Software Defined Networking (SDN)

Andrea Bianco
andrea.bianco@polito.it
http://www.telematica.polito.it/

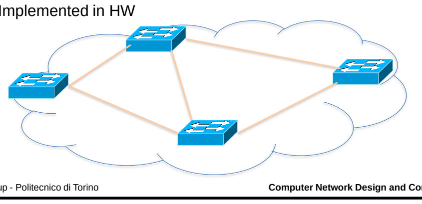
Outline

- SDN
  - Motivations and definitions
  - Centralized architecture
  - Flow based forwarding
- Openflow protocol
- Advances
  - Distributed controllers
  - Stateful switches

Rexford – Computer Network class

Traditional computer networks

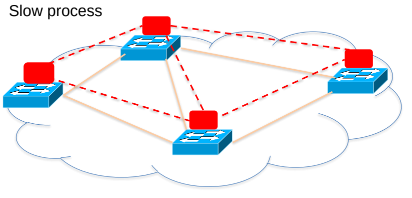
- Data plane
  - Local algorithms, dealing with packets
    - Forwarding, filtering, scheduling, buffering, marking, rate-limiting, measuring at the packet level
  - Packet transmission time scale
    - Very fast processing
    - Implemented in HW



Rexford – Computer Network class

Traditional computer networks

- Control plane
  - Distributed algorithms
    - Topology discovery, topology tracking, route computation, installing forwarding rules, traffic engineering
  - Seconds time scale, flow time scale
    - Slow process



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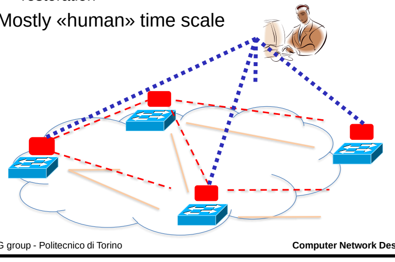
Traditional computer networks

- Management plane
  - Local/global algorithms with coordination
    - Measurement, configuration, monitoring, protection and restoration
  - Mostly «human» time scale



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Traditional computer networks

- Features
  - Incredible success (from research experiments to global commercial infrastructure)
  - «In principle» complexity at the edge
    - «Only» packet forwarding inside
    - Complexity at the edge (SW) enables fast innovation
    - Host running increasingly complex applications (SW)
      - Web, P2P, social networks, virtual reality, video streaming
  - Inside the network?
    - Closed equipments, SW and HW intermixed, vendor specific interfaces, many more features beside forwarding, too many protocols
    - Slow and costly development and management

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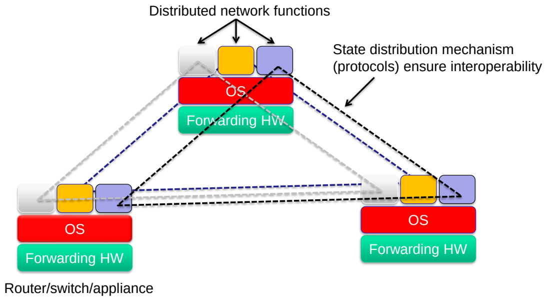
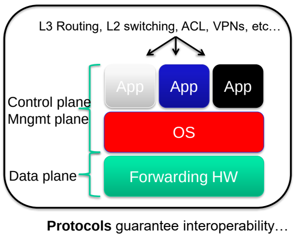
Classic network paradigm



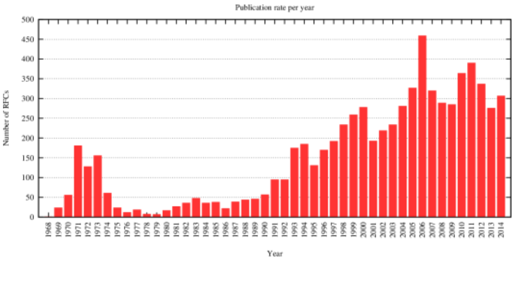
Closed platform

- Configuration interfaces vary
  - Different vendors
  - Different devices of the same vendors
  - Different firmware versions of the same device



Protocols guarantee interoperability…

Too many protocols/standards?



