Attacking the Brain: Races in the SDN Control Plane

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Software-Defined Networking (SDN) is a novel programmable network paradigm that separates the control logic from the data plane.
SDN Control Plane – New Achilles' Heel

- Control Plane Saturation (CCS’13, DSN’15)
- Topology Poisoning (NDSS’15)
- State Manipulation (In this paper!)
Harmful Race Conditions in the Brain

The network states maintained in the SDN control plane is subject to harmful race conditions.

- Non-adversarial causality: asynchronous network events and non-determinist schedules.
- Adversarial causality: an attacker can intentionally inject *right* network events to exploit vulnerabilities -- *State Manipulation Attacks*
How Does It Look like?

NIO thread
(Switch Connection)

switchAdded()
1: this.switches.put(dpid, sw);}
2: addUpdateToQueue(update);

switchStatusChanged()
...

addUpdateToQueue(update)
3: this.updates.put(update);

Controller

Main Thread
(Looper)

run()
5: update = updates.take();
6: update.dispatch();
...

Dispatch()
7: listener.switchActivated();

Controller

switchActivated()
8: sw = switchService.getSwitch(dpid);
9: sw.setEnabledPortNumber();

LinkDiscoveryManager

getSwitch(dpid)
10: return this.switches.get(dpid);

Race Condition 1
What Can It Cause?

- System Crash
- Connection Disruption
- Service Disruption
- Service Chain Interference
- Privacy Leakage
- ...
A Real Vulnerability in LoadBalancer

Control Plane

Data Plane

Internet

Client (10.0.0.1)

Switch 1

Switch 2

Switch 3

Server Replica (10.0.0.4)

Floodlight (LoadBalancer)
A Real Vulnerability in LoadBalancer

Client send requests to public service
Switch issues Packet-In message to SDN controller
A Real Vulnerability in LoadBalancer

1. Client send requests to public service
2. Switch issues Packet-In message to SDN controller
3. SDN controller select Server replica and instruct switch to install flow rules to translate traffic between client and server replica

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Floodlight (LoadBalancer)
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1. Client send requests to public service
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3. SDN controller select Server replica and instruct switch to install flow rules to translate traffic between client and server replica
4. The communication between Client and public service is successfully set up
A Real Vulnerability in LoadBalancer

1. Client send requests to public service (10.10.10.10)
2. Switch issues Packet-In message to SDN controller
3. SDN controller select Server replica and instruct switch to install flow rules to translate traffic between client and server replica
4. The communication between Client and public service is successfully set up
A Real Vulnerability in LoadBalancer

```
root@mininet-vm:~# ping 10.10.10.10
PING 10.10.10.10 (10.10.10.10) 56(84) bytes of data.
64 bytes from 10.0.0.4: icmp_seq=2 ttl=64 time=9.45 ms
64 bytes from 10.0.0.4: icmp_seq=3 ttl=64 time=7.33 ms
64 bytes from 10.0.0.4: icmp_seq=4 ttl=64 time=7.29 ms
64 bytes from 10.0.0.4: icmp_seq=5 ttl=64 time=7.45 ms
64 bytes from 10.0.0.4: icmp_seq=6 ttl=64 time=6.28 ms
64 bytes from 10.0.0.4: icmp_seq=7 ttl=64 time=6.57 ms
64 bytes from 10.0.0.4: icmp_seq=8 ttl=64 time=6.95 ms
64 bytes from 10.0.0.4: icmp_seq=9 ttl=64 time=6.23 ms
64 bytes from 10.0.0.4: icmp_seq=10 ttl=64 time=7.94 ms
64 bytes from 10.0.0.4: icmp_seq=11 ttl=64 time=6.91 ms
64 bytes from 10.0.0.4: icmp_seq=12 ttl=64 time=6.04 ms
64 bytes from 10.0.0.4: icmp_seq=13 ttl=64 time=7.16 ms
--- 10.10.10.10 ping statistics ---
13 packets transmitted, 12 received, 7% packet loss, time 12026ms
rtt min/avg/max/mdev = 6.044/7.137/9.458/0.888 ms
root@mininet-vm:~#
```
Research Questions

- How to detect harmful race conditions in the SDN control plane?
- How to exploit harmful race conditions by an external attacker?
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- How to exploit harmful race conditions by an external attacker?

