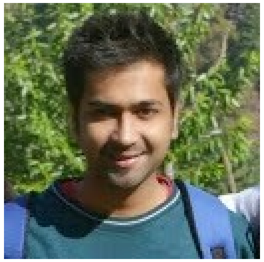
Sphinx: Detecting Security Attacks in Software-Defined Networks

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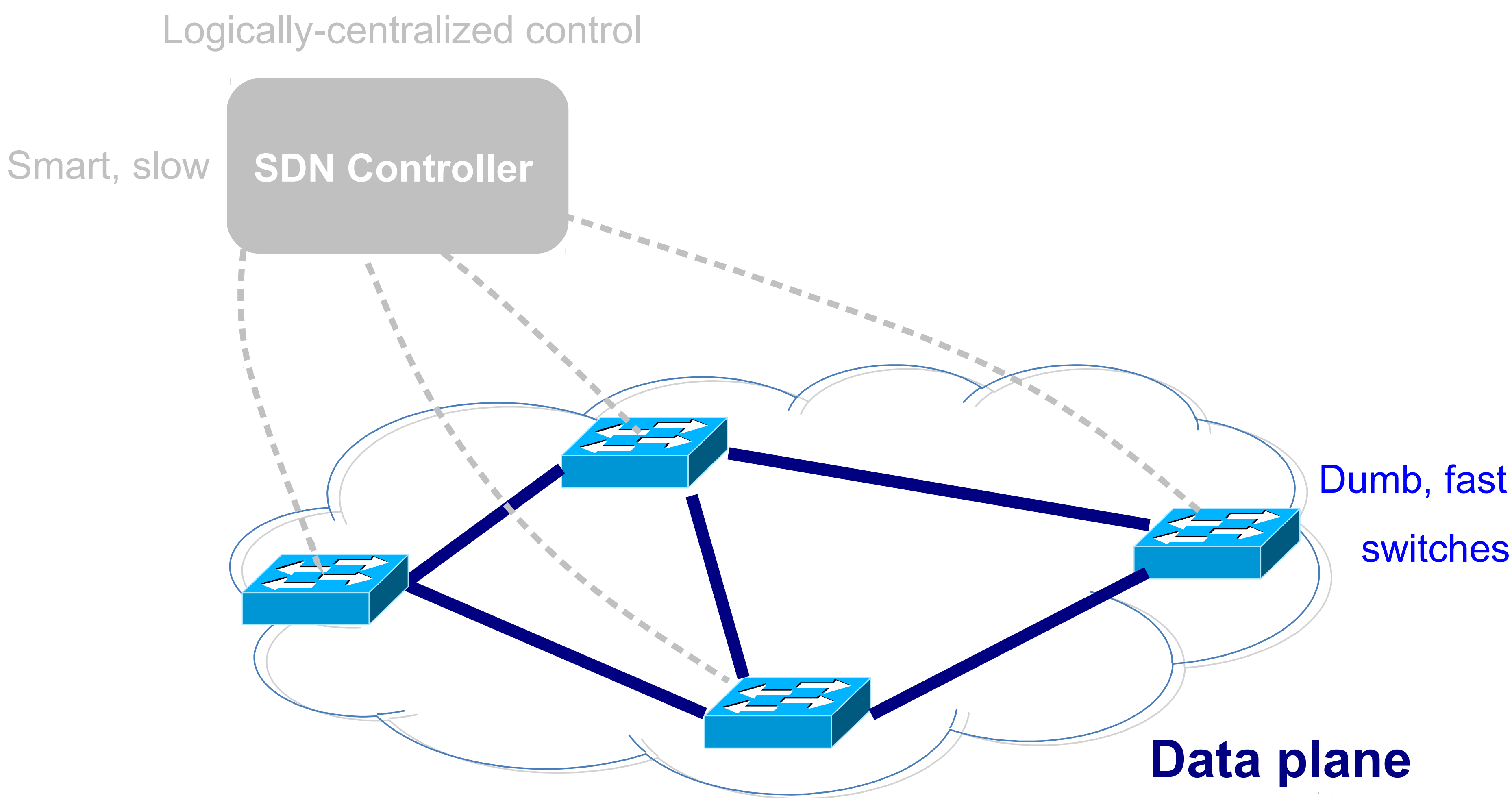
Software-Defined Network (SDN)



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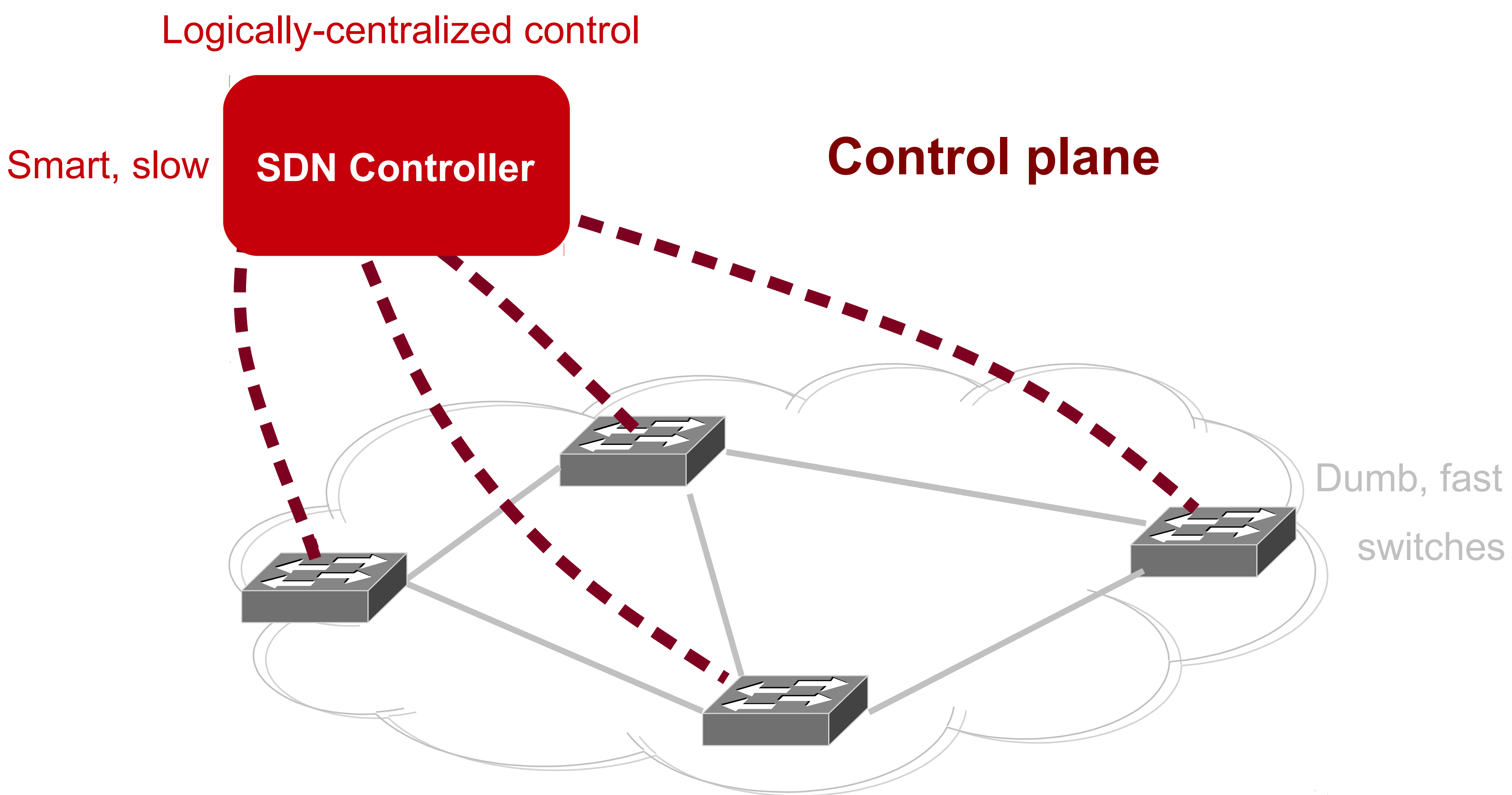

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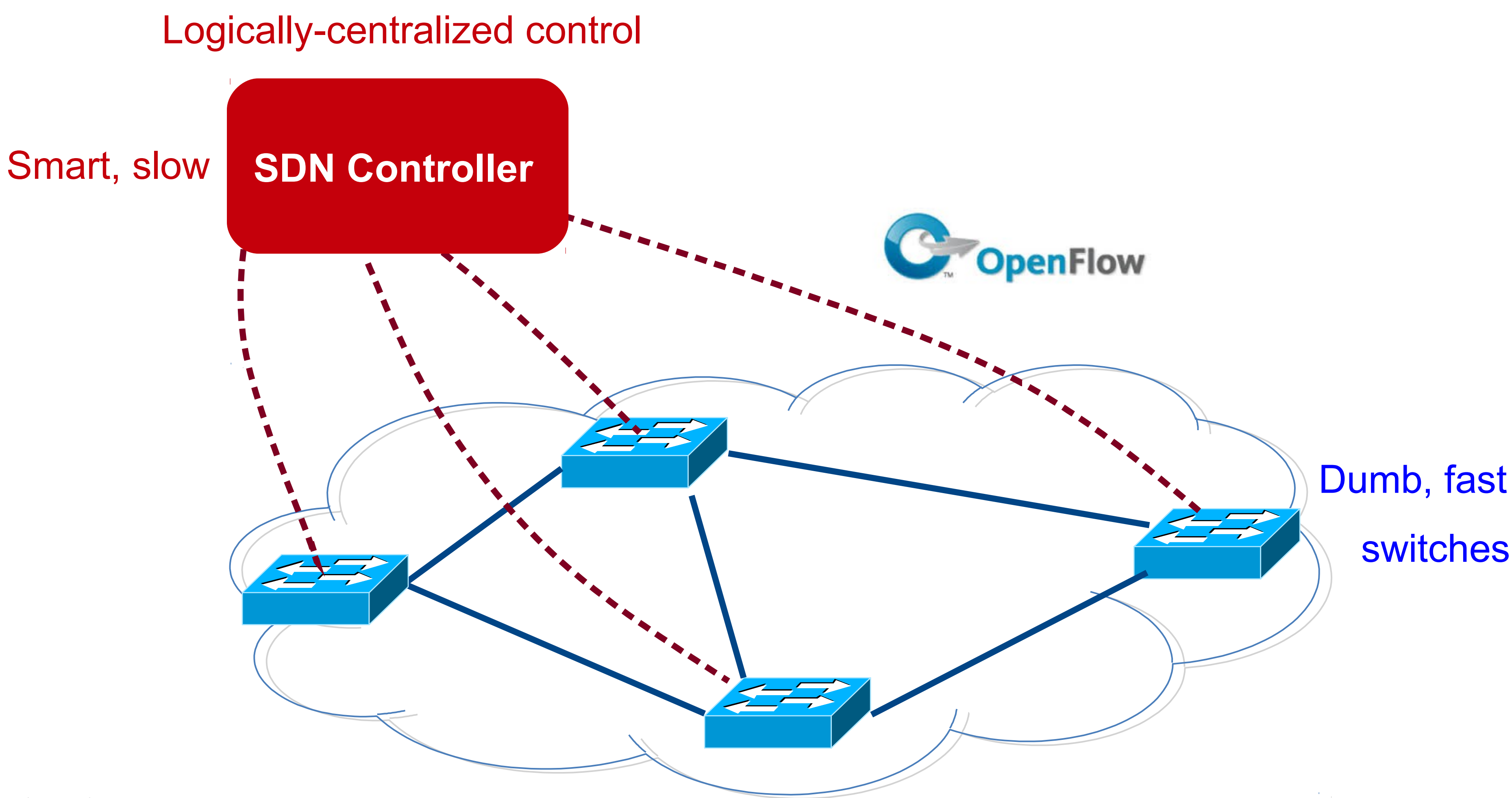

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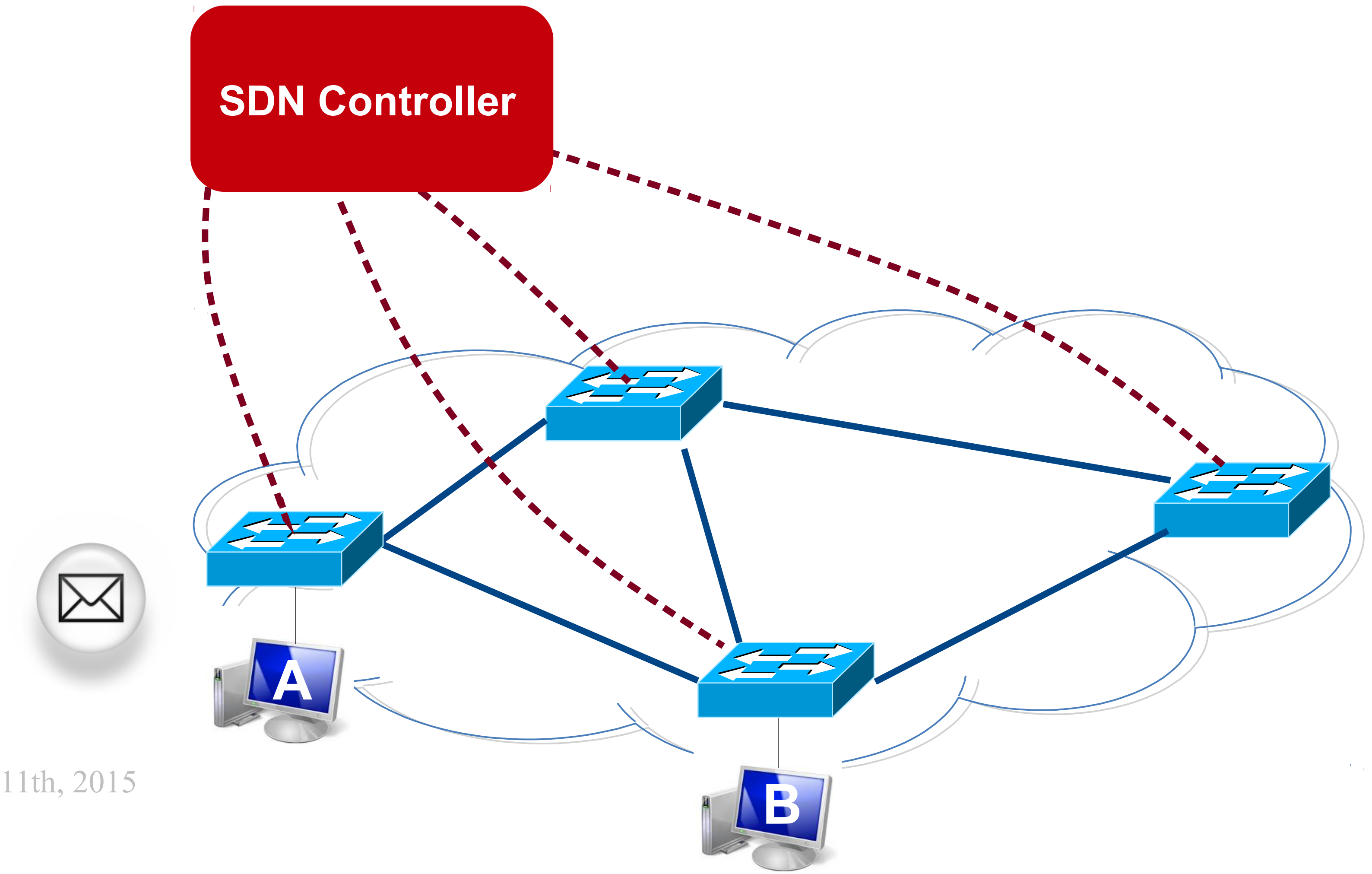