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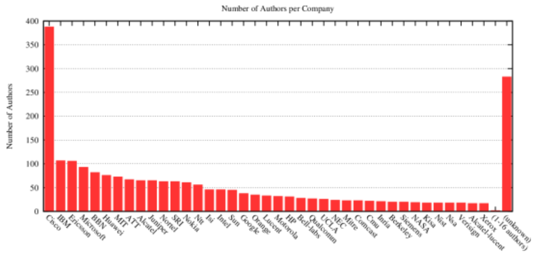
Vendors dominated



Software Defined Networking*

- "New" key elements
  - Clean interface (API) between data and control plane
  - Logically centralized control plane
    - Control plane out of forwarding devices
    - Control plane (SW) may run on general purpose HW
    - Global network view
    - SDN controller or Network Operating Systems
      - Network programmability
      - New architecture
  - Flow based switching
    - Programmed by the centralized controller
    - Very flexible flow definition
  - Network applications running on top of NOS

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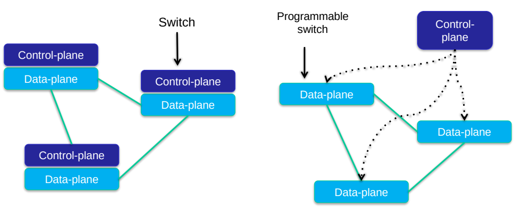
The new (centralized) model*

Traditional networking
Distributed

Software-Defined Networking
Centralized



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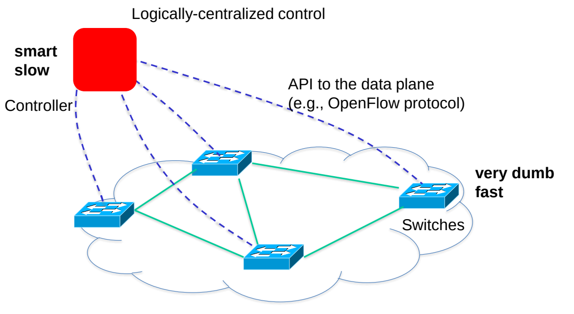
Centralized control



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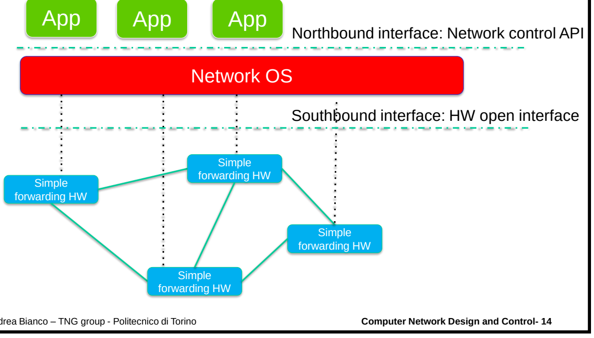
SND architecture: interfaces

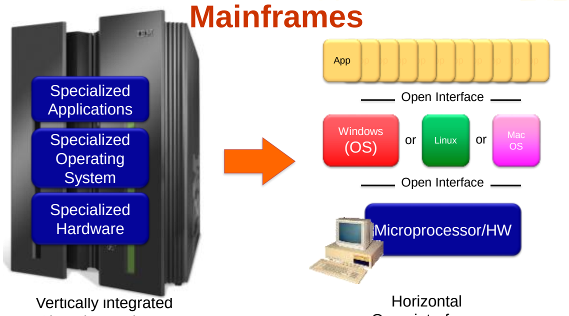


A Helpful Analogy

From Nick McKeown’s talk
“Making SDN Work” at the
Open Networking Summit, April 2012