Our Solution: ConGuard
Key Insight: Harmful race conditions are rooted by two race operations upon shared network states that are not commutative, i.e., mutating the scheduling order of them leads to a different state though the two operations can be well-synchronized (e.g., by using locks).
We dynamically log a sequence of critical operations to model the operations of SDN control plane from instrumented SDN control plane.
Critical Operations in Execution Trace

- **read(T,V)**: reads variable V in thread T
- **write(T,V)**: writes variable V in thread T
- **init(A)**: initializes application A
- **terminate(A)**: terminates application A
- **dispatch(E)**: dispatches event E
- **receive(H,E)**: receives event E by event handler H
- **schedule(TA)**: instantiates a singleton task TA
- **end(TA)**: terminates a singleton task TA
We develop happens-before relations to model concurrency semantics of the SDN control plane.

We utilize graph-based approach to locate race operations.
Race Detection

- Pre-processing
  - Prune operations on thread-local or immutable variable
  - Duplicated operations removal
- Graph-based Race Detection Algorithm
  - Use DAG to model operations
    - operations $\rightarrow$ nodes
    - happens-before $\rightarrow$ edges
  - Reachability Check in the graph $\rightarrow$ Race Operations
Adversarial State Racing

- We instrument control logic to force an erroneous execution order, e.g., the state update executes before the state references.
Exploitation of Harmful Race Conditions

- Thread Model
  - No need of compromised SDN controllers, apps, switches and protocol
  - Control channel is well protected by SSL/TLS
  - Compromised hosts/virtual machines
  - Inject 7 network events, 2 of them need in-band deployment of SDN
Exploitation of Harmful Race Conditions

Attack Strategies
- Repeat ordered event sequences <trigger event, update event>
- Feedback Probing
- Exploit larger vulnerable windows

Attacker

Inject trigger event

Inject update event

Handle events/ check state operation

Update State Operation

Vulnerable Window

Reference State Operation

Probe Attack Result
Evaluation

- Implementation of ConGuard
  - On Floodlight, ONOS and OpenDaylight controllers with 34 apps.
  - Input Generator: Mininet & Rest API scripts
  - Instrumentation & Static Analysis: ASM framework

- Totally pinpoint 15 unknown harmful race conditions
# Race Detection Result

<table>
<thead>
<tr>
<th>Controller</th>
<th>Version</th>
<th>Preprocessing Reduction</th>
<th>Race Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floodlight</td>
<td>1.1</td>
<td>96.6%</td>
<td>153</td>
</tr>
<tr>
<td>Floodlight</td>
<td>1.2</td>
<td>87.2%</td>
<td>184</td>
</tr>
<tr>
<td>OpenDaylight</td>
<td>0.1.7</td>
<td>92.1%</td>
<td>221</td>
</tr>
<tr>
<td>ONOS</td>
<td>1.2</td>
<td>98.1%</td>
<td>13</td>
</tr>
</tbody>
</table>
Effectiveness of HB rules

- In Floodlight Controller

![Diagram showing 258 HB rules leading to 153 rules with 105 false alerts]
All located 15 harmful race conditions with 4 harmful impacts:

- System Crash (4 of them)
- Connection Disruption (7 of them)
- Service Disruption (13 of them)
- Service Chain Interference (7 of them)
## Correlation of External Events

