Introduction to OpenFlow

Raj Jain
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu

These slides and audio/video recordings of this class lecture are at:

http://www.cse.wustl.edu/~jain/cse570-18/

Overview

1. Planes of Networking
2. OpenFlow
3. OpenFlow Operation
4. OpenFlow Switches including Open vSwitch
5. OpenFlow Evolution
6. Current Limitations and Issues

Note: This is the first module of four modules on OpenFlow, OpenFlow Controllers, SDN and NFV in this course.

Planes of Networking

- **Data Plane**: All activities involving as well as resulting from data packets sent by the end user, e.g.,
  - Forwarding
  - Fragmentation and reassembly
  - Replication for multicasting
- **Control Plane**: All activities that are necessary to perform data plane activities but do not involve end-user data packets
  - Making routing tables
  - Setting packet handling policies (e.g., security)
  - Base station beacons announcing availability of services

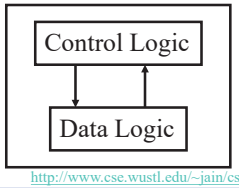
Ref: Open Data Center Alliance Usage Model: Software Defined Networking Rev 1.0,"
http://www.opendatacenteralliance.org/docs/Software_Defined_Networking_Master_Usage_Model_Rev1.0.pdf

Planes of Networking (Cont)

- **Management Plane**: All activities related to provisioning and monitoring of the networks
  - Fault, Configuration, Accounting, Performance and Security (**FCAPS**).
  - Instantiate new devices and protocols (Turn devices on/off)
  - Optional ⇒ May be handled manually for small networks.
- **Services Plane**: Middlebox services to improve performance or security, e.g.,
  - Load Balancers, Proxy Service, Intrusion Detection, Firewalls, SSL Off-loaders
  - Optional ⇒ Not required for small networks

Data vs. Control Logic

- Data plane runs at line rate,
  e.g., 100 Gbps for 100 Gbps Ethernet ⇒ Fast Path
  ⇒ Typically implemented using special hardware,
  e.g., Ternary Content Addressable Memories (TCAMs)
- Some exceptional data plane activities are handled by the CPU in the switch ⇒ Slow path
  e.g., Broadcast, Unknown, and Multicast (BUM) traffic
- All control activities are generally handled by CPU

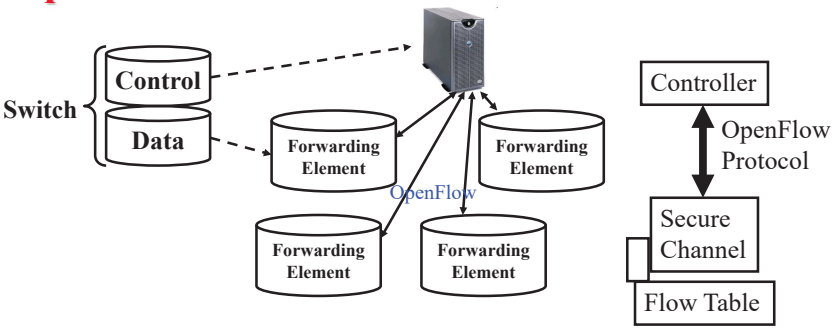


OpenFlow: Key Ideas

1. Separation of control and data planes
2. Centralization of control
3. Flow based control

Ref: N. McKeown, et al., ``OpenFlow: Enabling Innovation in Campus Networks," ACM SIGCOMM CCR, Vol. 38, No. 2, April 2008, pp. 69-74.

Separation of Control and Data Plane



- Control logic is moved to a controller
- Switches only have forwarding elements
- One expensive controller with a lot of cheap switches
- OpenFlow is the protocol to send/receive forwarding rules from controller to switches

OpenFlow V1.0

- On packet arrival, match the header fields with flow entries in a table, if any entry matches, update the counters indicated in that entry and perform indicated actions

Flow Table:

Header Fields	Counters	Actions
Header Fields	Counters	Actions
…	…	…
Header Fields	Counters	Actions

Ingress Port	Ether Source	Ether Dest	VLAN ID	VLAN Priority	IP Src	IP Dst	IP Proto	IP ToS	Src L4 Port	Dst L4 Port