N. Mc Keown – ONS 2012

Mainframes

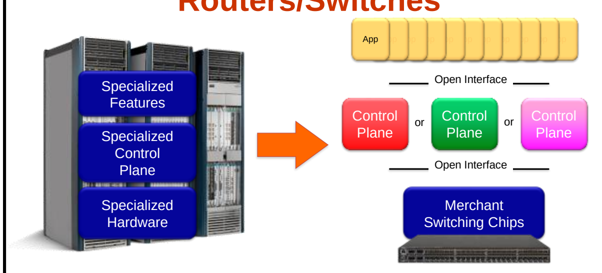


Vertically integrated
Closed, proprietary
Slow innovation
Small industry

Horizontal
Open interfaces
Rapid innovation
Huge industry

N. Mc Keown– ONS 2012

Routers/Switches



Vertically integrated
Closed, proprietary
Slow innovation

Horizontal
Open interfaces
Rapid innovation

Flow-based forwarding*

- Protocol-less or protocol-oblivious forwarding
  - Not exactly true (set of predefined fields)
- Simple packet-handling rules
  - Pattern/rule: match packet header bits
  - Actions: drop, forward, modify, send to controller
  - Priority: disambiguate overlapping patterns

OpenFlow/SDN tutorial, Srini Seetharaman

Flow based forwarding: table entries

Rule	Action	Stats

Stats: Packet + byte counters

Action:
1. Forward packet to zero or more ports
2. Encapsulate and forward to controller
3. Send to normal processing pipeline
4. Modify Fields
5. Any extensions you add!

Rule:

Switch Port	MAC src	MAC dest	Eth type	VLAN Id	VLAN pcp	IP Src	IP Dst	IP ToS	IP Prot	L4 sport	L4 dport

+ mask what fields to match

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Unifies different kinds of “boxes”

- Router
  - Match: longest destination IP prefix
  - Action: forward
- L2 MAC Switch
  - Match: destination MAC address
  - Action: forward or flood
- Firewall
  - Match: IP addresses and TCP/UDP port numbers
  - Action: permit or deny
- NAT
  - Match: IP address and TCP/UDP port
  - Action: rewrite address and port

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OpenFlow/SDN tutorial, Srini Seetharaman

Examples of “boxes”

Switching

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	00:1f:..	*	*	*	*	*	*	*	port6

Flow Switching

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
port3	00:20..	00:1f..	0800	vlan1	1.2.3.4	5.6.7.8	4	17264	80	port4

Firewall

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	*	*	*	*	*	*	*	22	drop

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OpenFlow/SDN tutorial, Srini Seetharaman

Examples of "boxes"

Routing

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	*	*	*	*	5.6.7.8	*	*	*	port3

VLAN Switching

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	00:1f..	*	vlan1	*	*	*	*	*	port6 port7 port9

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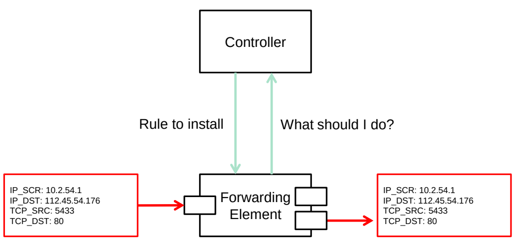
Bifulco talk at ewsdn2014

Controller to switch interaction



...	L3_SRC	L3_DST	L4_SRC	L4_DST	...	Action
	Any	112/8	Any	Any		Fwd-to: 2

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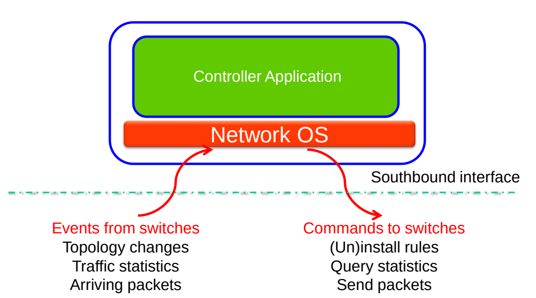
SDN controller: network programmability



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Example of applications

- Dynamic access control
- Seamless mobility/migration
- Server load balancing
- Network virtualization
- Using multiple wireless access points
- Traffic engineering
- Energy-efficient networking
- Adaptive traffic monitoring
- Denial-of-Service attack detection
- …….