<table>
<thead>
<tr>
<th>Controller</th>
<th>Application</th>
<th>Bug#</th>
<th>Correlated Attack Event Pairs &lt;trigger event, update event&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flood-light</strong></td>
<td>Link Discovery Manager</td>
<td>1*</td>
<td>&lt;SWITCH_JOIN, SWITCH_LEAVE&gt;, &lt;PORT_UP, SWITCH_LEAVE&gt;</td>
</tr>
<tr>
<td></td>
<td>2*</td>
<td>&lt;SWITCH_JOIN, SWITCH_LEAVE&gt;, &lt;PORT_UP, SWITCH_LEAVE&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3*</td>
<td>&lt;SWITCH_JOIN, SWITCH_LEAVE&gt;, &lt;PORT_UP, SWITCH_LEAVE&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DHCP Server</td>
<td>4*</td>
<td>&lt;SWITCH_JOIN, SWITCH_LEAVE&gt;, &lt;PORT_UP, SWITCH_LEAVE&gt;</td>
</tr>
<tr>
<td></td>
<td>5*</td>
<td>&lt;GFP_PACKET_IN, SWITCH_LEAVE&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6*</td>
<td>&lt;GFP_PACKET_IN, SWITCH_LEAVE&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7†</td>
<td>&lt;GFP_PACKET_IN, REST_REQUEST&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8†</td>
<td>&lt;GFP_PACKET_IN, REST_REQUEST&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9†</td>
<td>&lt;GFP_PACKET_IN, REST_REQUEST&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Load Balancer</td>
<td>10†</td>
<td>&lt;REST_REQUEST, SWITCH_LEAVE&gt;</td>
</tr>
<tr>
<td></td>
<td>Statistics</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ONOS</strong></td>
<td>SegmentRouting</td>
<td>11</td>
<td>&lt;GFP_PACKET_IN, HOST_LEAVE&gt;</td>
</tr>
<tr>
<td></td>
<td>DHCP Relay</td>
<td>12</td>
<td>&lt;GFP_PACKET_IN, HOST_LEAVE&gt;</td>
</tr>
<tr>
<td><strong>OpenDay-light</strong></td>
<td>Host Tracker</td>
<td>13†</td>
<td>&lt;REST_REQUEST, HOST_LEAVE&gt;</td>
</tr>
<tr>
<td></td>
<td>Web UI</td>
<td>15†</td>
<td>&lt;REST_REQUEST, SWITCH_LEAVE&gt;</td>
</tr>
</tbody>
</table>

* in-band
† REST API
Remote Exploitations

Average trials to get a successful exploitation

<table>
<thead>
<tr>
<th>Bug #</th>
<th>Attack Case</th>
<th>Trials (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(SWITCH_JOIN, SWITCH_LEAVE)</td>
<td>10.6</td>
</tr>
<tr>
<td>2</td>
<td>(SWITCH_JOIN, SWITCH_LEAVE)</td>
<td>78.4</td>
</tr>
<tr>
<td>3</td>
<td>(SWITCH_JOIN, SWITCH_LEAVE)</td>
<td>120</td>
</tr>
<tr>
<td>4</td>
<td>(SWITCH_JOIN, SWITCH_LEAVE)</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>(OFP_PACKET_IN, SWITCH_LEAVE)</td>
<td>67.6</td>
</tr>
<tr>
<td>6</td>
<td>(OFP_PACKET_IN, SWITCH_LEAVE)</td>
<td>106.8</td>
</tr>
<tr>
<td>11</td>
<td>(OFP_PACKET_IN, HOST_LEAVE)</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>(OFP_PACKET_IN, HOST_LEAVE)</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>(HOST_LEAVE, HOST_JOIN)</td>
<td>-</td>
</tr>
</tbody>
</table>
Potential Defense Schemes

- Safety Check
  - Ensure consistent state at the reference location
- Deterministic Execution Runtime
  - Guarantee the deterministic execution of state operations
- Sanitizing External Network Events
  - Anomaly detection system to sanitize suspicious state update events
Conclusion

- We report State Manipulation Attacks that target the SDN control plane.
- We design ConGuard framework to pinpoint and exploit harmful race conditions in the SDN control plane.
- We present an extensive evaluation of ConGuard that uncovered 15 unknown vulnerabilities (we have helped developers patch most of them already).
Thanks for attention!
Q&A