Ref: http://archive.openflow.org/documents/openflow-spec-v1.0.0.pdf

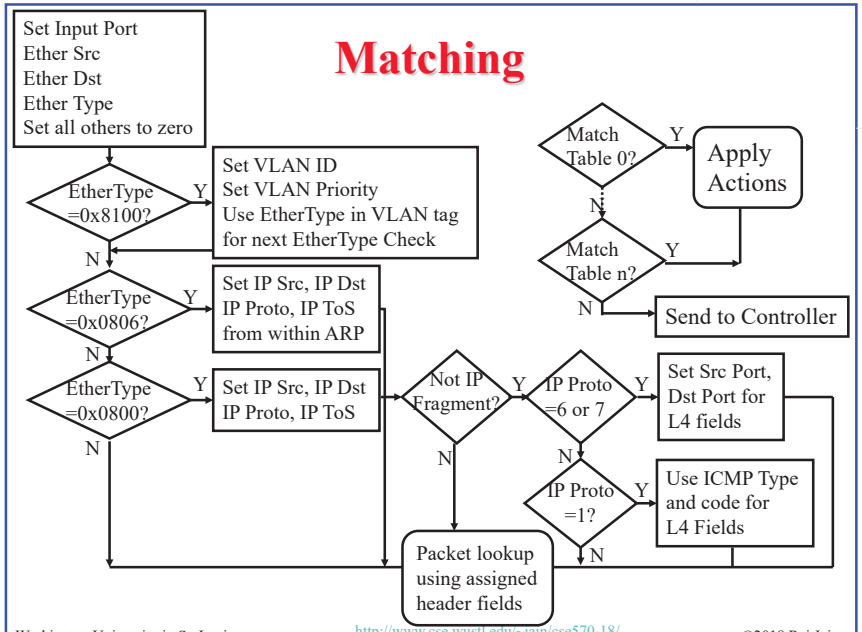
Flow Table Example

Port	Src MAC	Dst MAC	VLAN ID	Priority	EtherType	Src IP	Dst IP	IP Proto	IP ToS	Src L4 Port ICMP Type	Dst L4 Port ICMP Code	Action	Counter
*	*	0A:C8:*	*	*	*	*	*	*	*	*	*	Port 1	102
*	*	*	*	*	*	*	192.168.*.*	*	*	*	*	Port 2	202
*	*	*	*	*	*	*	*	*	*	21	21	Drop	420
*	*	*	*	*	*	*	*	0x806	*	*	*	Local	444
*	*	*	*	*	*	*	*	0x1*	*	*	*	Controller	1

- Idle timeout: Remove entry if no packets received for this time
- Hard timeout: Remove entry after this time
- If both are set, the entry is removed if either one expires.

Ref: S. Azodolmolky, "Software Defined Networking with OpenFlow," Packt Publishing, October 2013, 152 pp., ISBN:978-1-84969-872-6 (Safari Book)

Matching



Counters

Per Table	Per Flow	Per Port	Per Queue
Active Entries	Received Packets	Received Packets	Transmit Packets
Packet Lookups	Received Bytes	Transmitted Packets	Transmit Bytes
Packet Matches	Duration (Secs)	Received Bytes	Transmit overrun errors
	Duration (nanosecs)	Transmitted Bytes	
		Receive Drops	
		Transmit Drops	
		Receive Errors	
		Transmit Errors	
		Receive Frame Alignment Errors	
		Receive Overrun erorrs	
		Receive CRC Errors	
		Collisions	

Actions

- Forward to Physical Port *i* or to *Virtual Port*:
  - **All**: to all interfaces except incoming interface
  - **Controller**: encapsulate and send to controller
  - **Local**: send to its local networking stack
  - **Table**: Perform actions in the flow table
  - **In_port**: Send back to input port
  - **Normal**: Forward using traditional Ethernet
  - **Flood**: Send along minimum spanning tree except the incoming interface
- Enqueue: To a particular queue in the port ⇒ QoS
- Drop
- Modify Field: E.g., add/remove VLAN tags, ToS bits, Change TTL

Actions (Cont)

- Masking allows matching only selected fields, e.g., Dest. IP, Dest. MAC, etc.
- If header matches an entry, corresponding actions are performed and counters are updated
- If no header match, the packet is queued and the header is sent to the controller, which sends a new rule. Subsequent packets of the flow are handled by this rule.
- Secure Channel: Between controller and the switch using TLS
- Modern switches already implement flow tables, typically using Ternary Content Addressable Memories (TCAMs)
- Controller can change the forwarding rules if a client moves
  ⇒ Packets for mobile clients are forwarded correctly
- Controller can send flow table entries beforehand (**Proactive**) or Send on demand (**Reactive**). OpenFlow allows both models.