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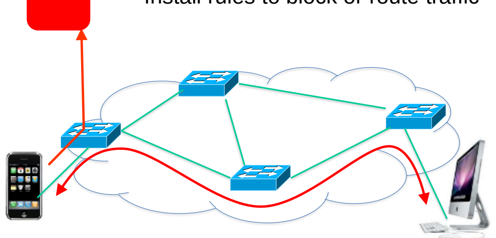
Application: Dynamic access control

- Inspect first packet of a connection
- Consult the access control policy
- Install rules to block or route traffic



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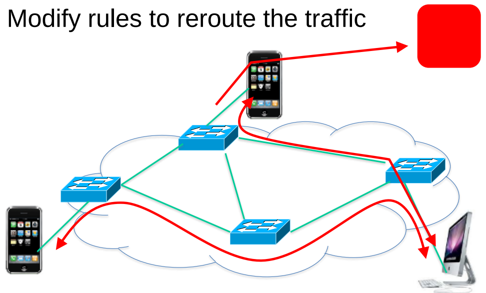
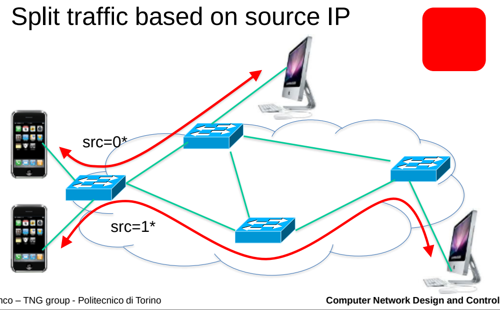
Application: Seamless mobility/migration

- See host send traffic at new location
- Modify rules to reroute the traffic



Application
Server load balancing

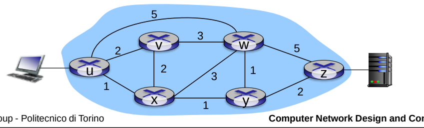
- Pre-install load-balancing policy
- Split traffic based on source IP



Traffic engineering: difficult with traditional routing

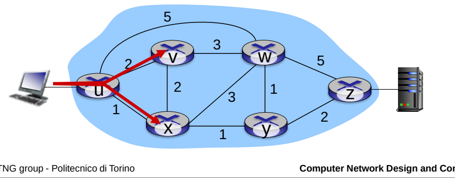
Hp. Destination based routing

- What if network operator wants
  - u-to-z traffic to flow along uvwz
  - x-to-z traffic to flow xwyz?
- Need to define link weights so traffic routing algorithm computes routes (or need a new routing algorithm)
- Does not work
  - Modifies many routes
  - Cannot change weights to route each individual flow



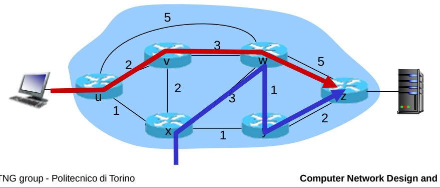
Traffic engineering: difficult with traditional routing

- What if network operator wants to split u-to-z traffic along uvwz and uxyz (load balancing)?
- Can't do it (or need a new routing algorithm)



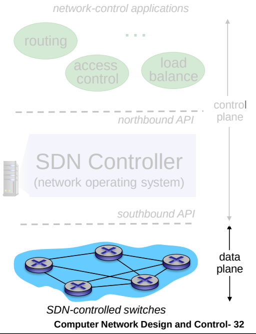
Traffic engineering: difficult with traditional routing

- What if we wants to route blue and red traffic differently?
- Can't do it (with destination based forwarding, and LS, DV routing)



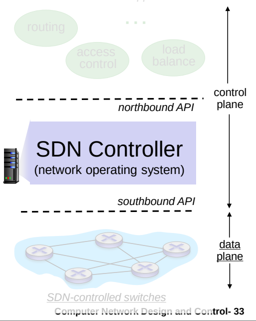
SDN: switches

- Data plane switches
  - Fast, simple, commodity switches implementing generalized data-plane forwarding in HW
  - Switch flow table computed, installed by controller
  - API for table-based switch control
    - Defines what is controllable and what is not
  - Protocol for communicating with controller



