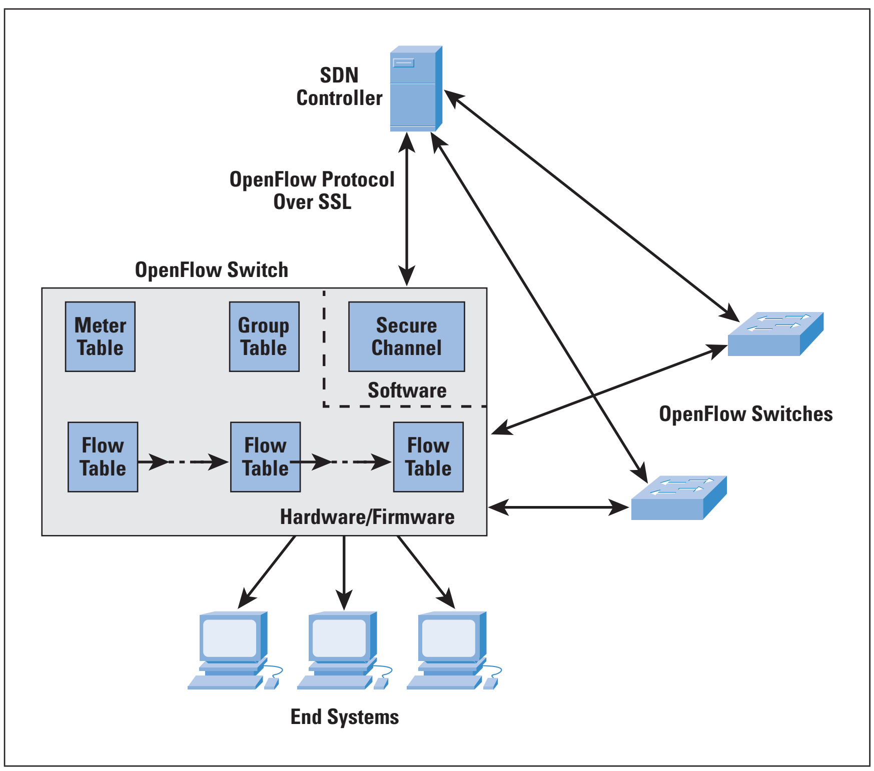
Both of these requirements are addressed by *OpenFlow,* which is both a protocol between SDN controllers and network devices, as well as a specification of the logical structure of the network switch functions[6, 7]. OpenFlow is defined in the *OpenFlow Switch Specification,* published by the *Open Networking Foundation* (ONF). ONF is a consortium of software providers, content delivery networks, and networking equipment vendors whose purpose is to promote software-defined networking.

This discussion is based on the current OpenFlow specification, Version 1.3.0, June 25, 2012[8]. The original specification, 1.0, was developed at Stanford University and was widely implemented. OpenFlow 1.2 was the first release from ONF after inheriting the project from Stanford. OpenFlow 1.3 significantly expands the functions of the specification. Version 1.3 is likely to become the stable base upon which future commercial implementations for OpenFlow will be built. ONF intends for this version to be a stable target for chip and software vendors, so little if any change is planned for the foreseeable future[9].

Logical Switch Architecture

Figure 3 illustrates the basic structure of the OpenFlow environment. An SDN controller communicates with OpenFlow-compatible switches using the OpenFlow protocol running over the *Secure Sockets Layer* (SSL). Each switch connects to other OpenFlow switches and, possibly, to end-user devices that are the sources and destinations of packet flows. Within each switch, a series of tables—typically implemented in hardware or firmware—are used to manage the flows of packets through the switch.

Figure 3: OpenFlow Switch



The OpenFlow specification defines three types of tables in the logical switch architecture. A *Flow Table* matches incoming packets to a particular flow and specifies the functions that are to be performed on the packets. There may be multiple flow tables that operate in a pipeline fashion, as explained subsequently. A flow table may direct a flow to a *Group Table,* which may trigger a variety of actions that affect one or more flows. A *Meter Table* can trigger a variety of performance-related actions on a flow.

Before proceeding, it is helpful to define what the term *flow* means. Curiously, this term is not defined in the OpenFlow specification, nor is there an attempt to define it in virtually all of the literature on OpenFlow. In general terms, a flow is a sequence of packets traversing a network that share a set of header field values. For example, a flow could consist of all packets with the same source and destination IP addresses, or all packets with the same VLAN identifier. We provide a more specific definition subsequently.