Open vSwitch

- Open Source Virtual Switch
- Nicira Concept
- Can Run as a stand alone hypervisor switch or as a distributed switch across multiple physical servers
- Default switch in XenServer 6.0, Xen Cloud Platform and supports Proxmox VE, VirtualBox, Xen KVM
- Integrated into many cloud management systems including OpenStack, openQRM, OpenNebula, and oVirt
- Distributed with Ubuntu, Debian, Fedora Linux. Also FreeBSD
- Intel has an accelerated version of Open vSwitch in its own Data Plane Development Kit (**DPDK**)

Ref: http://openvswitch.org/

Open vSwitch Features

- Inter-VM communication monitoring via:
  - **NetFlow**: Cisco protocol for sampling and collecting traffic statistics (RFC 3954)
  - **sFlow**: Similar to NetFlow by sflow.org (RFC 3176)
  - **Jflow**: Juniper's version of NetFlow
  - **NetStream**: Huawei's version of NetFlow
  - **IPFIX**: IP Flow Information Export Protocol (RFC 7011) - IETF standard for NetFlow
  - SPAN, RSPAN: Remote Switch Port Analyzer – port mirroring by sending a copy of all packets to a monitor port
  - **GRE-tunneled mirrors**: Monitoring device is remotely connected to the switch via a GRE tunnel

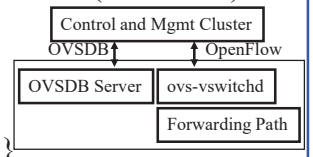
Open vSwitch Features (Cont)

- Link Aggregation Control Protocol (LACP)
- IEEE 802.1Q VLAN
- IEEE 802.1ag Connectivity Fault Management (CFM)
- Bidirectional Forwarding Detection (BFD) to detect link faults (RFC 5880)
- IEEE 802.1D-1998 Spanning Tree Protocol (STP)
- Per-VM traffic policing
- OpenFlow
- Multi-table forwarding pipeline
- IPv6
- GRE, VXLAN, IPSec tunneling
- Kernel and user-space forwarding engine options

OVSDB

- Open vSwitch Database Management Protocol (OVSDB)
- Monitoring capability using publish-subscribe mechanisms
- Stores both provisioning and operational state
- Java Script Object Notation (JSON) used for schema format and for JSON-RPC over TCP for wire protocol (RFC 4627)

<database-schema>
"name": <id>
"version": <version>
"tables": {<id>: <table-schema>,…}

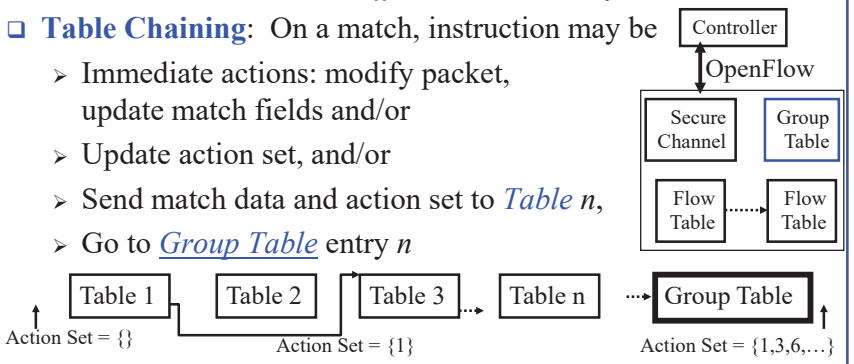


- RPC Methods: List databases, Get Schema, Update, Lock, …
- Open vSwitch project includes open source OVSDB client and server implementations