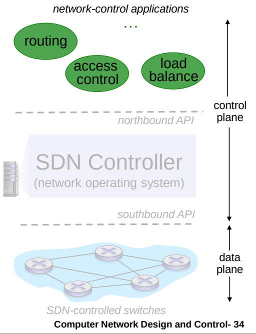
SDN controller

- SDN controller (network OS):
  - Maintain network state information
  - Interacts with network control applications "above" via northbound API
  - Interacts with network switches "below" via southbound API



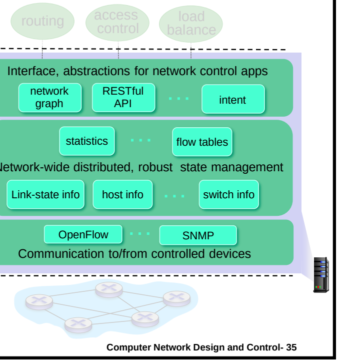
SDN application

- Network-control apps:
  - "Brains" of control: implement control functions using lower-level services, API provided by SND controller
  - Unbundled: can be provided by 3rd party: distinct from routing vendor, or SDN controller



SDN controller components

- Interface layer to network control apps
  - Abstraction API
- State management layer
  - Distributed database
    - State of network links, switches etc
- Communication layer



SDN: pros and cons

- Potential benefits
  - Easier and faster innovation
  - Exploits global network view
    - Traffic enginering
    - Traffic steering
    - Security
    - ….
  - Simpler switches
    - Less costly
    - Less power hungry
  - «Avoids» device misconfiguration
  - Virtual resource management
- Potential drawbacks
  - Performance
    - Overheads
    - Scalability
    - Bottleneck
  - Single point of failure
  - Interoperability

SDN where?

- Campus LAN
- Data center
- WAN (google) to interconnect data centers
- ISP?
- 5G networks

The role of the scenario

- Datacenter
  - Very large number of devices
    - Spatially collocated
  - Low and predictable delays between devices
  - Dedicated network for control
    - Out of band control traffic

- ISP/POP
  - Lower number of devices
    - Spatially distributed
  - High and unpredictable latencies
  - Control and data share the same resources
    - In band control traffic

Level of aggregation

- Flow Based
  - Every flow is individually set up by controller
  - Exact-match flow entries
  - Flow table contains one entry per flow
  - Suited for fine grain control, e.g. campus networks
- Group Based
  - One flow entry covers large groups of flows
  - Wildcard flow entries
  - Flow table contains one entry per category/group of flows
  - Suited for large number of flows, e.g. ISPs

Level of aggregation

- High aggregation level
  - Dealing with few large objects
  - Reduced occupation of forwarding table
  - Reduced signaling overhead and controller load
  - Coarse granularity in the control of flow Qos
    - A flow steering moves a large amount of traffic
  - Less elements to deal with for load balancing but more difficult to balance

Reactive vs. Proactive

- Reactive
  - Flow table empty at boot
  - First packet of a flow sent to the controller
  - Controller inserts flow entries
  - Dynamic network

  - Every flow incurs small (?) additional flow setup time
  - Large control traffic
  - Large load on the controller
  - Efficient use of flow table
  - If control connection lost, switch has limited utility
- Proactive
  - Controller pre-populates flow table in switch at boot
  - Zero additional flow setup time
  - Static network

  - Loss of control connection does not disrupt traffic
  - Essentially requires aggregated (wildcard) rules
    - Reduced table size

OpenFlow protocol

Andrea Bianco
andrea.bianco@polito.it
http://www.telematica.polito.it/

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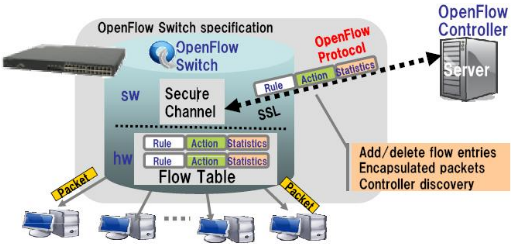
Flow based forwarding