Flow-Table Components

The basic building block of the logical switch architecture is the flow table. Each packet that enters a switch passes through one or more flow tables. Each flow table contains entries consisting of six components:

- *Match Fields:* Used to select packets that match the values in the fields.
- *Priority:* Relative priority of table entries.
- *Counters:* Updated for matching packets. The OpenFlow specification defines a variety of timers. Examples include the number of received bytes and packets per port, per flow table, and per flow-table entry; number of dropped packets; and duration of a flow.
- *Instructions:* Actions to be taken if a match occurs.
- *Timeouts:* Maximum amount of idle time before a flow is expired by the switch.
- *Cookie:* Opaque data value chosen by the controller. May be used by the controller to filter flow statistics, flow modification, and flow deletion; not used when processing packets.

A flow table may include a *table-miss* flow entry, which renders all Match Fields wildcards (every field is a match regardless of value) and has the lowest priority (priority 0). The Match Fields component of a table entry consists of the following required fields:

- *Ingress Port:* The identifier of the port on the switch where the packet arrived. It may be a physical port or a switch-defined virtual port.
- *Ethernet Source and Destination Addresses:* Each entry can be an exact address, a bitmasked value for which only some of the address bits are checked, or a wildcard value (match any value).

- *IPv4 or IPv6 Protocol Number:* A protocol number value, indicating the next header in the packet.
- *IPv4 or IPv6 Source Address and Destination Address:* Each entry can be an exact address, a bitmasked value, a subnet mask value, or a wildcard value.
- *TCP Source and Destination Ports:* Exact match or wildcard value.
- *User Datagram Protocol (UDP) Source and Destination Ports:* Exact match or wildcard value.

The preceding match fields must be supported by any OpenFlow-compliant switch. The following fields may be optionally supported:

- *Physical Port:* Used to designate underlying physical port when packet is received on a logical port.
- *Metadata:* Additional information that can be passed from one table to another during the processing of a packet. Its use is discussed subsequently.
- *Ethernet Type:* Ethernet Type field.
- *VLAN ID and VLAN User Priority:* Fields in the IEEE 802.1Q Virtual LAN header.
- *IPv4 or IPv6 DS and ECN:* Differentiated Services and Explicit Congestion Notification fields.
- *Stream Control Transmission Protocol (SCTP) Source and Destination Ports:* Exact match or wildcard value.
- *Internet Control Message Protocol (ICMP) Type and Code Fields:* Exact match or wildcard value.
- *Address Resolution Protocol (ARP) Opcode:* Exact match in Ethernet Type field.
- *Source and Target IPv4 Addresses in Address Resolution Protocol (ARP) Payload:* Can be an exact address, a bitmasked value, a subnet mask value, or a wildcard value.
- *IPv6 Flow Label:* Exact match or wildcard.
- *ICMPv6 Type and Code fields:* Exact match or wildcard value.
- *IPv6 Neighbor Discovery Target Address:* In an IPv6 Neighbor Discovery message.
- *IPv6 Neighbor Discovery Source and Target Addresses:* Link-layer address options in an IPv6 Neighbor Discovery message.
- *Multiprotocol Label Switching (MPLS) Label Value, Traffic Class, and Bottom of Stack (BoS):* Fields in the top label of an MPLS label stack.

Thus, OpenFlow can be used with network traffic involving a variety of protocols and network services. Note that at the MAC/link layer, only Ethernet is supported. Thus, OpenFlow as currently defined cannot control Layer 2 traffic over wireless networks.

We can now offer a more precise definition of the term *flow.* From the point of view of an individual switch, a flow is a sequence of packets that matches a specific entry in a flow table. The definition is packet-oriented, in the sense that it is a function of the values of header fields of the packets that constitute the flow, and not a function of the path they follow through the network. A combination of flow entries on multiple switches defines a flow that is bound to a specific path.

The *instructions component* of a table entry consists of a set of instructions that are executed if the packet matches the entry. Before describing the types of instructions, we need to define the terms "Action" and "Action Set." Actions describe packet forwarding, packet modification, and group table processing operations. The OpenFlow specification includes the following actions:

- *Output:* Forward packet to specified port.
- *Set-Queue:* Sets the queue ID for a packet. When the packet is forwarded to a port using the output action, the queue id determines which queue attached to this port is used for scheduling and forwarding the packet. Forwarding behavior is dictated by the configuration of the queue and is used to provide basic QoS support.
- *Group:* Process packet through specified group.
- *Push-Tag/Pop-Tag:* Push or pop a tag field for a VLAN or MPLS packet.
- *Set-Field:* The various Set-Field actions are identified by their field type; they modify the values of respective header fields in the packet.
- *Change-TTL:* The various Change-TTL actions modify the values of the IPv4 Time To Live (TTL), IPv6 Hop Limit, or MPLS TTL in the packet.