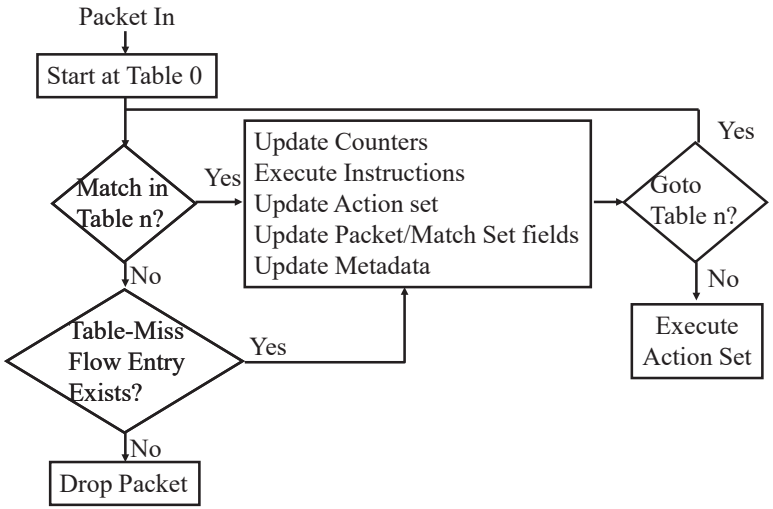
Ref: B. Pfaff and B. Davie, "The Open vSwitch Database Management Protocol," IETF draft, Oct 2013, http://tools.ietf.org/html/draft-pfaff-ovsdb-proto-04

OpenFlow V1.1

- V1: Perform action on a match. Ethernet/IP only. Single Path Did not cover MPLS, Q-in-Q, ECMP, and efficient Multicast
- V1.1 Introduced *Table chaining, Group Tables, and added MPLS Label and MPLS traffic class to match fields*.
- **Table Chaining**: On a match, instruction may be
  - Immediate actions: modify packet, update match fields and/or
  - Update action set, and/or
  - Send match data and action set to *Table n*,
  - Go to *Group Table* entry *n*



OpenFlow V1.1 (Cont)



Source: OpenFlow Switch Specification, V1.4.1

OpenFlow V1.1 (Cont)

- On a miss, the instruction may be to send packet to controller or continue processing with the sequentially next table
- Group Tables: each entry has a variable number of buckets
  - **All**: Execute each bucket. Used for Broadcast, Multicast.
  - **Select**: Execute one *switch selected* bucket. Used for port mirroring. Selection may be done by hashing some fields.
  - **Indirect**: Execute one *predefined* bucket.
  - **Fast Failover**: Execute the first live bucket ⇒ Live port
- New Features supported:
  - **Multipath**: A flow can be sent over one of several paths
  - **MPLS**: multiple labels, traffic class, TTL, push/pop labels
  - **Q-in-Q**: Multiple VLAN tags, push/pop VLAN headers
  - **Tunnels**: via virtual ports

Ref: http://archive.openflow.org/documents/openflow-spec-v1.1.0.pdf

OpenFlow V1.2

1. **IPv6 Support**: Matching fields include IPv6 source address, destination address, protocol number, traffic class. ICMPv6 type, ICMPv6 code, IPv6 neighbor discovery header fields, and IPv6 flow labels.
2. **Extensible Matches**: Type-Length-Value (TLV) structure. Previously the order and length of match fields was fixed.
3. **Experimenter extensions** through dedicated fields and code points assigned by ONF

Ref: https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow/openflow-spec-v1.2.pdf

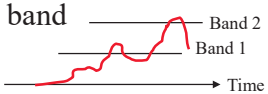
OpenFlow 1.3

- **IPv6 extension headers**: Can check if Hop-by-hop, Router, Fragmentation, Destination options, Authentication, Encrypted Security Payload (ESP), unknown extension headers are present
- **MPLS Bottom-of-Stack bit** matching
- **MAC-in-MAC** encapsulation
- **Tunnel ID meta data**: Support for tunnels (VxLAN, …)
- **Per-Connection Event Filtering**: Better filtering of connections to multiple controllers
- Many **auxiliary connections** to the controller allow to exploit parallelism
- Better **capability negotiation**: Requests can span multiple messages
- More general **experimenter capabilities** allowed
- A separate flow entry for **table miss actions**

Ref: https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow/openflow-spec-v1.3.0.pdf

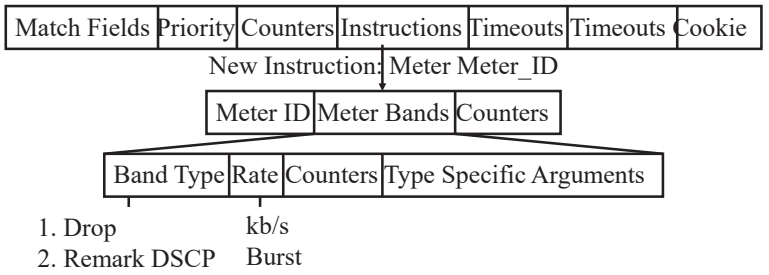
OpenFlow V1.3 (Cont)