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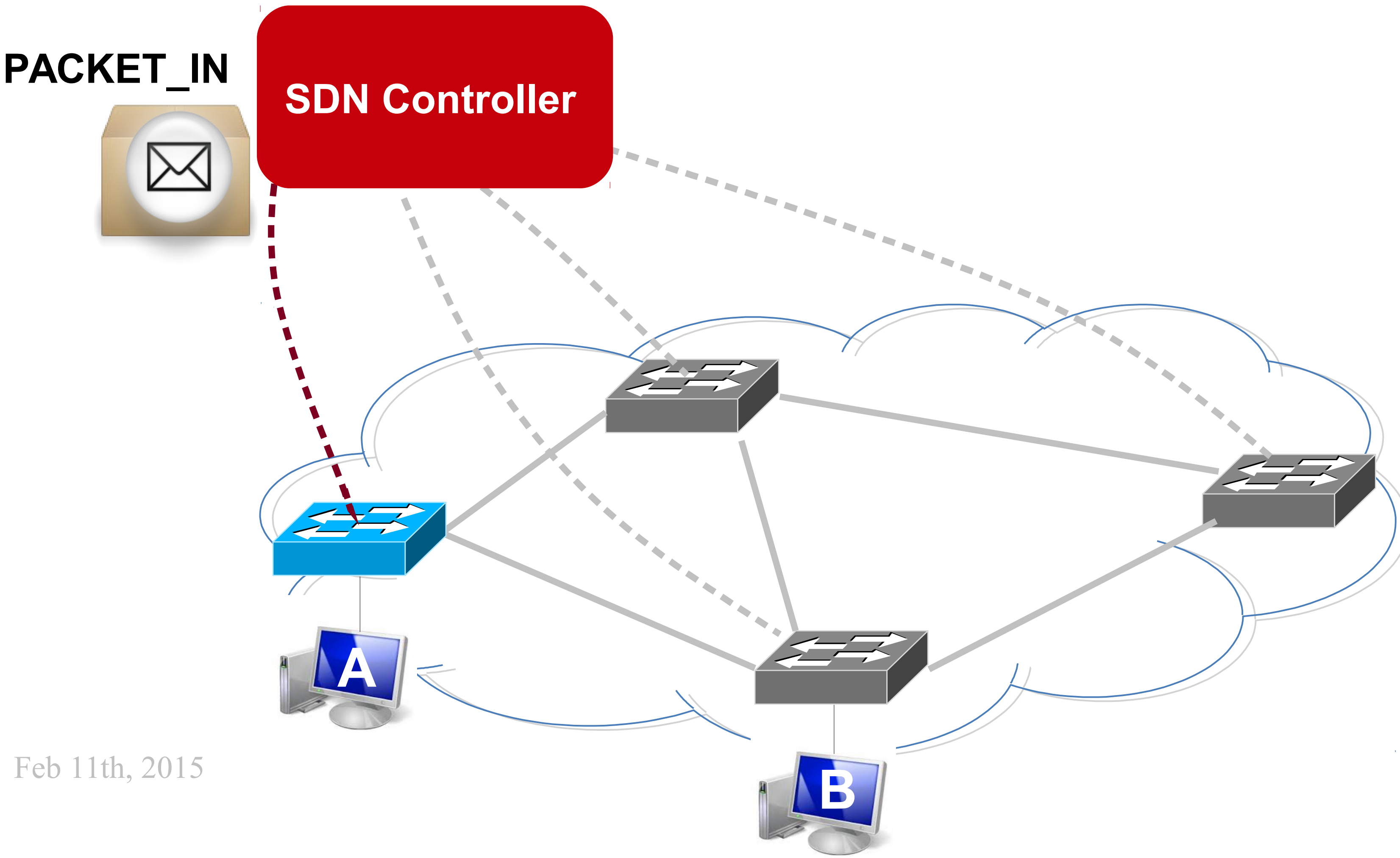

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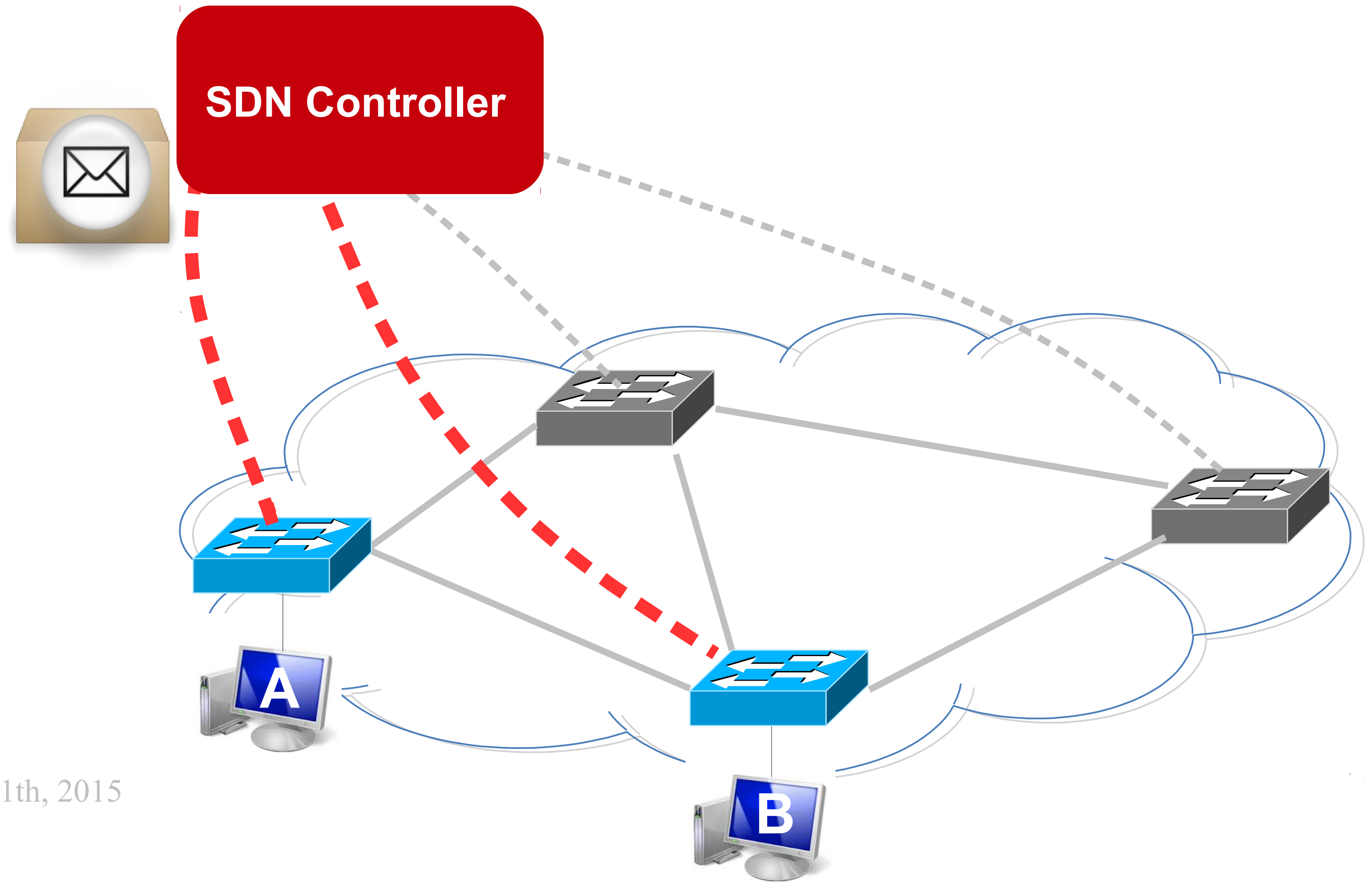

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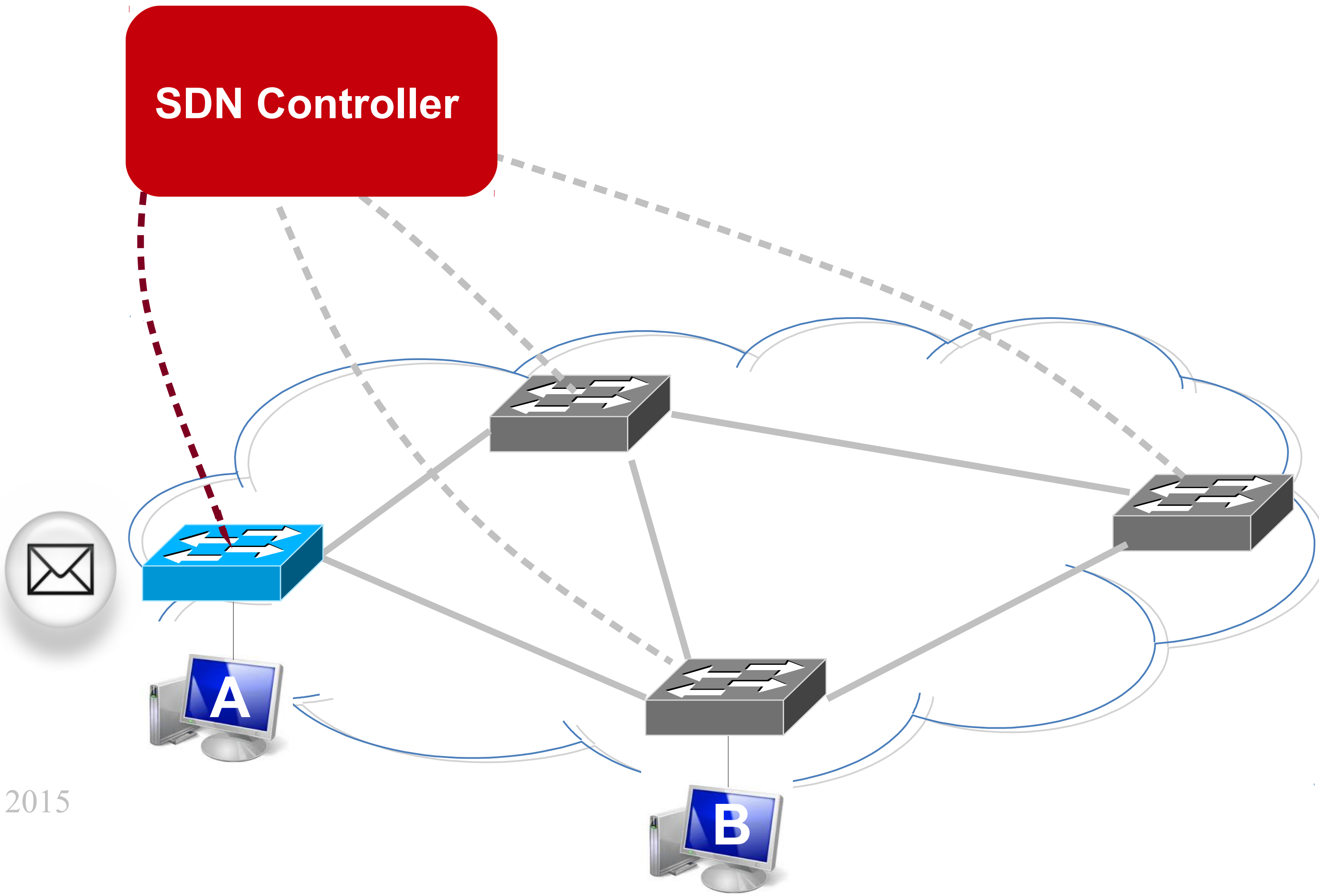