OpenFlow/SDN tutorial, Srini Seetharaman

OpenFlow protocol

OpenFlow Controller

OpenFlow Protocol (SSL/TCP)

Control Path | OpenFlow

Data Path (Hardware)

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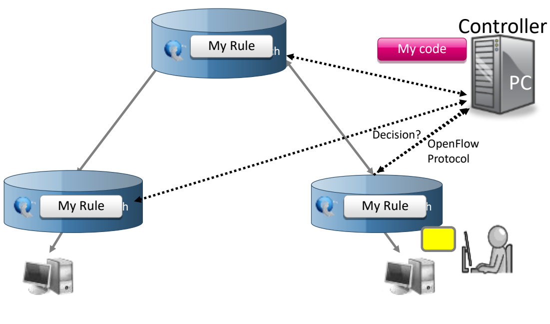
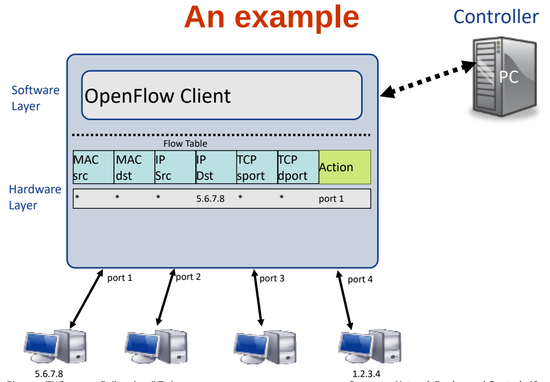
OpenFlow protocol use



OpenFlow/SDN tutorial, Srini Seetharaman

An example



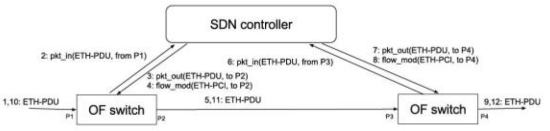
OpenFlow protocol messages

- Controller-to-switch
  - Initiated by the controller and used to directly manage or inspect the state of the switch
    - Features, Config, Modify State, Read State, Packet Out, Barrier
- Asynchronous
  - Sent to the controller without controller soliciting
    - Packet-in, Flow Removed/Expiration, Port status, Error, …
- Symmetric
  - Sent without solicitation in any direction
    - Hello, Echo, Experimenter/Vendor

OpenFlow (main) messages

- Packet_in
  - Switch to controller
  - Carries a packet copy (possibly only the header)
    - What is best?
  - Generated by default in case of table miss
- Packet_out
  - Controller to switch
  - Send the packet out of a specified port
  - Carries the full packet or the switch buffer id
- Flow_mod
  - Controller to switch
  - Modify flow tables
  - Carries match-action rule to install

OpenFlow example

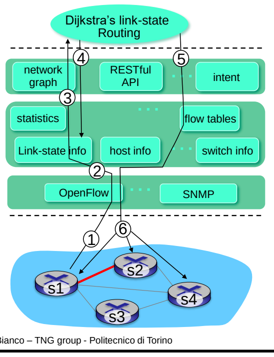


SDN architecture in action

Andrea Bianco
andrea.bianco@polito.it
http://www.telematica.polito.it/

From Kurose Ross: Computer Networking

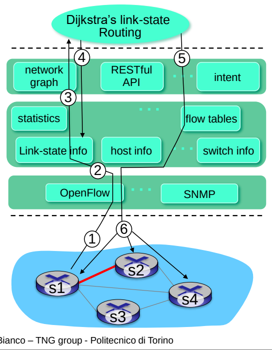
An example



1. S1, experiencing link failure using OpenFlow port status message to notify controller
2. SDN controller receives OpenFlow message, updates link status info
3. Dijkstra's routing algorithm application has previously registered to be called when ever link status changes. It is called.
4. Dijkstra's routing algorithm access network graph info, link state info in controller, computes new routes