- **Cookies**: A cookie field with policy identifier is added to messages containing new packets sent to the controller. This helps controller process the messages faster than if it had to search its entire database.
- **Duration**: Duration field has been added to most stats. Helps compute rates.
- Per-flow counters can be disabled to improve performance
- Per Flow Meters and meter bands
- **Meter**: Switch element that can measure and control the rate of packets/bytes.
  - **Meter Band**: If the packet/byte rate exceeds a pre-defined threshold ⇒ the meter has triggered the band
  - A meter may have multiple bands



OpenFlow V1.3 (Cont)

- If on triggering a band the meter drops the packet, it is called rate limiter.
- Other QoS and policing mechanisms can be designed using these meters
- **Per-Flow QoS**: Meters are attached to a flow entry not to a queue or a port.
- Multiple flow entries can all point to the same meter.



OpenFlow V1.4

- **Optical ports**: Configure and monitor transmit and receive frequencies of lasers and their power
- **Improved Extensibility**: Type-Length-Value (TLV) encodings at most places ⇒ Easy to add new features in future
- **Extended Experimenter Extension API**: Can easily add ports, tables, queues, instructions, actions, etc.
- More information when a packet is sent to controller, e.g., no match, invalid TTL, matching group bucket, matching action, ..
- Controllers can select a subset of flow tables for monitoring
- Switches can **evict** entries of lower importance if table full
- Switches can notify controller if table is getting full
- Atomic execution of a **bundle** of instructions

Ref: https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow/openflow-spec-v1.4.0.pdf

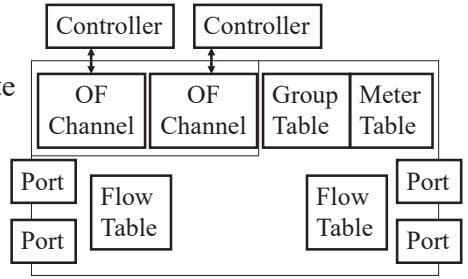
OpenFlow V1.4.1

1. **Bundle**: Atomic Instruction Group
   - A group of instructions from the controller that are either all executed or all not executed
   - A bundle may be sent to many switches and then applied at approximately same time on commit request from the controller
2. **Flow Table Monitoring**: Synchronization in a multi-controller system
   - Notify a controller if a set of flow table entries is modified by another controller
3. Bug fixes

Ref: OpenFlow Switch Specification, V 1.4.1, March 26, 2015

OpenFlow V1.5

1. **Egress Tables**: actions to be done when exiting through a port (encapsulate or decapsulate a packet, tunnels)
2. **Packet Type**: Can now handle non-Ethernet packets, e.g., IP packets

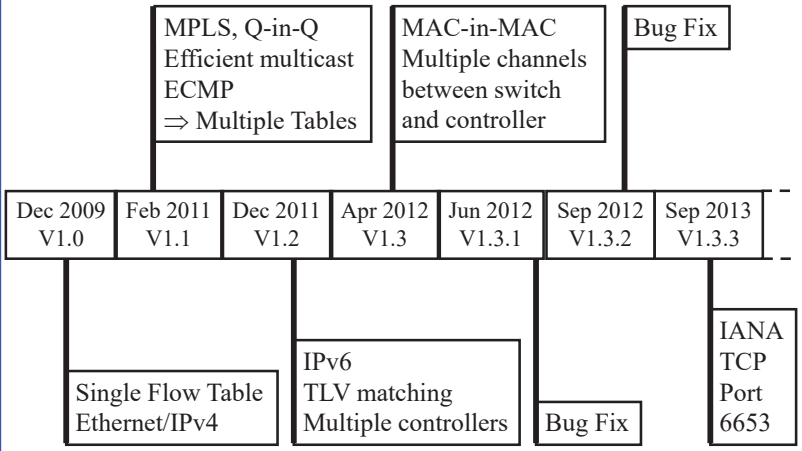


3. **TCP Flags Matching**: Syn, Ack, and Fin may be used to detect beginning and end of a TCP connection