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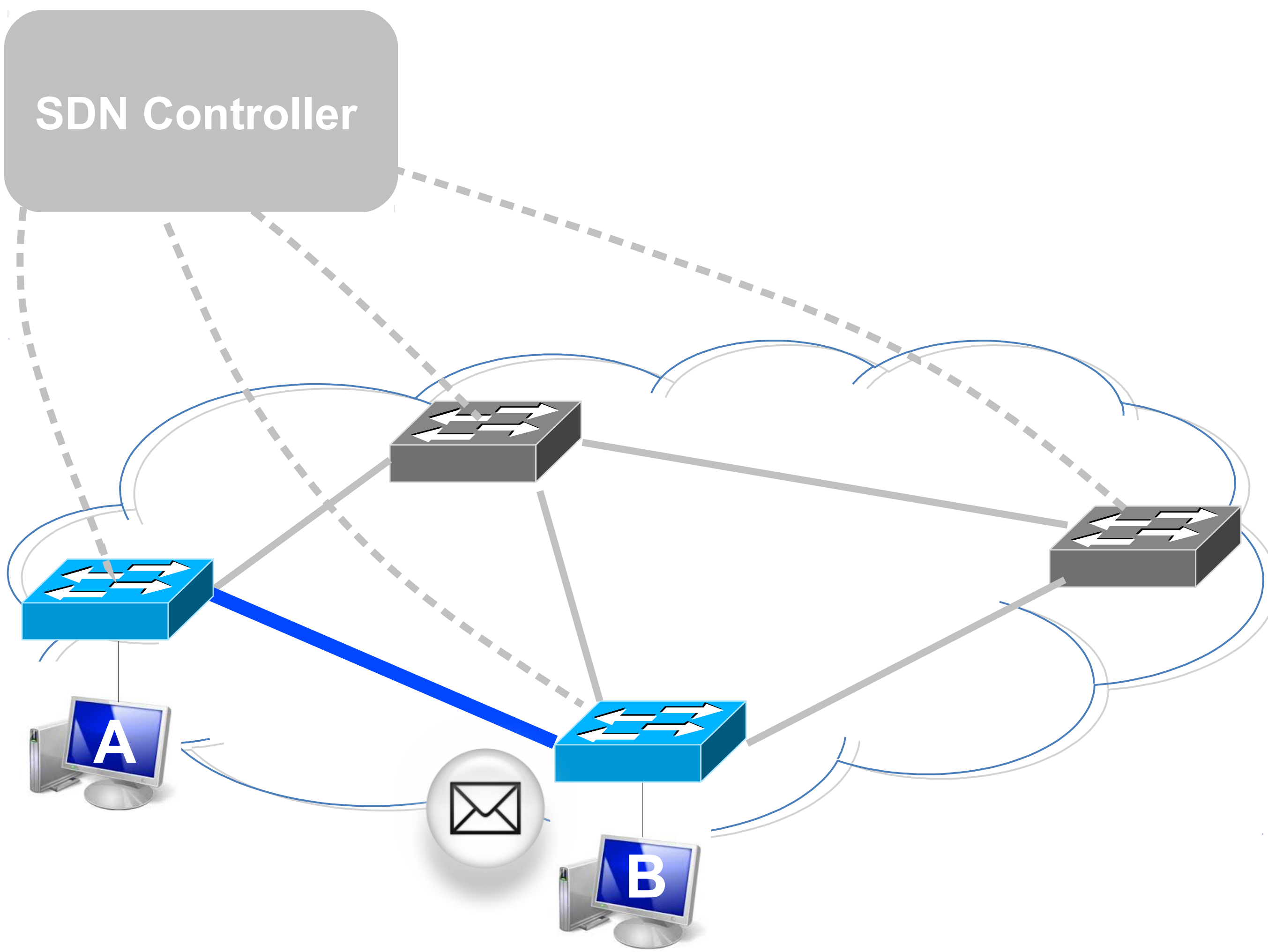
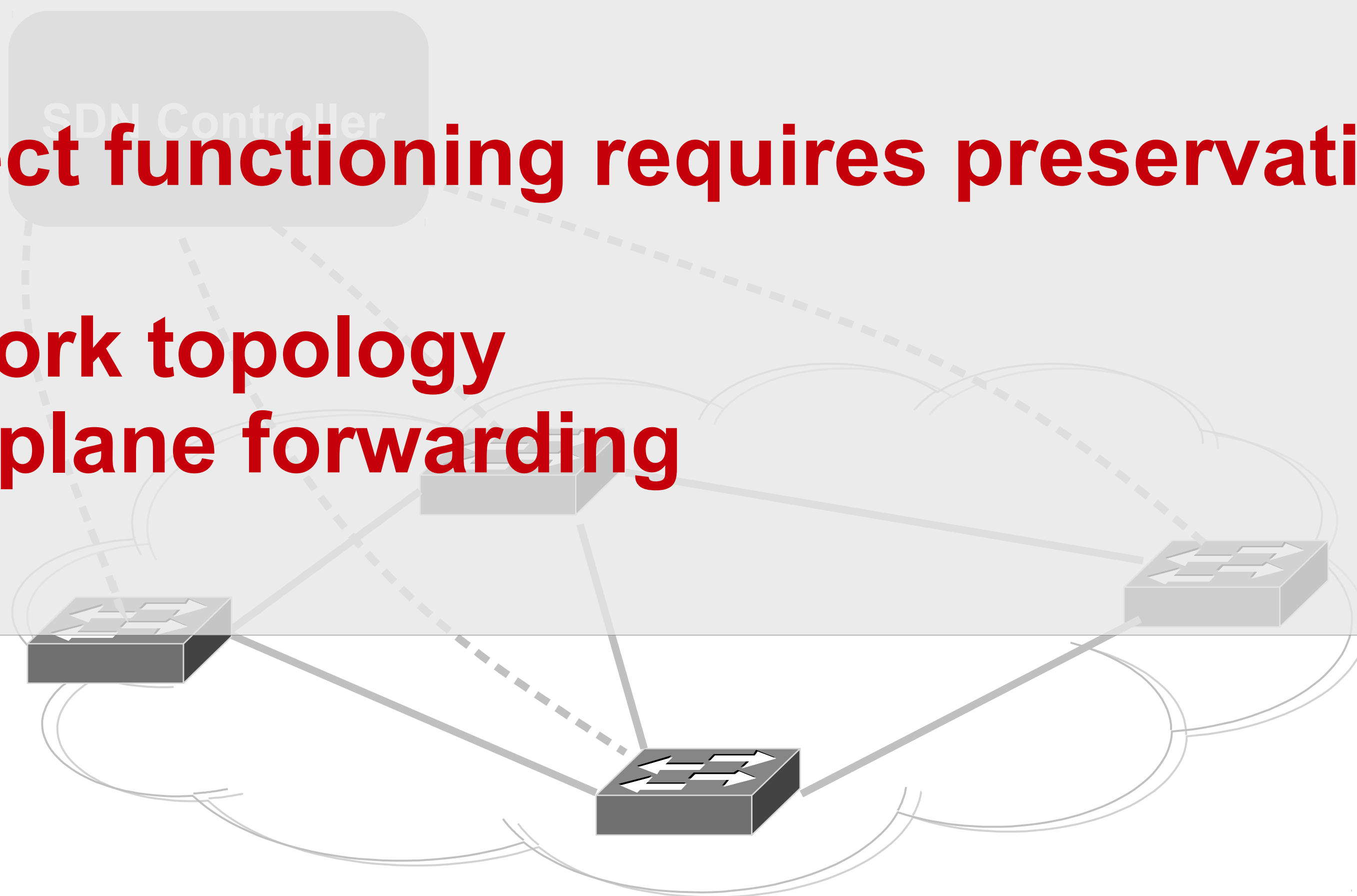


Software-Defined Network (SDN)

Correct functioning requires preservation of

- **Network topology**
- **Data plane forwarding**



Outline

- SDN Overview
- **Motivation**
- Sphinx
- Implementation
- Evaluation
- Conclusion

Vulnerable SDNs

- OpenFlow operational semantics
  - All unmatched packets are forwarded to the controller

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- OpenFlow operational semantics
  - All unmatched packets are forwarded to the controller
- Attacks afflicting traditional networks affect SDNs too
  - Traditional defenses do not work in SDNs
- Attacks possible from compromised switches and end hosts
  - Soft switches on end host servers attractive targets for attackers

Several Attacks Possible

- Network topology
  - Corrupt routing table (ARP)
  - Fake topology (LLDP)
  - Multicast (IGMP)

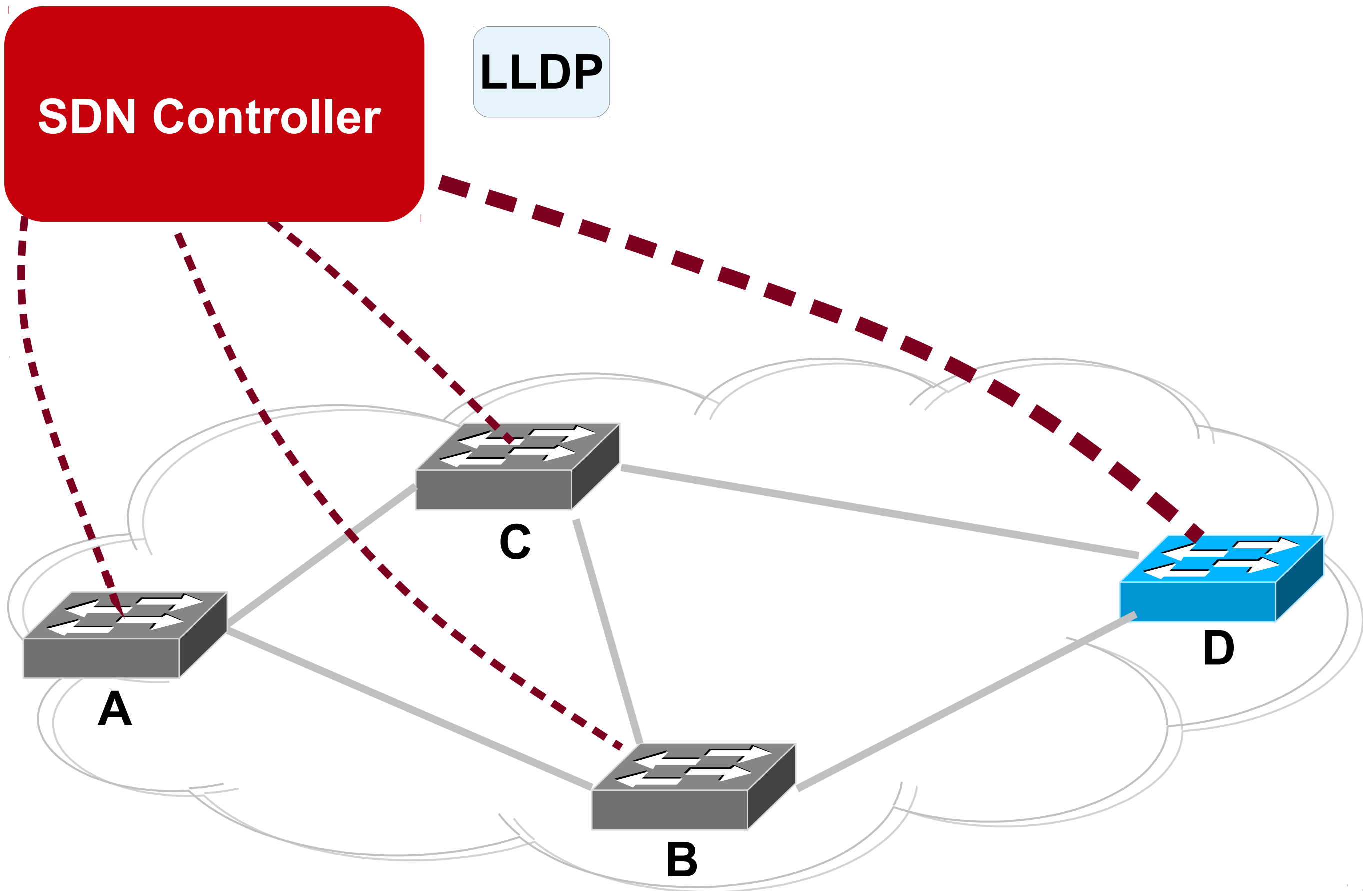
- Data plane forwarding
  - Switch TCAM exhaustion
  - Switch blackhole

Controller Vulnerability

- Security analysis of four popular available SDN controllers

Attack	OpenDaylight	Floodlight	POX	Maestro
ARP poisoning	Y	Y	Y	Y
Fake topology	Y	Y	N	Y
Controller DoS	Y	N	Y	Y
Network DoS	Y	Y	Y	Y
TCAM exhaustion	N	Y	Y	Y
Switch blackhole	Y	Y	Y	Y

Fake Network Topology Attack



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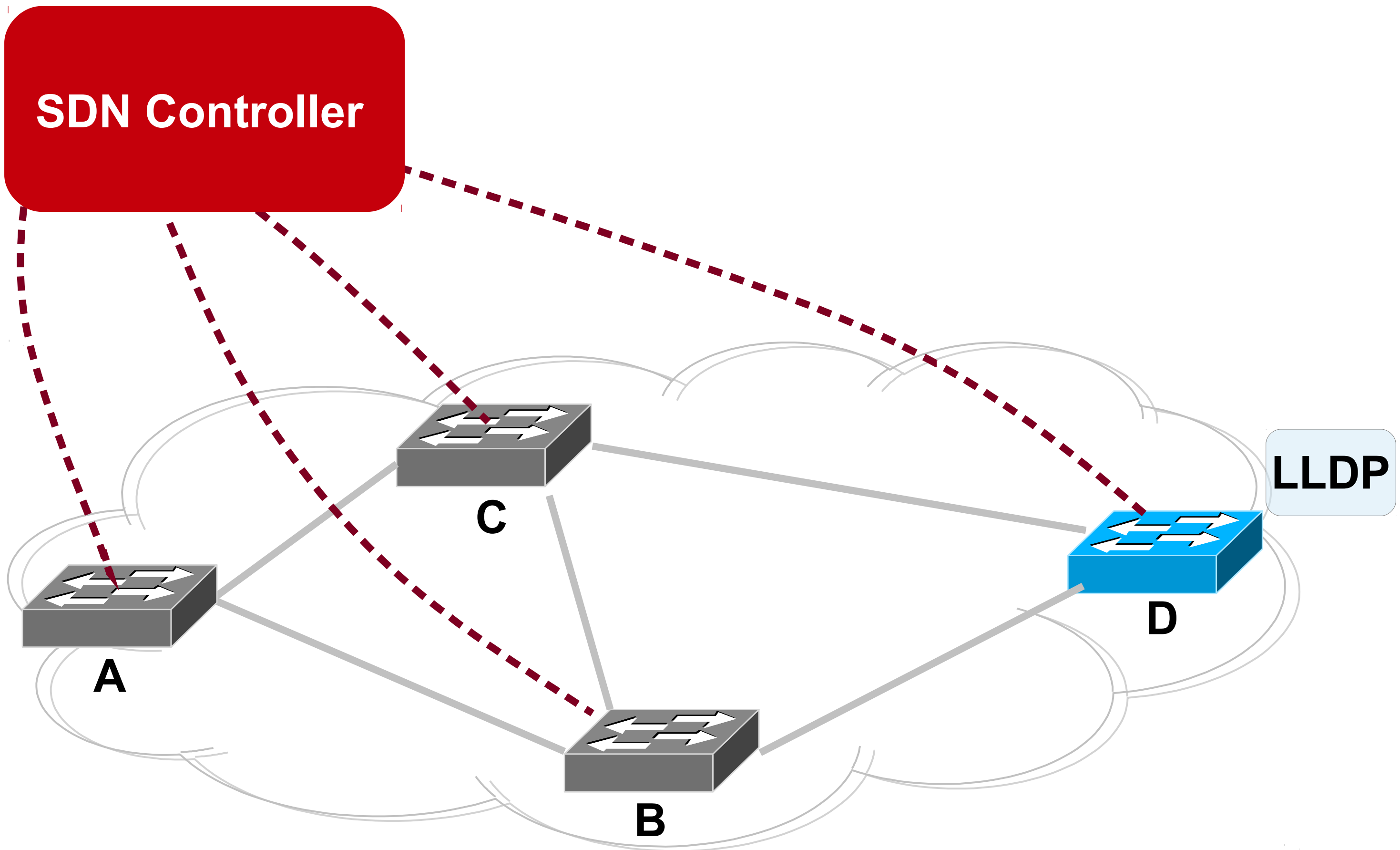