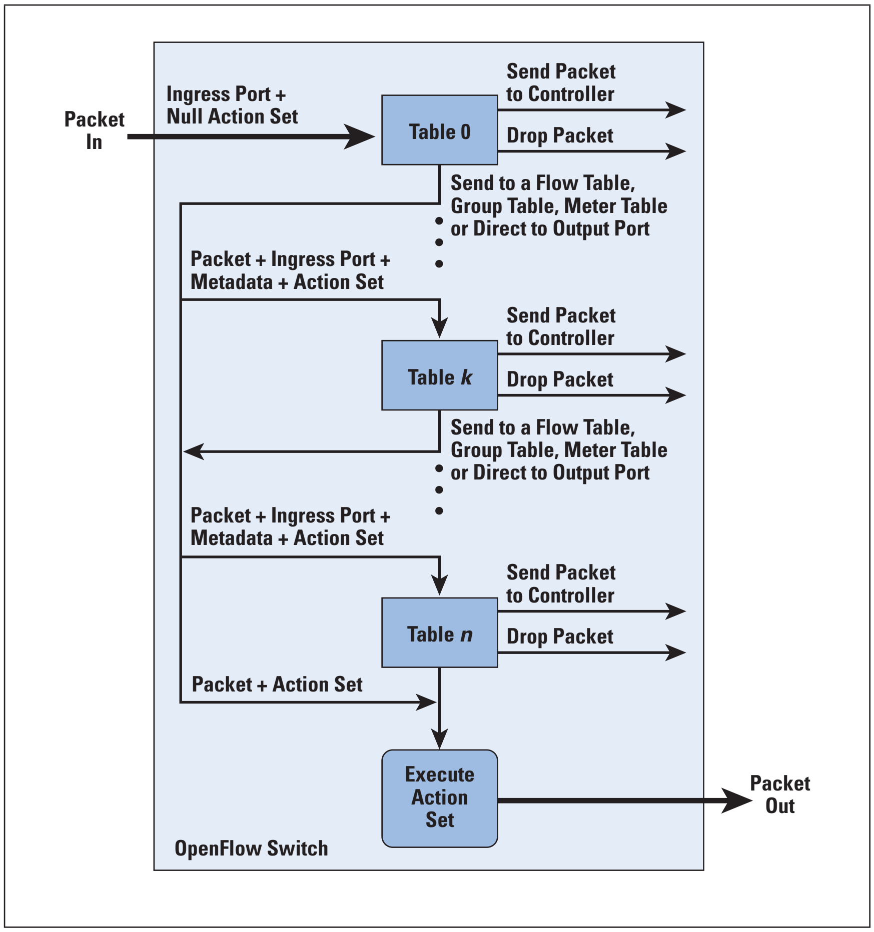
An *Action Set* is a list of actions associated with a packet that are accumulated while the packet is processed by each table and executed when the packet exits the processing pipeline. Instructions are of four types:

- *Direct packet through pipeline:* The Goto-Table instruction directs the packet to a table farther along in the pipeline. The Meter instruction directs the packet to a specified meter.
- *Perform action on packet:* Actions may be performed on the packet when it is matched to a table entry.
- *Update action set:* Merge specified actions into the current action set for this packet on this flow, or clear all the actions in the action set.
- *Update metadata:* A metadata value can be associated with a packet. It is used to carry information from one table to the next.

Flow-Table Pipeline

A switch includes one or more flow tables. If there is more than one flow table, they are organized as a pipeline as shown in Figure 4, with the tables labeled with increasing numbers starting with 0.

Figure 4: Packet Flow Through OpenFlow-Compliant Switch



When a packet is presented to a table for matching, the input consists of the packet, the identity of the ingress port, the associated metadata value, and the associated action set. For Table 0, the metadata value is blank and the action set is null. Processing proceeds as follows:

1. Find the highest-priority matching flow entry. If there is no match on any entry and there is no table-miss entry, then the packet is dropped. If there is a match only on a table-miss entry, then that entry specifies one of three actions:

   a. Send packet to controller. This action will enable the controller to define a new flow for this and similar packets, or decide to drop the packet.

   b. Direct packet to another flow table farther down the pipeline.

   c. Drop the packet.

2. If there is a match on one or more entries other than the table-miss entry, then the match is defined to be with the highest-priority matching entry. The following actions may then be performed:

   a. Update any counters associated with this entry.

   b. Execute any instructions associated with this entry. These instructions may include updating the action set, updating the metadata value, and performing actions.

   c. The packet is then forwarded to a flow table further down the pipeline, to the group table, or to the meter table, or it could be directed to an output port.

For the final table in the pipeline, forwarding to another flow table is not an option.

If and when a packet is finally directed to an output port, the accumulated action set is executed and then the packet is queued for output.