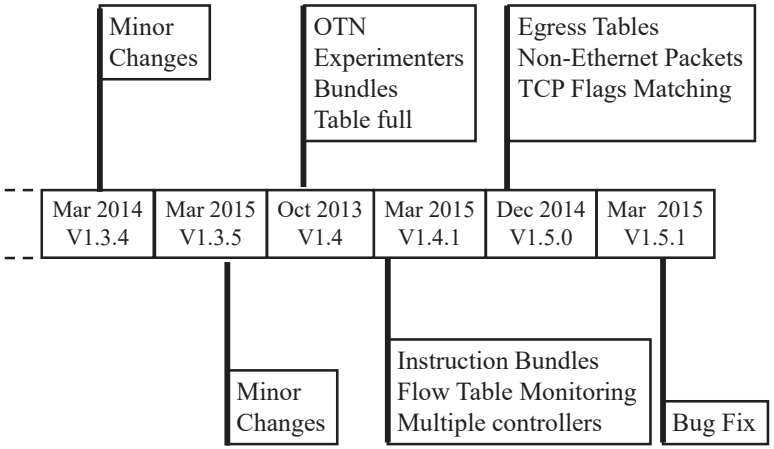
OpenFlow V1.5.1: Bug Fixes, March 2015

Ref: OpenFlow Switch Specification, V 1.5.1, March 26, 2015, https://www.opennetworking.org/wp-content/uploads/2014/10/openflow-switch-v1.5.1.pdf

OpenFlow Evolution Summary



OpenFlow Evolution Summary (Cont)



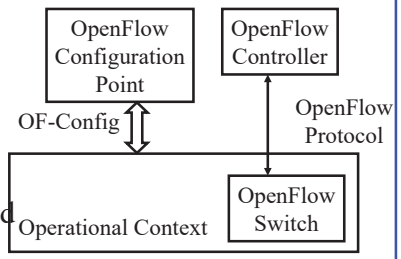
Bootstrapping

- Switches require initial configuration: Switch IP address, Controller IP address, Default gateway
- Switches connect to the controller
- Switch provides configuration information about ports
- Controller installs a rule to forward LLDP packets to controller and then sends, one by one, LLDP packets to be sent out to port i (i=1, 2, …, n) which are forwarded to respective neighbors. The neighbors send the packets back to controller.
- Controller determines the topology from LLDP packets
- LLDP is a one-way protocol to advertise the capabilities at fixed intervals.

Ref: S. Sharma, et al., "Automatic Bootstrapping of OpenFlow Networks," 19th IEEE Workshop on LANMAN, 2013, pp. 1-6, http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6528283 (Available to subscribers only)

OpenFlow Configuration Protocol (OF-Config)

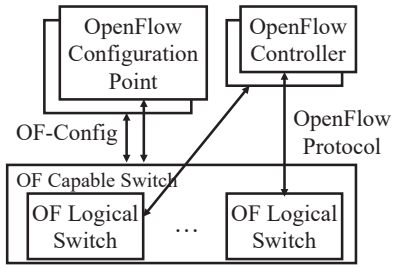
- **OpenFlow Control Point**: Entity that configures OpenFlow switches
- **OF-Config**: Protocol used for configuration and management of OpenFlow Switches.
  Assignment of OF controllers so that switches can initiate connections to them:
  - IP address of controller
  - Port number at the controller
  - Transport protocol: TLS or TCP
  - Configuration of queues (min/max rates) and ports
  - Enable/disable receive/forward speed, media on ports



Ref: Cisco, "An Introduction to OpenFlow," Feb 2013, http://www.cisco.com/web/solutions/trends/open_network_environment/docs/cisco_one_webcastan_introduction_to_openflowfebruary142013.pdf

OF-Config (Cont)

- A physical switch = one or more logical switches each controlled by an OF Controller
- OF-Config allows configuration of logical switches.



Ref: ONF, "OpenFlow Management and Configuration Protocol (OF-Config 1.1.1)," March 23, 2013, https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow-config/of-config-1-1-1.pdf

OF-Config Concepts

- **OF Capable Switch**: Physical OF switch. Can contain one or more OF logical switches.
- **OpenFlow Configuration Point**: configuration service
- **OF Controller**: Controls logical switch via OF protocol
- **Operational Context**: OF logical switch
- **OF Queue**: Queues of packets waiting for forwarding
- **OF Port**: forwarding interface. May be physical or logical.
- **OF Resource**: ports, queues, certificates, flow tables and other resources of OF capable switches assigned to a logical switch
- **Datapath ID**: 64-ID of the switch. Lower 48-bit = Switch MAC address, Upper 16-bit assigned by the operator