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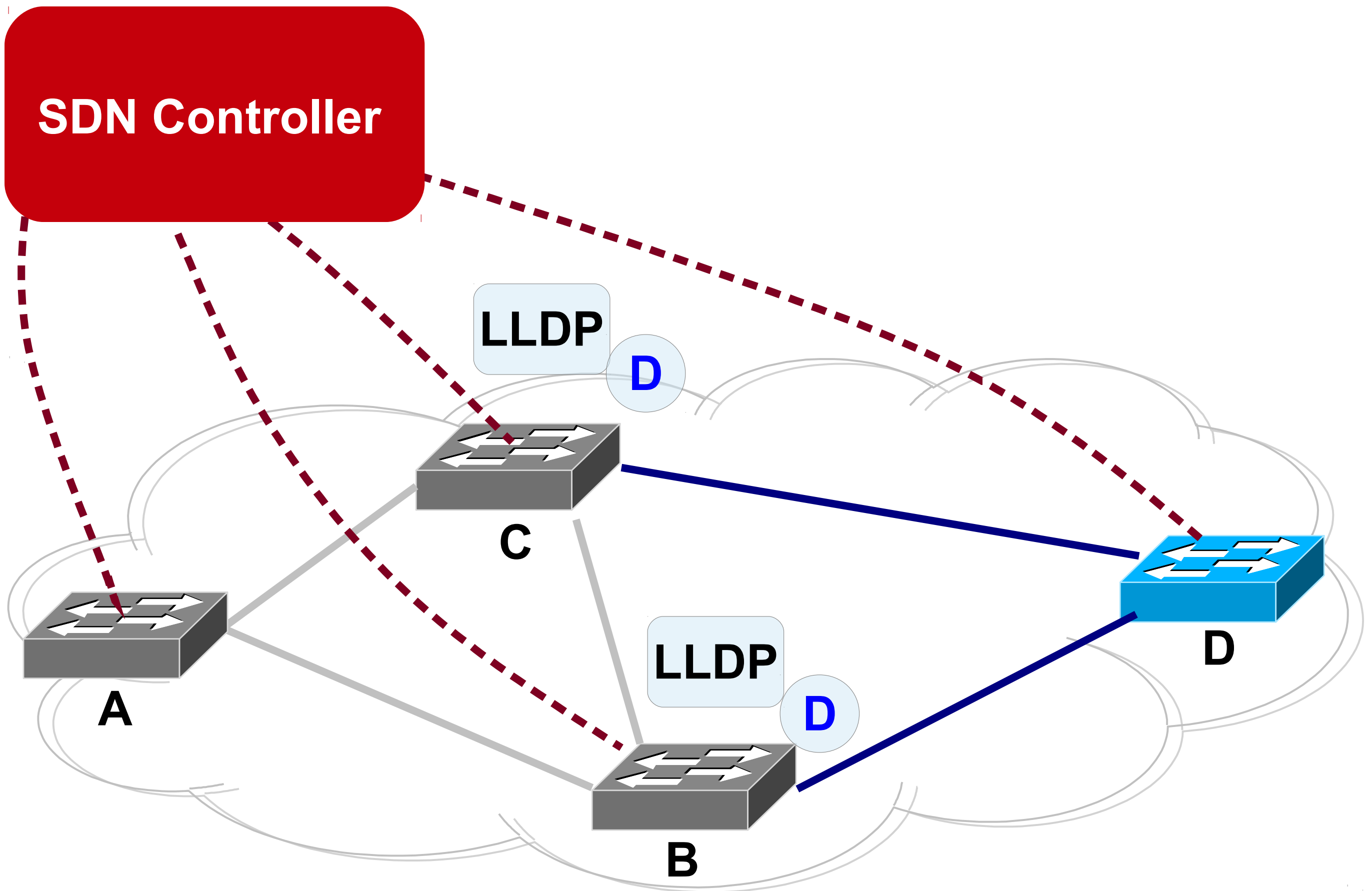

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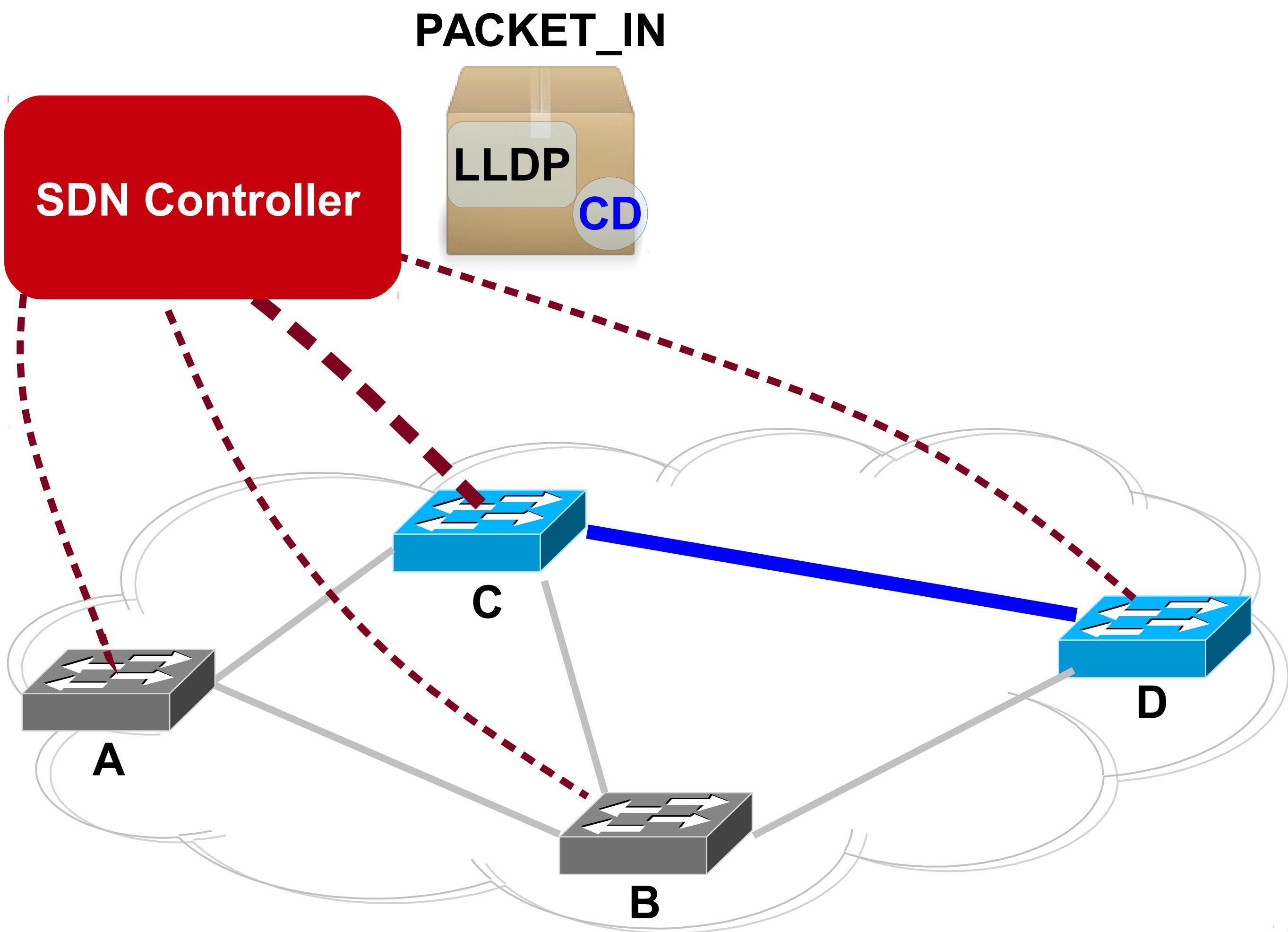

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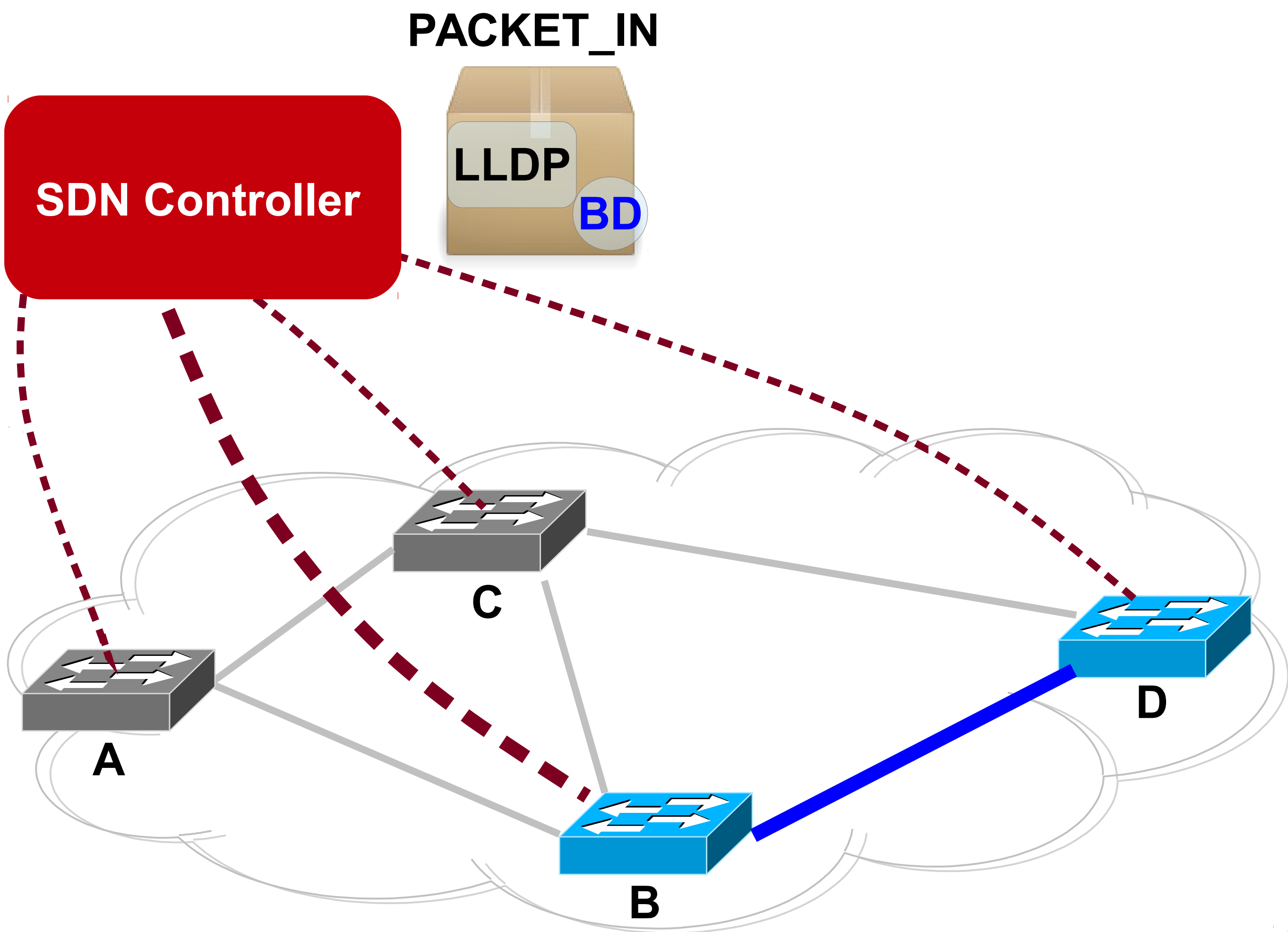