From Kurose Ross: Computer Networking

An example



5 Link state routing app interacts with flow-table-computation component in SDN controller, which computes new flow tables needed

6 Controller uses OpenFlow to install new tables in switches that need updating

Distributed controllers

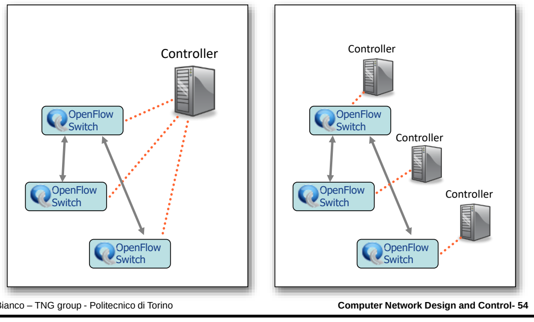
Andrea Bianco
andrea.bianco@polito.it
http://www.telematica.polito.it/

Srini Seetharaman, OpenFlow/SDN tutorial

Centralized vs Distributed Control

Centralized Control

Distributed Control



Why distributed/multiple controllers? *

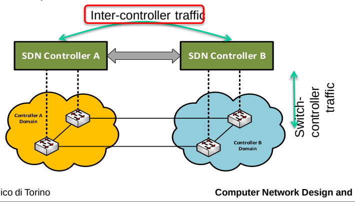
- To enhance resilience to failures
  - Controller failures can be managed
  - Still to deal with failures in data and control plane
- To solve scalability issues
  - Faster controllers
    - Limited scaling
  - More proactive rules to reduce number of requests
    - Limited flexibility
  - Multiple controllers
    - Permit load balancing to reduce processing load
    - Permit switch migration

Distributed controllers

- Virtual topology among controllers
  - to coordinate the operations of the controllers
  - peer, hierarchical, master/slave
- Network view maintenance
  - different levels of consistency (strong/weak) among the controllers
  - affects the reactivity
  - may lead to temporary rule conflicts

Control plane in distributed controllers

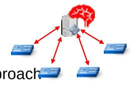
- Switch-controller (Sw-Ctr) traffic
  - Standardized
- Controller-controller (Ctr-Ctr) traffic (East-West-bound interfaces)
  - Proprietary
  - To get consistent view
  - May be non neglibile
  - Critical for reactivity



Stateful data plane

Andrea Bianco
andrea.bianco@polito.it
http://www.telematica.polito.it/

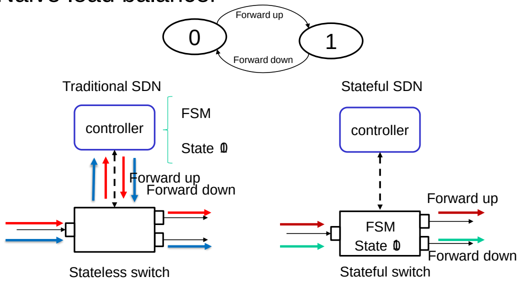
Stateful SDN dataplane



- Stateless approach (OpenFlow)
  - Stateless switches, all the states in the controller
  - Limited reactivity due to the (logically) centralized approach
- Stateful approach: OpenState, OpenPacketProcessor (OPP), P4
  - Permit some level of stateful processing (e.g., finite state machines) within switches
    - OpenState adds a state table (IF state A THEN IF state B THEN)
    - OpenPacketProcessor: state defined with multiple variables, counters,
    - P4 much more flexible (description language of HW behavior)
  - Enabled by new generation of hardware
    - 6.5Tbps Tofino chipset @ Barefoot Networks

Toy example

- Naive load balancer



Stateful benefits

- Improve network reactivity
  - Simple local decisions at the switch
  - Reduced controller load
  - Reduced signaling overhead
- Permits to gracefully move functionalities
  - Balance central vs distributed control
- Not all switches need to be stateful
  - State positioning or distribution