OF-Config Evolution

- V1.0 (Jan 2012): Based on OpenFlow V1.2
  - Assign controllers to logical switches
  - Retrieve logical switch configurations
  - Configure ports and queues
- V1.1 (May 2012): Based on OpenFlow V1.3
  - Configuration of certificates
  - Capability Discovery: Retrieve logical switch capabilities
  - Configure logical tunnels (VXLAN, NVGRE, …)
- V1.1.1 (Jan 2013): Bug Fix. Versioning support
- V1.2 (2014):
  - OF-Config version negotiation
  - Assigning resources to logical switches

Ref: https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow-config/of-config1dot0-final.pdf
https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow-config/of-config-1.1.pdf
https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow-config/of-config-1-1-1.pdf

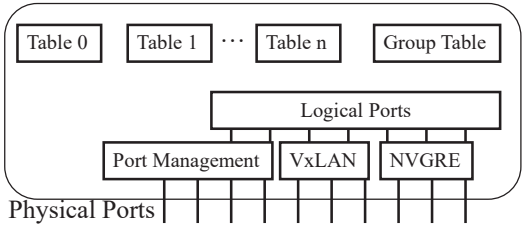
OpenFlow Notification Framework

- **Notification**: Event triggered messages, e.g., link down
- **Publish/subscribe model**: Switch = publisher. OpenFlow controller or OpenFlow config points, and others can subscribe. They will be notified about the events they subscribe.
- Use **ITU-T M.3702** Notifications: Attribute value change, Communication alarm, Environmental alarm, Equipment alarm, QoS alarm, Processing error alarm, Security alarm, State change, Object creation and deletion
- **Pre-existing Notifications**: Do not fit in the framework but will be recognized.
  - OpenFlow: Packet-in, Flow removed, Port Status, Error, Hello, Echo request, Echo reply, Experimenter
  - OpenFlow Config: OpenFlow logical switch instantiation, OpenFlow capability switch capability change, Successful OpenFLow session establishment, Failed OpenFlow session establishment, Port failure or recovery

Ref: https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow-config/of-notifications-framework-1.0.pdf

Implementation Issues

- 40+ matching fields in a flow
- Multiple tables, each with a large number of flow entries
- Instructions and actions for each table
- Need VXLAN, NVGRE, etc. support
- For a large network, flow level programming can take a long time



Ref: R. Oshana and S. Addepalli, "Networking Trends- Software Defined Networking, Network Virtualization and Cloud Orchestration," Asia Power Arch. Conf, Oct 2012, https://www.power.org/wp-content/uploads/2012/10/13.-FSL-SDN-Openflow-and-Cloud-computing-UPD_Rob-Oshana.pdf

Summary

1. Four planes of Networking: Data, Control, Management, Service
2. OpenFlow separates control plane and moves it to a central controller ⇒ Simplifies the forwarding element
3. Switches match incoming packets with flow entries in a table and handle it as instructed. The controller supplies the flow tables and other instructions.
4. Many hardware and software based switches including Open vSwitch
5. OpenFlow has been extended to IPv4, MPLS, IPv6, and Optical Network. But more work ahead.

Reading List

- T. Nadeau and K. Gray, "SDN," O'Reilly, 2013, 384 pp, ISBN:978-1-449-34230-2B (Safari Book)
- Oswald Coker, Siamak Azodolmolky, "Software-Defined Networking with OpenFlow - Second Edition," Packt Publishing, October 2017, 246 pp., ISBN:978-1-78398-429-9 (Safari Book).
- William Stallings, "Foundations of Modern Networking: SDN, NFV, QoE, IoT, and Cloud," Addison-Wesley Professional, October 2015, 544 pp., ISBN:0-13-417539-5 (Safari Book).
- Kingston Smiler. S, "OpenFlow Cookbook," Packt Publishing, April 2015, 292 pp., ISBN:978-1-78398-795-5 (Safari Book).