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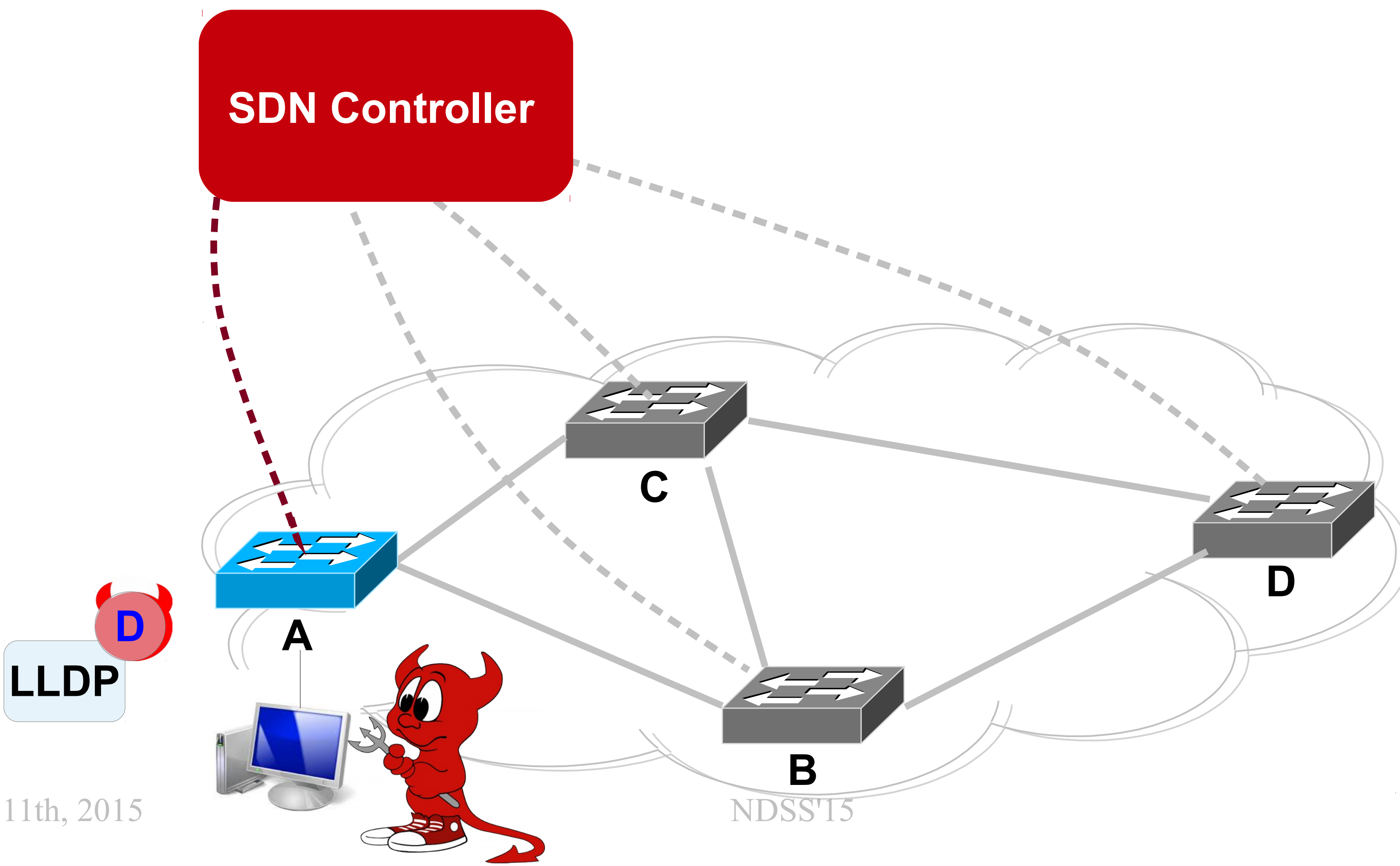

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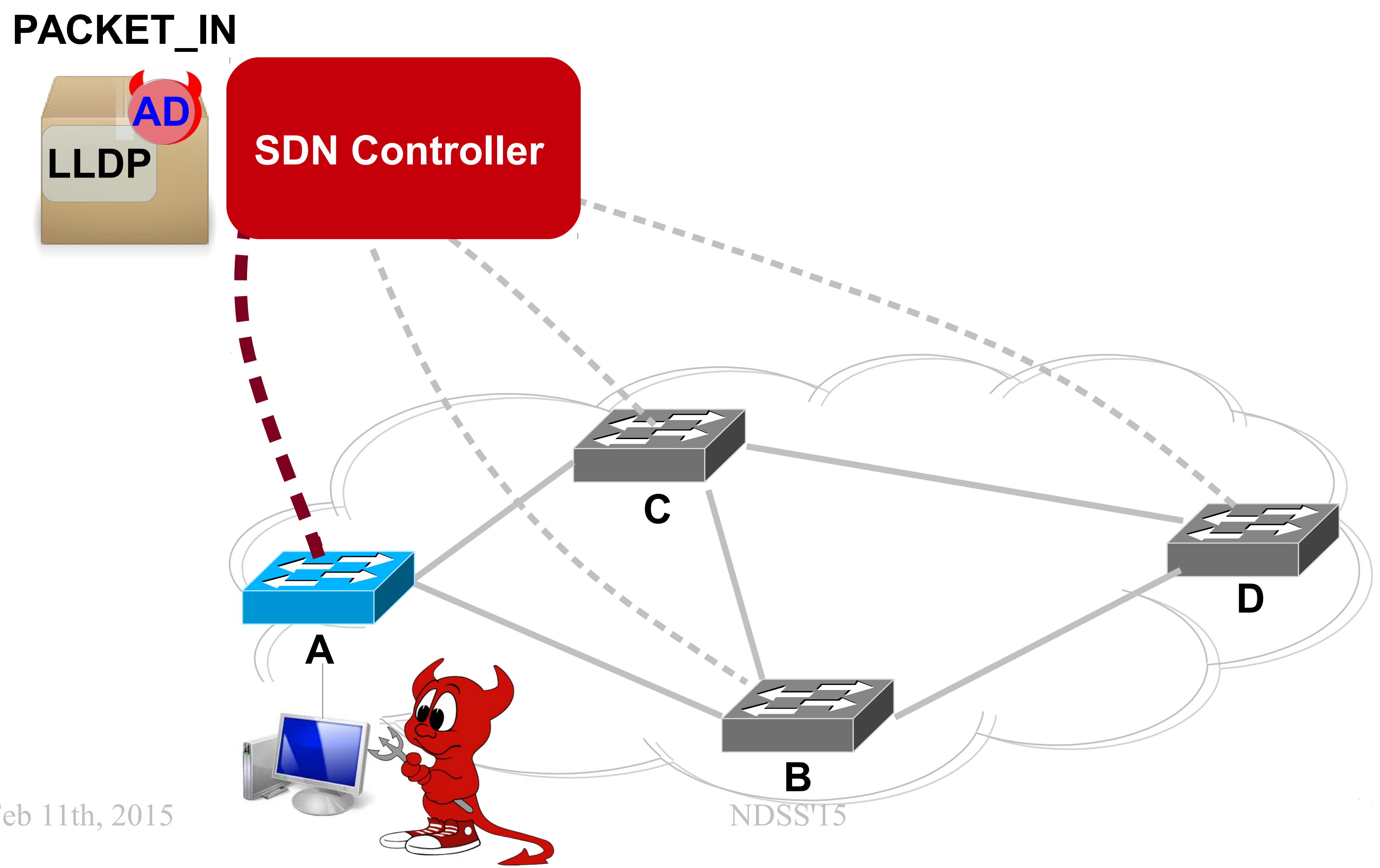

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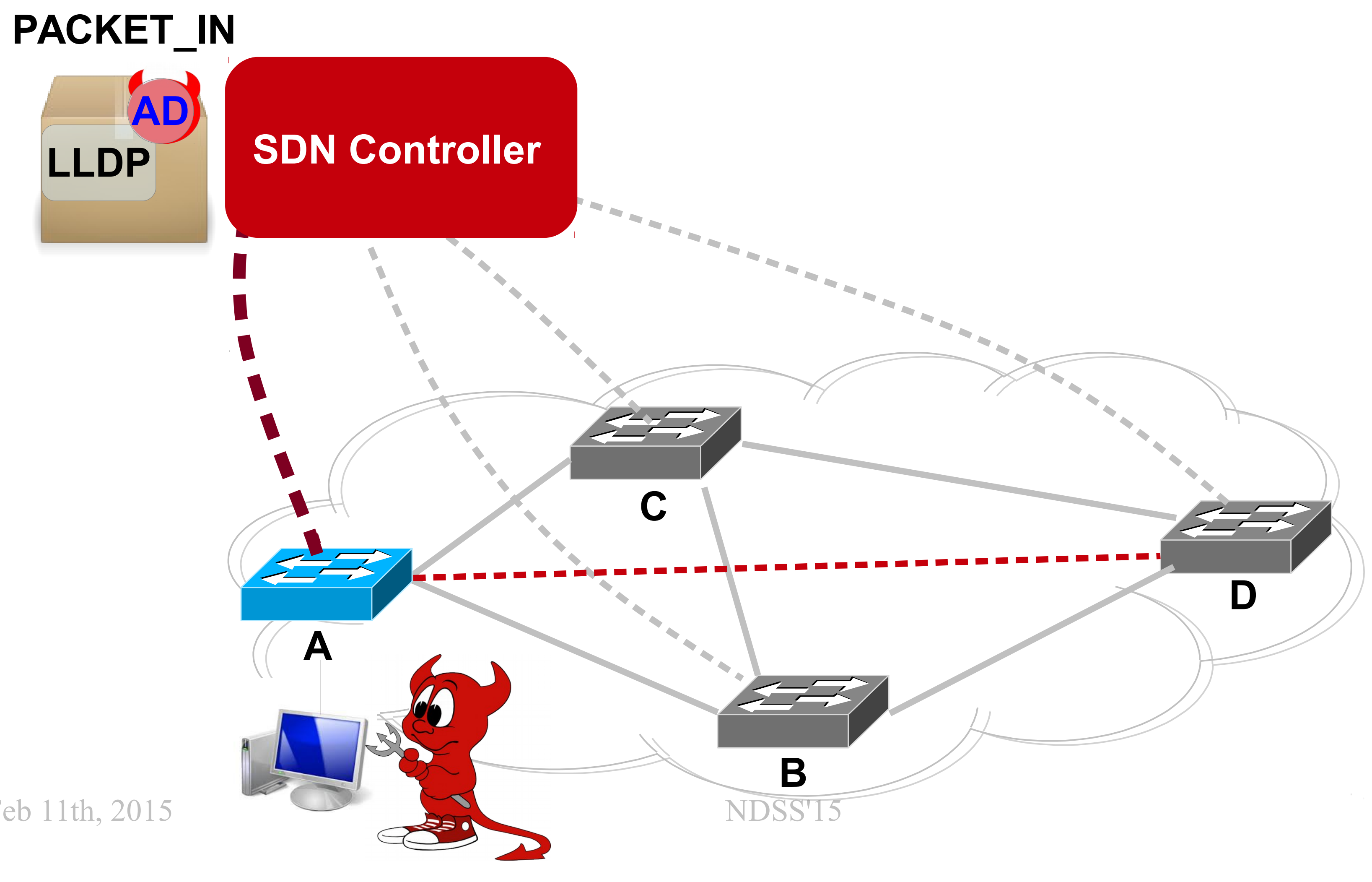
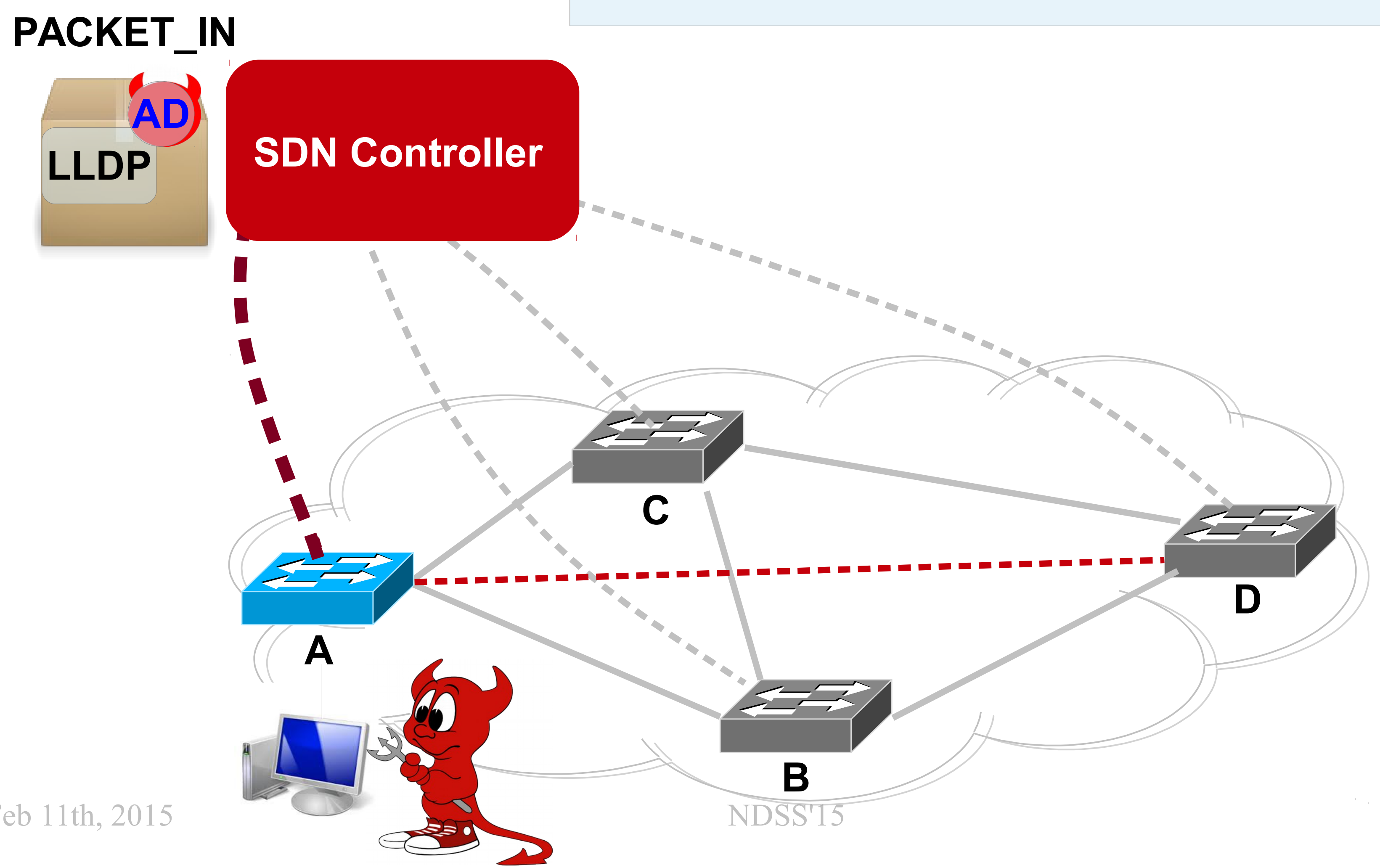