OpenFlow Protocol

The OpenFlow protocol describes message exchanges that take place between an OpenFlow controller and an OpenFlow switch. Typically, the protocol is implemented on top of SSL or *Transport Layer Security* (TLS), providing a secure OpenFlow channel.

The OpenFlow protocol enables the controller to perform add, update, and delete actions to the flow entries in the flow tables. It supports three types of messages, as shown in Table 1.

- *Controller-to-Switch:* These messages are initiated by the controller and, in some cases, require a response from the switch. This class of messages enables the controller to manage the logical state of the switch, including its configuration and details of flow- and group-table entries. Also included in this class is the Packet-out message. This message is used when a switch sends a packet to the controller and the controller decides not to drop the packet but to direct it to a switch output port.

- *Asynchronous:* These types of messages are sent without solicitation from the controller. This class includes various status messages to the controller. Also included is the Packet-in message, which may be used by the switch to send a packet to the controller when there is no flow-table match.

- *Symmetric:* These messages are sent without solicitation from either the controller or the switch. They are simple yet helpful. Hello messages are typically sent back and forth between the controller and switch when the connection is first established. Echo request and reply messages can be used by either the switch or controller to measure the latency or bandwidth of a controller-switch connection or just verify that the device is operating. The Experimenter message is used to stage features to be built into future versions of OpenFlow.

Table 1: OpenFlow Messages

Message	Description
Controller-to-Switch	
Features	Request the capabilities of a switch. Switch responds with a features reply that specifies its capabilities.
Configuration	Set and query configuration parameters. Switch responds with parameter settings.
Modify-State	Add, delete, and modify flow/group entries and set switch port properties.
Read-State	Collect information from switch, such as current configuration, statistics, and capabilities.
Packet-out	Direct packet to a specified port on the switch.
Barrier	Barrier request/reply messages are used by the controller to ensure message dependencies have been met or to receive notifications for completed operations.
Role-Request	Set or query role of the OpenFlow channel. Useful when switch connects to multiple controllers.
Asynchronous-Configuration	Set filter on asynchronous messages or query that filter. Useful when switch connects to multiple controllers.
Asynchronous	
Packet-in	Transfer packet to controller.
Flow-Removed	Inform the controller about the removal of a flow entry from a flow table.
Port-Status	Inform the controller of a change on a port.
Error	Notify controller of error or problem condition.
Symmetric	
Hello	Exchanged between the switch and controller upon connection startup.
Echo	Echo request/reply messages can be sent from either the switch or the controller, and they must return an echo reply.
Experimenter	For additional functions.

The OpenFlow protocol enables the controller to manage the logical structure of a switch, without regard to the details of how the switch implements the OpenFlow logical architecture.

Summary

SDNs, implemented using OpenFlow, provide a powerful, vendor-independent approach to managing complex networks with dynamic demands. The software-defined network can continue to use many of the useful network technologies already in place, such as virtual LANs and an MPLS infrastructure. SDNs and OpenFlow are likely to become commonplace in large carrier networks, cloud infrastructures, and other networks that support the use of big data.

References

[1] Greg Goth, "Software-Defined Networking Could Shake Up More than Packets," *IEEE Internet Computing*, July/August, 2011.

[2] Robin Layland,"The Dark Side of Server Virtualization," *Network World,* July 7, 2010.

[3] Open Networking Foundation, "Software-Defined Networking: The New Norm for Networks," ONF White Paper, April 12, 2012.

[4] Dell, Inc., "Software Defined Networking: A Dell Point of View," Dell White Paper, October 2012.

[5] Hongtao Yin, Haiyong Xie, Tina Tsou, Diego Lopez, Pedro Aranda, and Ron Sidi, "SDNi: A Message Exchange Protocol for Software Defined Networks (SDNS) across Multiple Domains," Internet Draft, work in progress, June 2012, `draft-yin-sdn-sdni-00.txt`

[6] Steven Vaughan-Nichols, "OpenFlow: The Next Generation of the Network?" *Computer,* August 2011.

[7] Thomas A. Limoncelli, "OpenFlow: A Radical New Idea in Networking," *Communications of the ACM,* August 2012.

[8] Open Networking Foundation, "OpenFlow Switch Specification Version 1.3.0," June 25, 2012.

[9] Sean Michael Kerner, "OpenFlow Protocol 1.3.0 Approved," *Enterprise Networking Planet,* May 17, 2012.

WILLIAM STALLINGS is an independent consultant and author of many books on security, computer networking, and computer architecture. His latest book is *Data and Computer Communications* (Pearson, 2013). He maintains a computer science resource site for computer science students and professionals at **`ComputerScienceStudent.com`**. He has a Ph.D. in computer science from M.I.T. He can be reached at **`ws@shore.net`**