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- ONF, "The OpenFlow Timeline," http://openflownetworks.com/of_timeline.php
- Open Data Center Alliance Usage Model: Software Defined Networking Rev 1.0," http://www.opendatacenteralliance.org/docs/Software_Defined_Networking_Master_Usage_Model_Rev1.0.pdf
- R. Oshana and S. Addepalli, "Networking Trends- Software Defined Networking, Network Virtualization and Cloud Orchestration," Asia Power Arch. Conf, Oct 2012, https://www.power.org/wp-content/uploads/2012/10/13.-FSL-SDN-Openflow-and-Cloud-computing-UPD_Rob-Oshana.pdf
- ONF, **Technical Library** (includes all OpenFlow, OF-Config, and other specifications), https://www.opennetworking.org/sdn-resources/technical-library

References (Cont)

- http://www.openvswitch.org/
- http://www.projectfloodlight.org/indigo/
- http://flowforwarding.github.io/LINC-Switch/
- http://github.com/CPqD/openflow-openwrt
- http://cpqd.github.io/ofsoftswitch13/
- http://sourceforge.net/projects/xorplus

Wikipedia Links

- http://en.wikipedia.org/wiki/OpenFlow
- http://en.wikipedia.org/wiki/Software-defined_networking
- http://en.wikipedia.org/wiki/Network_Functions_Virtualization
- http://en.wikipedia.org/wiki/Forwarding_plane
- http://en.wikipedia.org/wiki/NetFlow
- http://en.wikipedia.org/wiki/IP_Flow_Information_Export
- http://en.wikipedia.org/wiki/SFlow
- http://en.wikipedia.org/wiki/Northbound_interface
- http://en.wikipedia.org/wiki/Big_Switch_Networks

Wikipedia Links (Optional)

- http://en.wikipedia.org/wiki/Open_Data_Center_Alliance
- http://en.wikipedia.org/wiki/Virtual_Extensible_LAN
- http://en.wikipedia.org/wiki/Optical_Transport_Network
- http://en.wikipedia.org/wiki/Automatically_switched_optical_network
- http://en.wikipedia.org/wiki/Wavelength-division_multiplexing
- http://en.wikipedia.org/wiki/IEEE_802.1ad
- http://en.wikipedia.org/wiki/Transport_Layer_Security
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Acronyms

ACL	Access Control List
API	Application Programming Interface
ARP	Address Resolution Protocol
ASICs	Application Specific Integrated Circuit
BFD	Bidirectional Forwarding Detection
BUM	Broadcast, Unknown, and Multicast
CFM	Connectivity Fault Management
CPU	Central Processing Unit
DFCA	Dynamic Frequency Channel Allocation
DSCP	Differentiated Service Control Point
ECMP	Equal Cost Multipath
ESP	Encrytec Security Payload
FCAPS	Fault, Configuration, Accounting, Performance and Security
GRE	Generic Routing Encapsulation
ICMP	Internet Control Message Protocol
ID	Identifier

Acronyms (Cont)

IDS	Intrusion Detection System
IEEE	Institution of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
IGMP	Internet Group Multicast Protocol
IP	Internet Protocol
IPFIX	IP Flow Information Export Protocol
IPSec	IP Security
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
JSON	Java Script Object Notation
KVM	Kernel-based Virtual Machine
LACP	Link Aggregation Control Protocol
LLDP	Link Layer Discovery Protocol
MAC	Media Access Control
MAN	Metropolitan Area Network
MPLS	Multiprotocol Label Switching

Acronyms (Cont)

- NFV Network Function Virtualization
- NVGRE Network Virtualization using Generic Routing Encapsulation
- OF OpenFlow
- ONF Open Networking Foundation
- openQRM Open Qlusters Resource Manager
- OpenWRT Open WRT54G (Linksys product name) software
- OSPF Open Shortest Path First
- OTN Optical Transport Network
- OVSDB Open vSwitch Database
- PIM-SM Protocol Independent Multicast - Sparse Mode
- PIM Protocol Independent Multicast
- QoS Quality of Service
- RAN Radio area networks
- RFC Request for Comments
- RIP IGMP, IPv6, PIM-SM
- RIP Routing Information Protocol

Acronyms (Cont)

- RPC Remote Procedure Call
- RSPAN Remote Switch Port Analyzer
- SDN Software Defined Network
- SPAN Switch Port Analyzer
- SSL Secure Socket Layer
- STP Spanning Tree Protocol
- TCAM Ternary Content Addressable Memory
- TCP Transmission Control Protocol
- TLS Transport Level Security
- TLV Type-Length-Value
- ToS Type of Service
- TTL Time to Live
- TTP Table Typing Patterns
- UDP User Datagram Protocol
- VLAN Virtual Local Area Network
- VM Virtual Machine
- VxLAN Virtual Extensible Local Area Network
- WG Working Group

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