Fake Network Topology Attack

Video demo: http://goo.gl/zRG8bz



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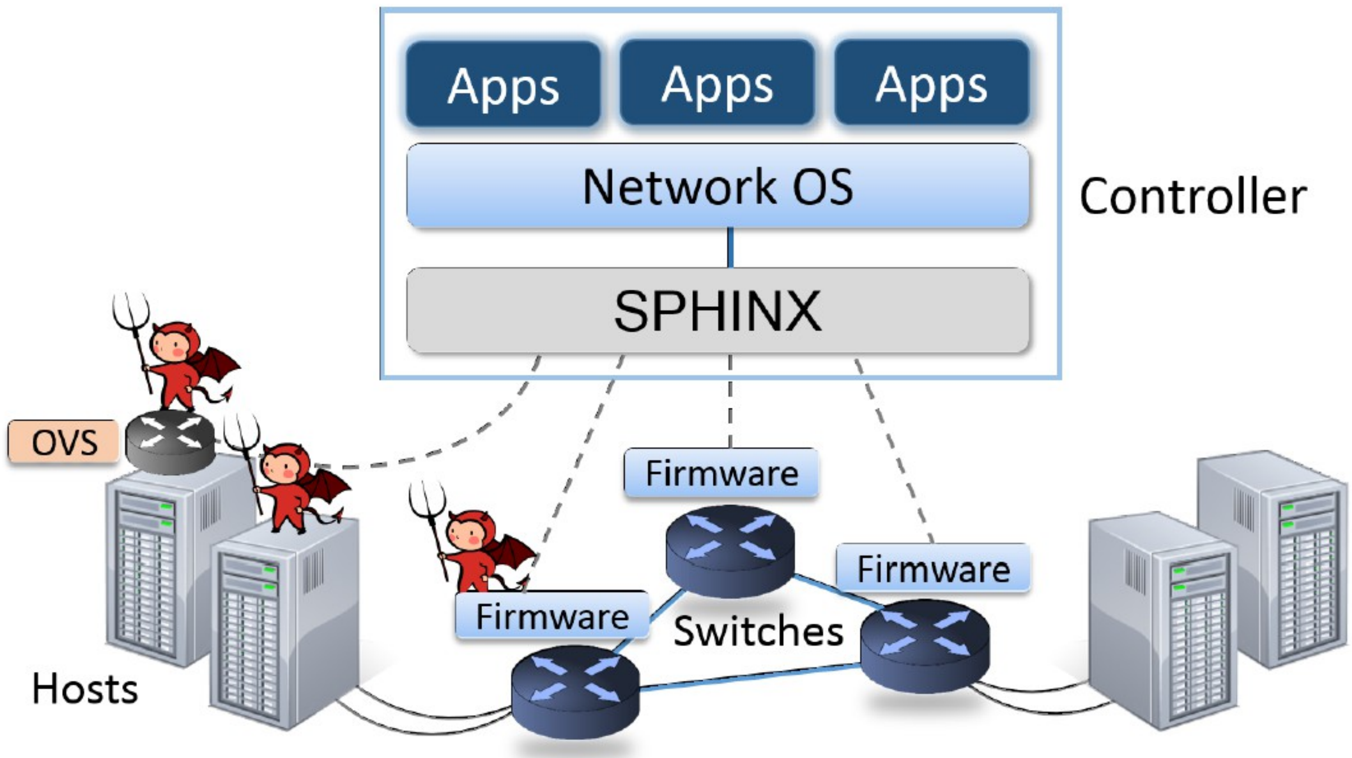
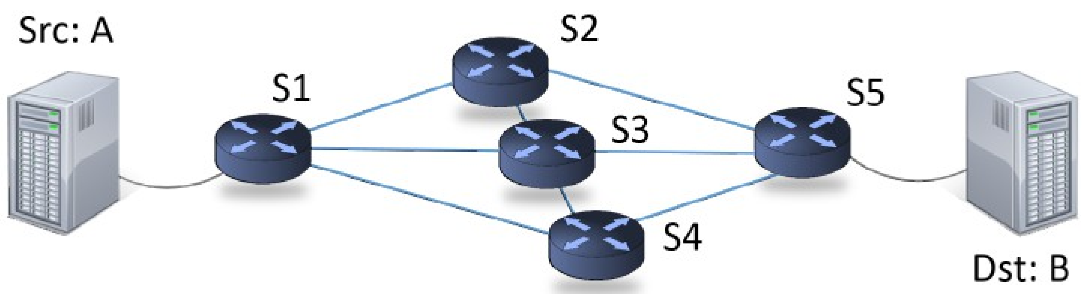
Detecting Security Threats in Real Time

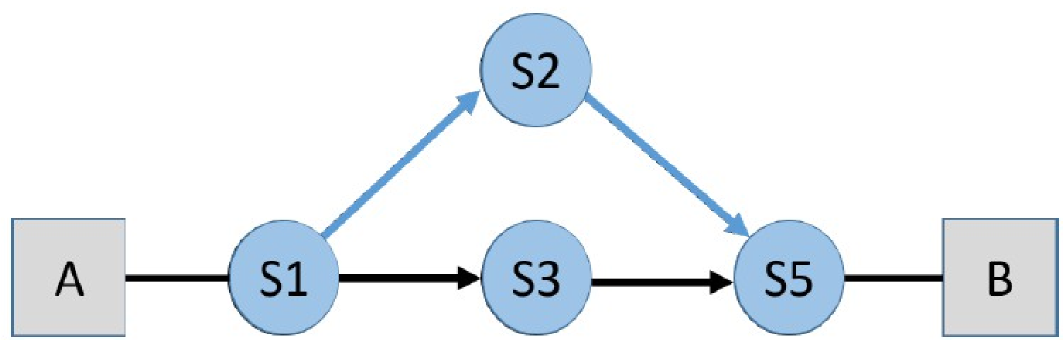
- Verify network actions using OpenFlow metadata
  - All controller communication mediated by a shim
  - Learn network behaviour and automatically generate network invariants



Key Idea: FlowGraphs

Exploit predictability and pattern in topological and data plane forwarding to detect violation





Time T1

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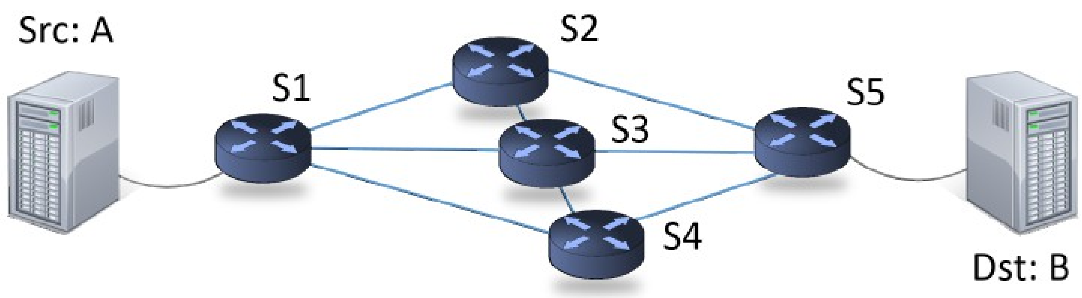
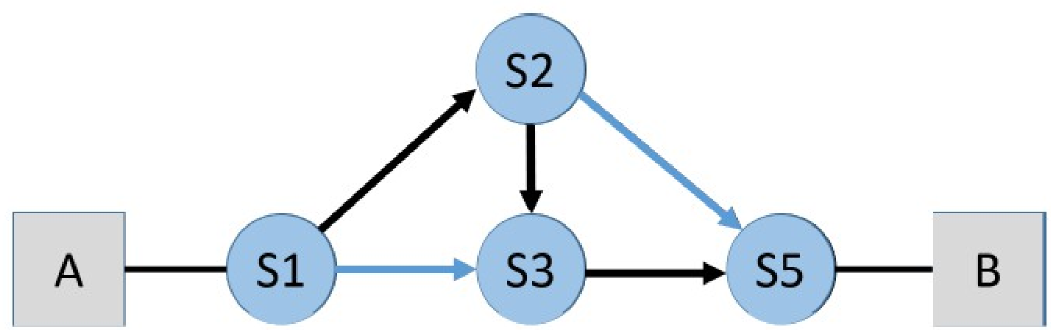
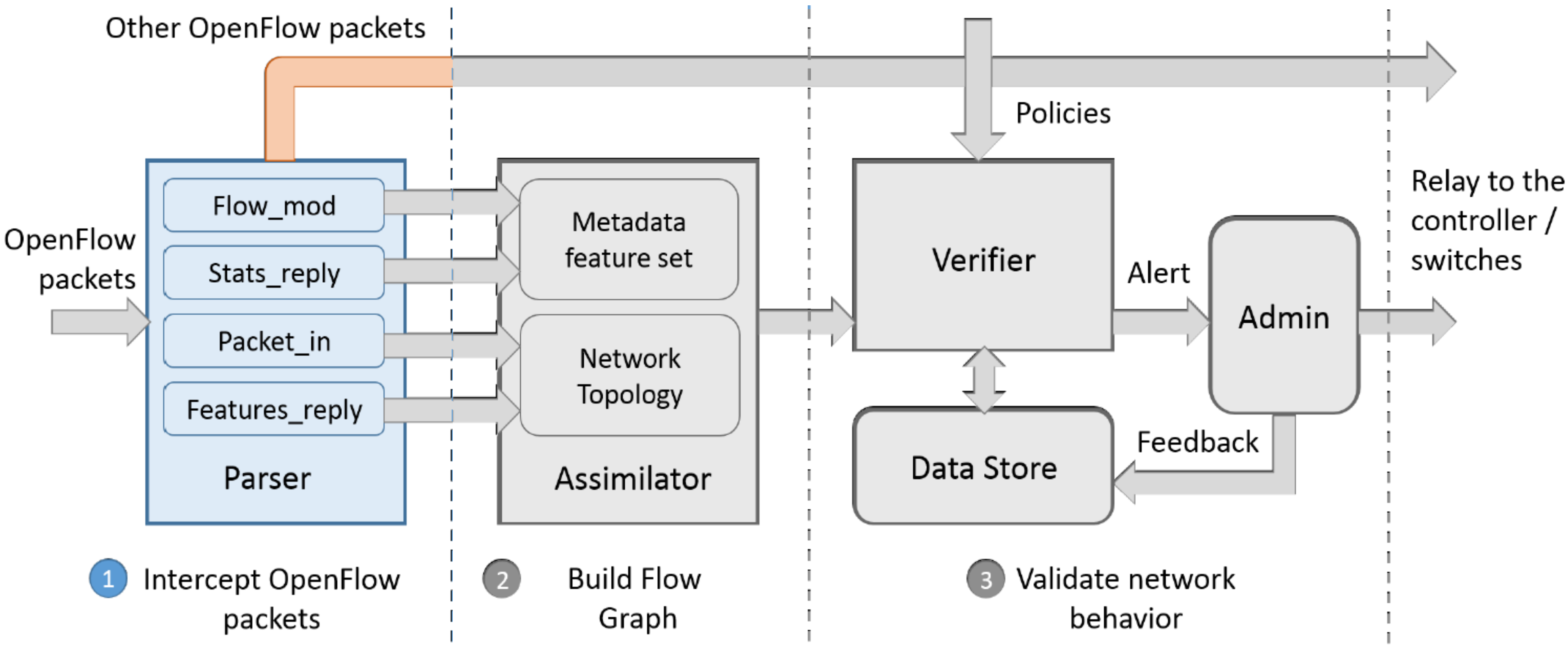




Time T2

Workflow (I)

- Intercept relevant OpenFlow messages to extract topological and forwarding metadata



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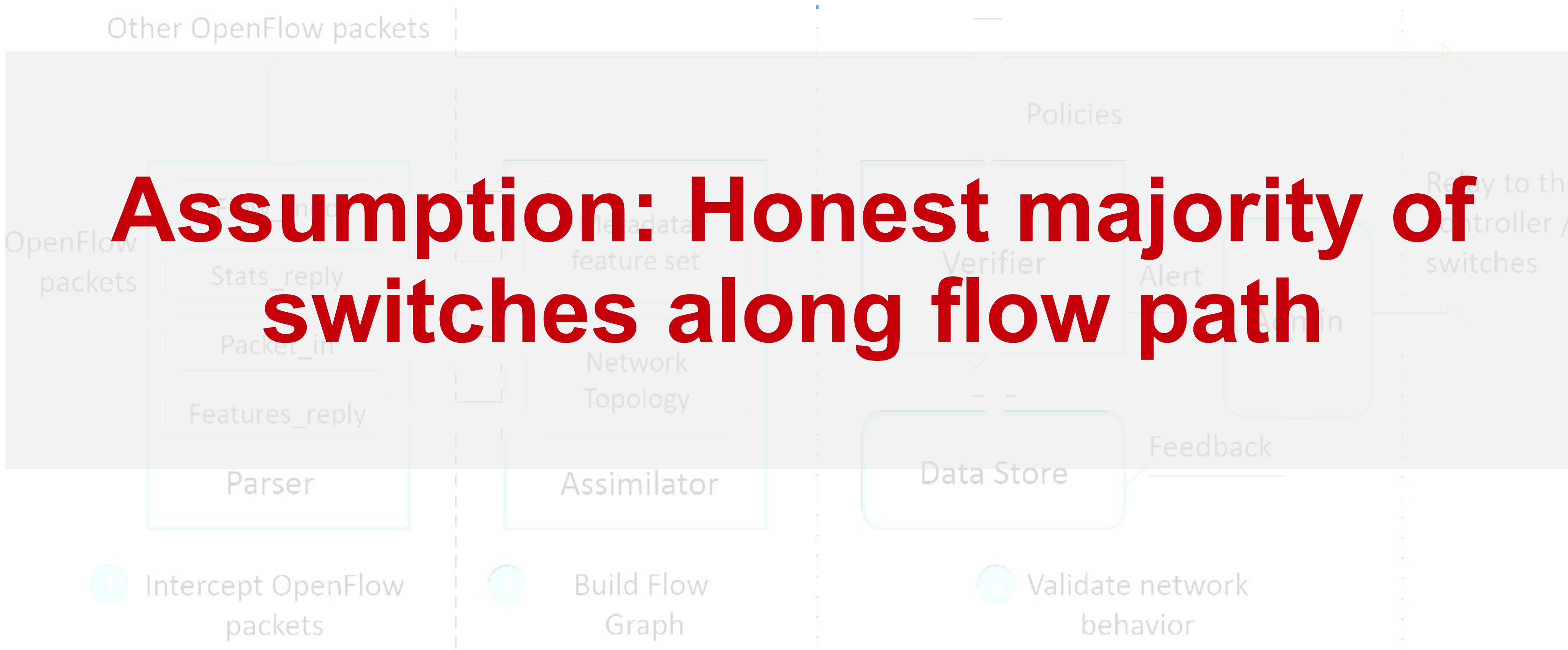
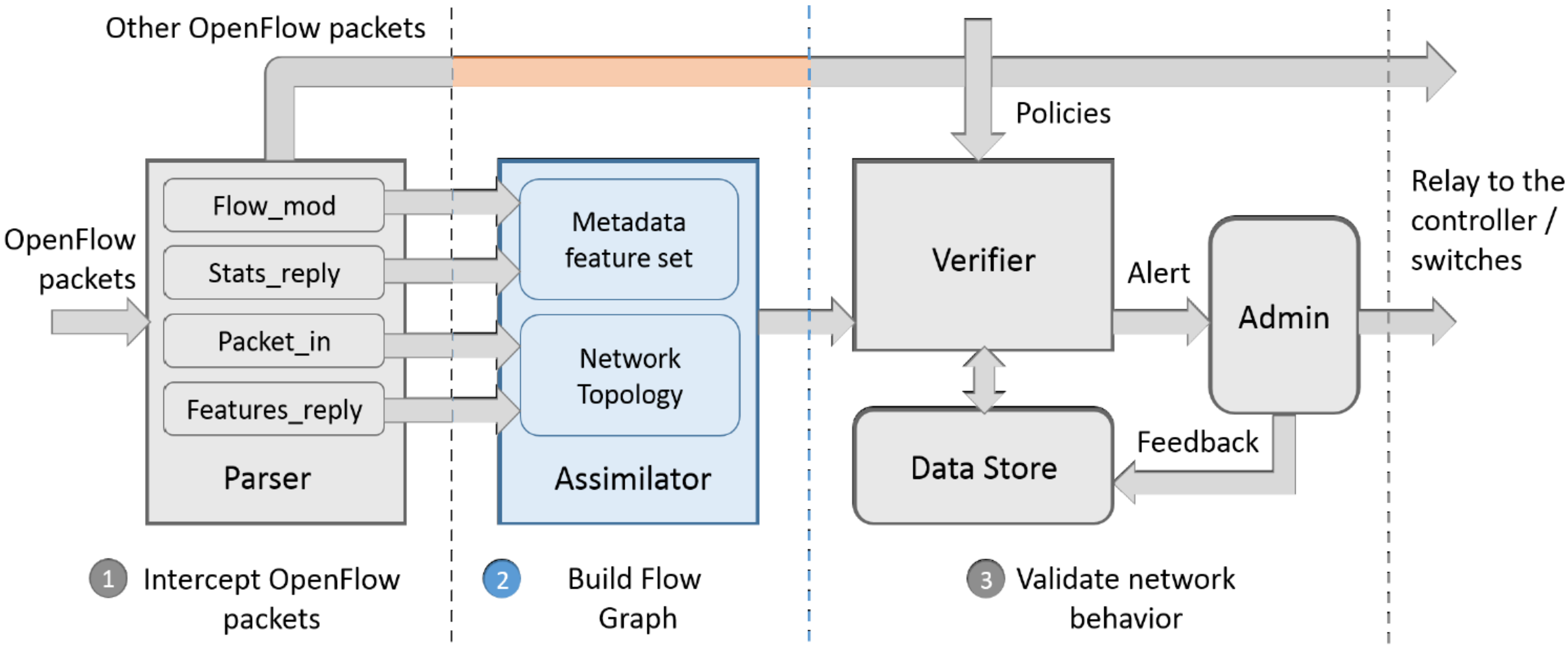


Assumption: Honest majority of switches along flow path

Workflow (II)

- Generate flowgraph constraints from the extracted metadata

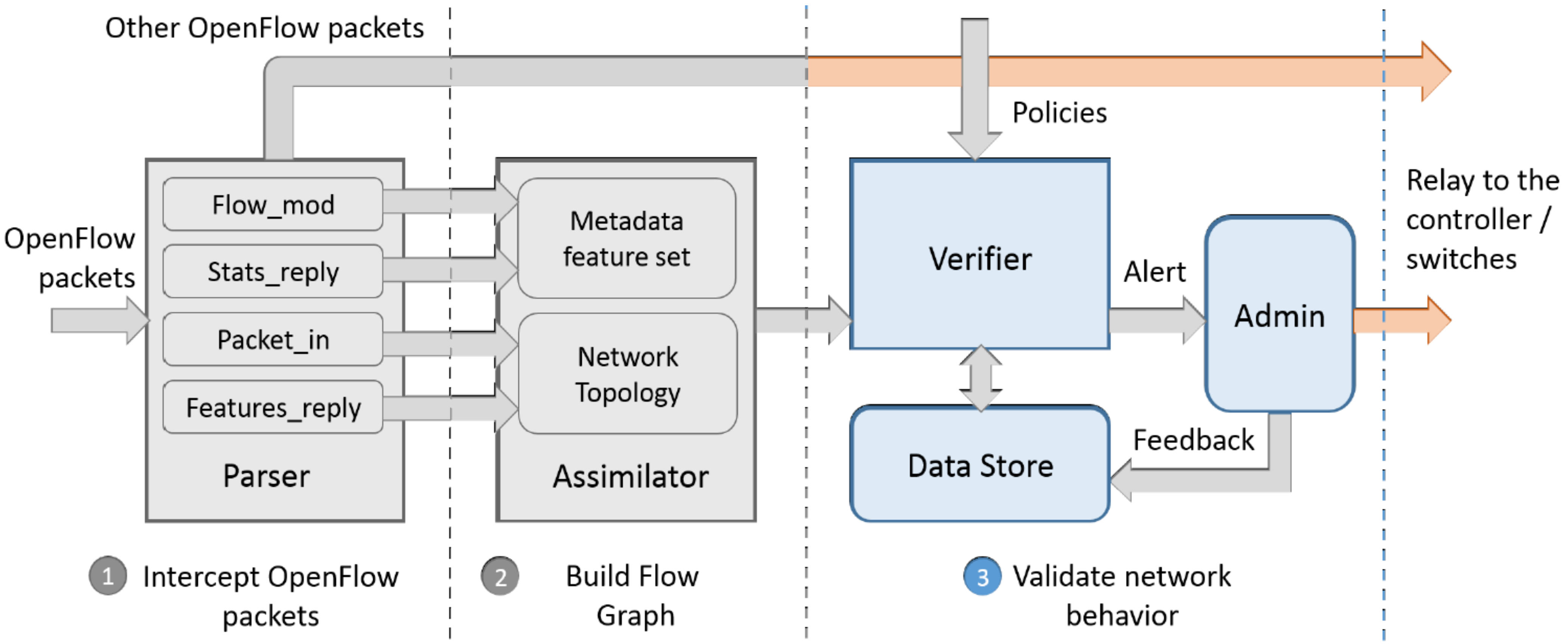


Accurate Characterization of Flows

- Maintain mapping of entities and allowed metadata
  - Hosts (Src MAC/IP/port, Dst MAC/IP/port)
  - Switches (Switch and in/out-port)
  - Flows (Flow match and statistics)
- Incrementally augment the flowgraph with such constraints

Workflow (III)

- Use custom algorithms to detect constraint violations on flowgraphs



Administrator Policies

- Specified in constraint language

Feature	Description
Subject	(SRCID, DSTID), where ∀ SRCID and DSTID ∈ {CONTROLLER | WAYPOINTID | HOSTID | $*$}
Object	{COUNTERS | THROUGHPUT | OUT-PORTS | PACKETS | BYTES | RATE | MATCH | WAYPOINT(S) | HOST(S) | LINK(S) | PORT(S) | etc.}
Operation	IN | UNIQUE | BOOL (TRUE, FALSE) | COMPARE ($\leq$, $\geq$, $=$, $\neq$) | etc.
Trigger	PACKET_IN | FLOW_MOD | PERIODIC

Administrator Policies

- Specified in constraint language

Feature	Description
Subject	(SrcID, DstID), where ∀ SrcID and DstID ∈ {Controller | WaypointID | HostID | $*$}
Object	{Counters | Throughput | Out-ports | Packets | Bytes | Rate | Match | Waypoint(s) | Host(s) | Link(s) | Port(s) | etc.}
Operation	In | Unique | Bool (True, False) | Compare ($\leq$, $\geq$, $=$, $\neq$) | etc.
Trigger	Packet_in | Flow_mod | Periodic

- Example policy to check if all flows from host H3 pass through specified waypoints S2 and S3

```
<Policy PolicyId="Waypoints">
    <Subjects><Subject value="H3, *" /></Subjects>
    <Objects>
        <Object><Waypoint value="S2" /></Object>
        <Object><Waypoint value="S3" /></Object>
    </Objects>
    <Operation value="IN" />
    <Trigger value="Periodic" />
</Policy>
```

Constraint Validation

- Topological state
  - Packet spoofing, controller DoS
  - Fast and deterministic

Constraint Validation

- Topological state
  - Packet spoofing, controller DoS
  - Fast and deterministic
- Forwarding state
  - Flow graph consistency, switch DoS, flow statistics
  - Both deterministic and probabilistic
  - Similarity Index (SI) categorizes nature of flow using statistics observed at switches along the flow path
    - Identify malicious switches along flow path

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Implementation

- Controller-agnostic proxy between the controller and the switches
  - Prototype compatible with OpenFlow (v1.1.0)
  - Works with OpenDaylight (v0.1.0) and Floodlight (v.0.90)
  - Written in ~2100 Java LOC
  - Uses the fast Netty I/O framework with separate queues for communication in either direction

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Experimental Setup

- Physical setup of three tiered datacenter topology with 14 switches
- Emulated Mininet network of up to 10K hosts
- Measure
  - Accuracy of deterministic and probabilistic verification
  - Performance impact on end user latency, throughput and policy verification

Accuracy (I)

- Attack detection times under different settings

Attack	Detection time (μs)	
	Physical testbed	$1K$ Mininet hosts
ARP poisoning	44	60
Fake topology	66	80
Controller DoS	75	900
Network DoS	75	164
TCAM exhaustion	n/a	n/a
Switch blackhole	75	900

- Measure false alarms generated in three diverse benign traffic traces (14min, 65min and 2hr)
  - Execution raised no alarms

Accuracy (II)

- Probabilistic verification – probability of false alarms and lack of genuine alarms at different margins of similarity (τ)
  - τ = x implies that SI observed at each switch in the flow path must lie between SI/x and SI*x
  - τ = 1 implies that all switches along the flow path must report the same flow statistics
  - τ = 1.045 corresponds to link loss rate of 1%

Accuracy (II)

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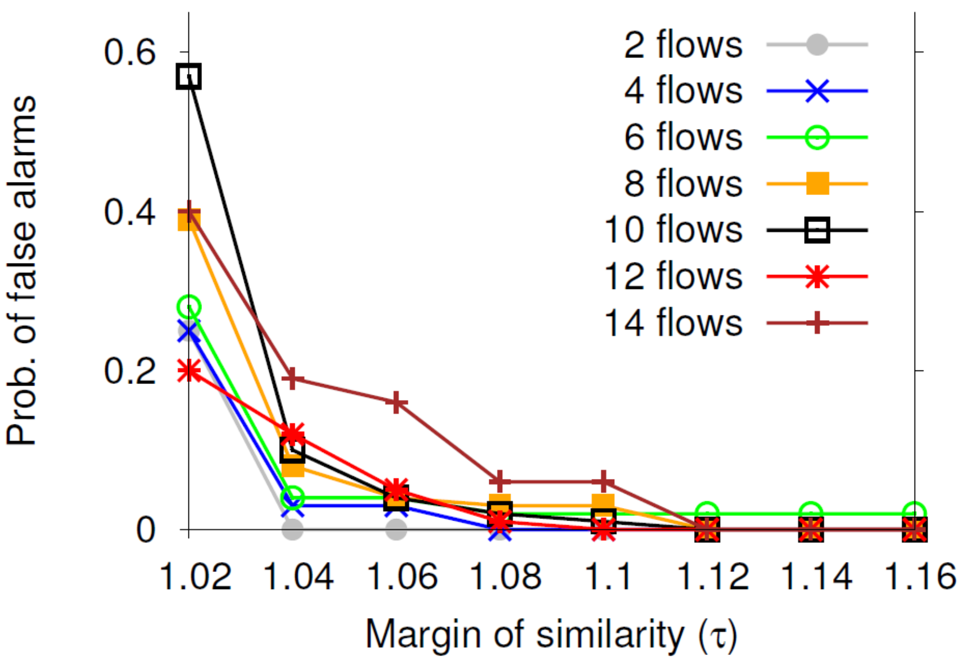
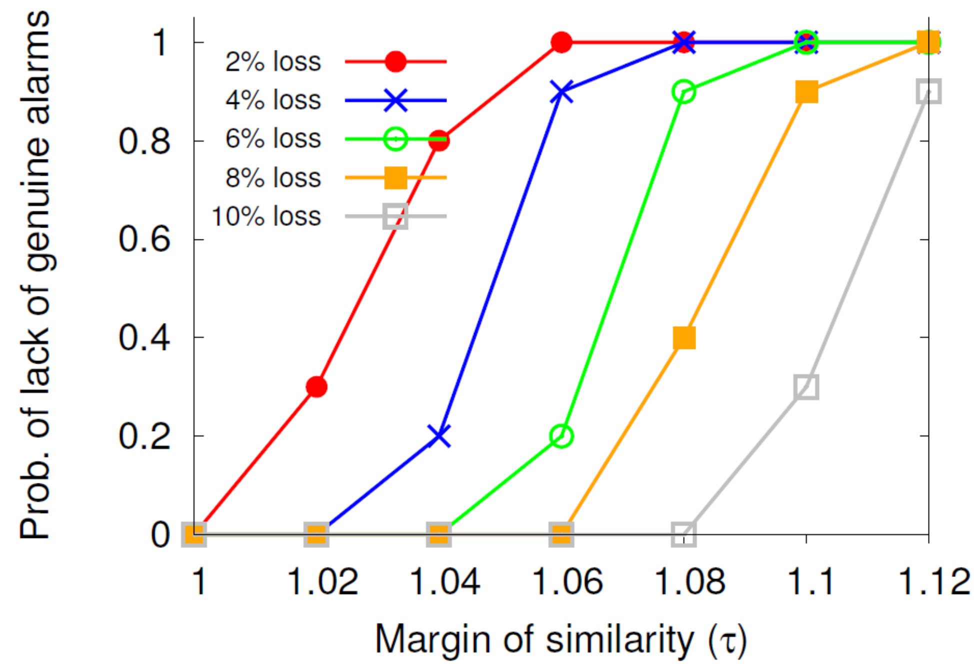
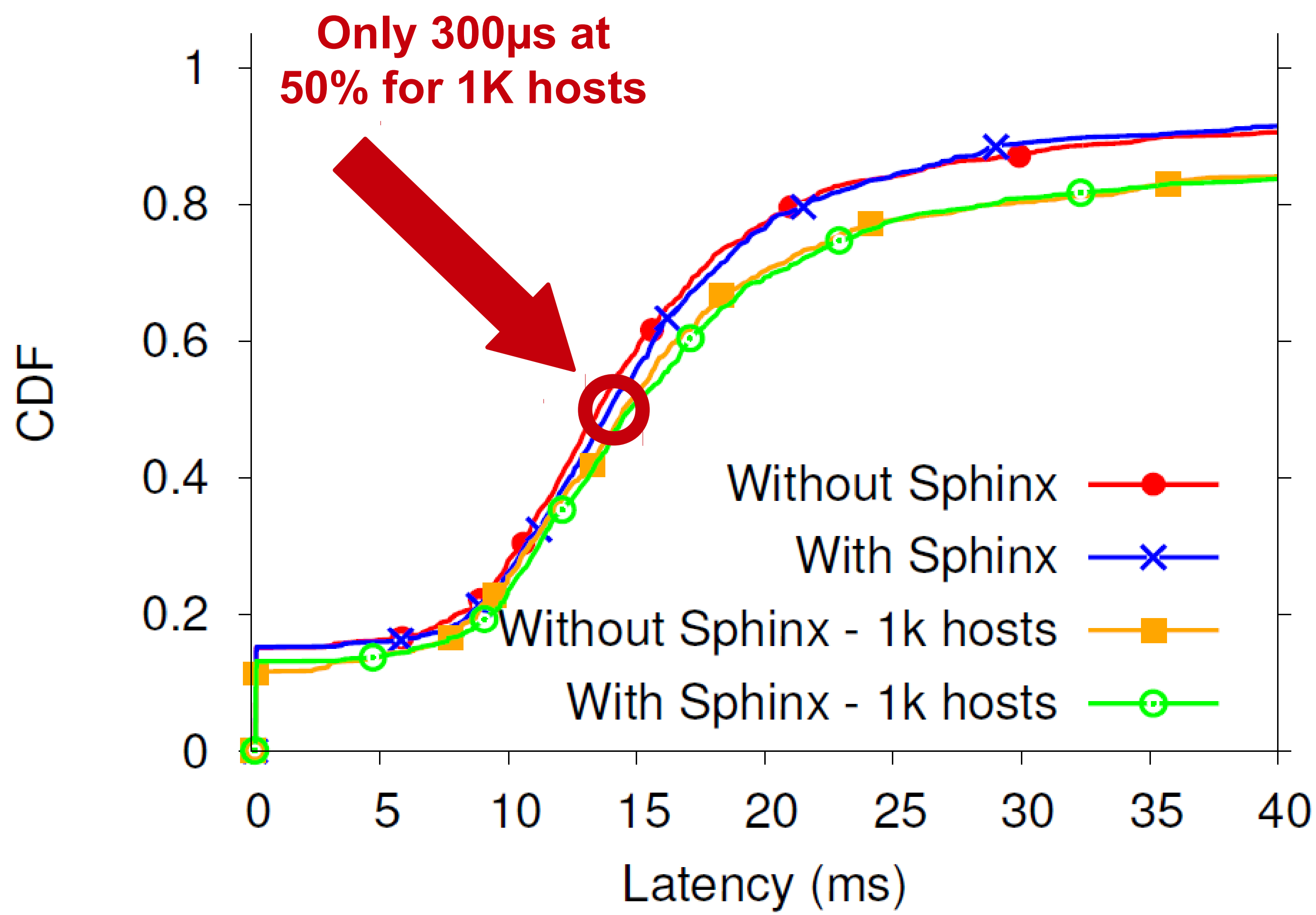




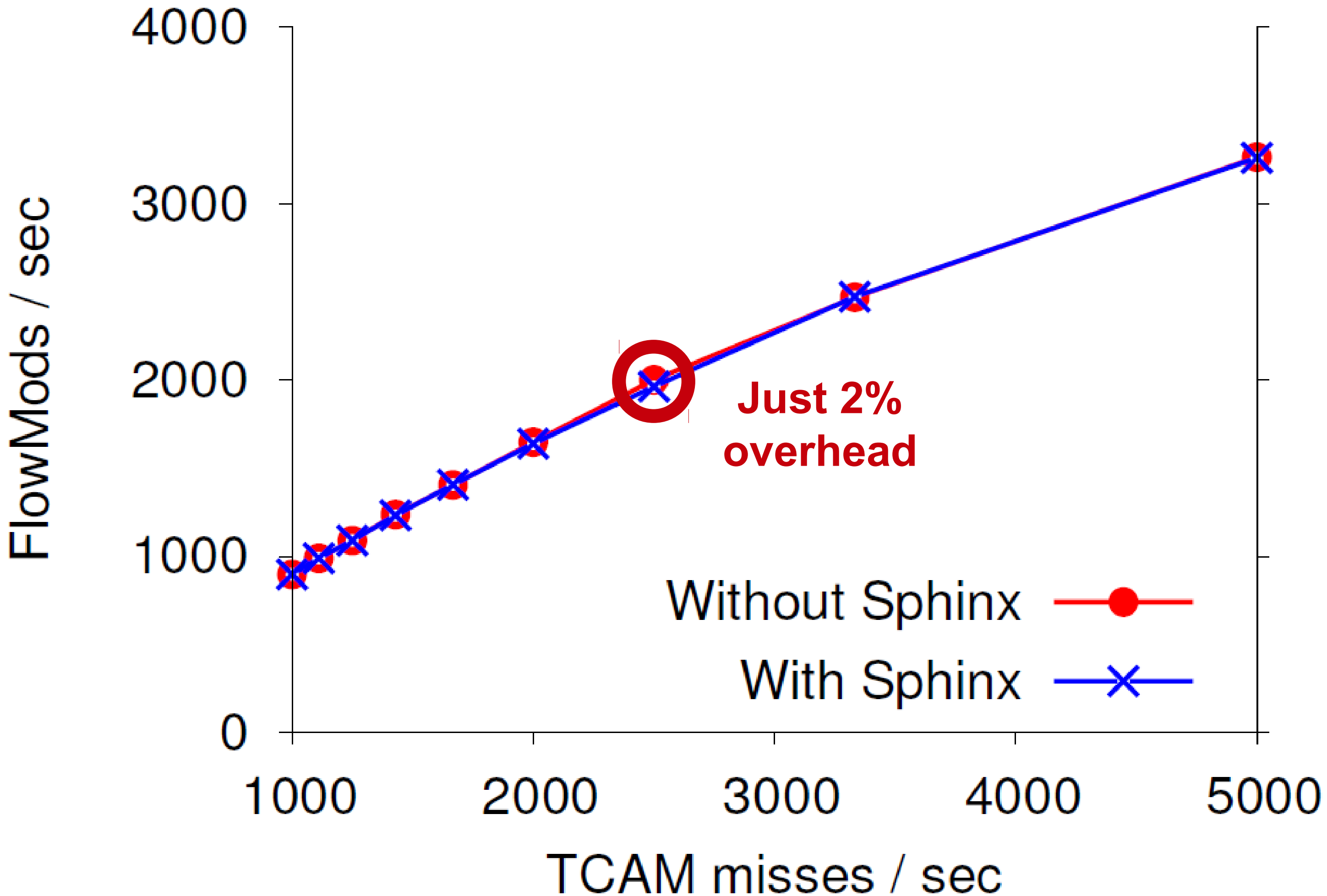
Performance (I)

- End user latency



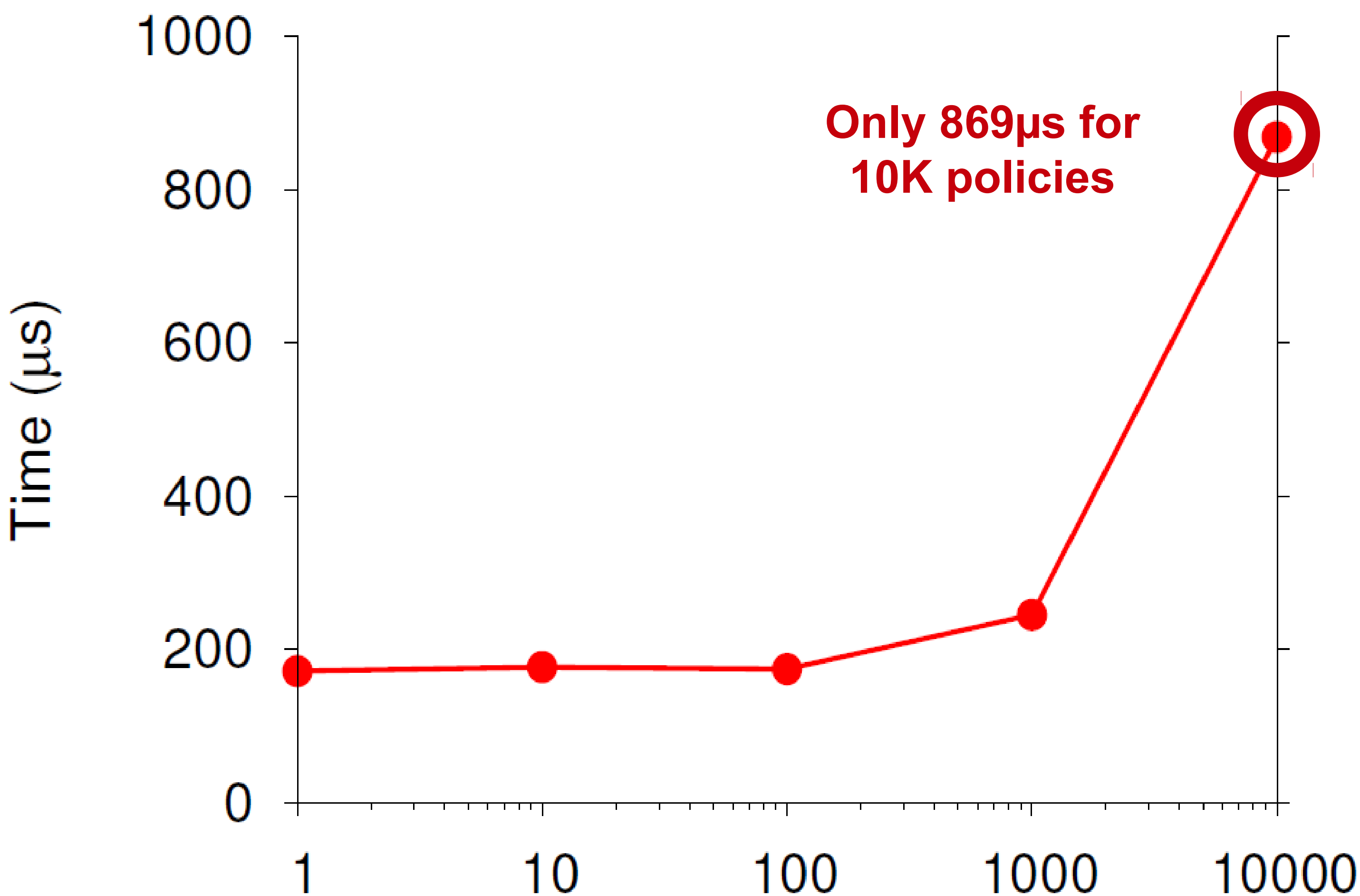
Performance (II)

- Throughput



Performance (III)

- Policy verification



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Conclusion

- Existing controllers are vulnerable to a wide array of attacks
- Sphinx is a controller agnostic tool that detects security threats originating within SDNs in real time
- Sphinx builds succinct metadata for each network flow and uses both deterministic and probabilistic checks to identify deviant behavior
- Our evaluation shows that Sphinx is practical and imposes minimal overheads

Thank You.

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