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***Abstract*—Topology discovery is one of the most critical tasks of Software-Defined Network (SDN) controllers. Current SDN controllers use the OpenFlow Discovery Protocol (OFDP) as the de-facto protocol for discovering the underlying network topology. In a previous work, we have shown the functional, performance and security limitations of OFDP. In this paper, we introduce and detail a novel protocol called secure and efficient OpenFlow Discovery Protocol sOTDP. sOFTDP requires minimal changes to OpenFlow switch design, eliminates major vulnerabilities in the topology discovery process and improves its performance. We have implemented sOFTDP as a topology discovery module in Floodlight for evaluation. The results show that our implementation is more secure than OFDP and previous security workarounds. Also, sOFTDP reduces the topology discovery time several orders of magnitude compared to the original OFDP and existing OFDP improvements.**

keywords - Software-Defined Networking, OpenFlow, Topology Discovery, security.

I. Introduction

Software-Defined Networking (SDN) introduces the separation between the control plane and the data plane of the network. SDN moves the control logic to a centralized entity called the controller. The controller instructs switches/routers in the data-plane as to how packets should be forwarded by installing forwarding rules in their forwarding tables. To do so, the de-facto standard protocol for communication between the controller and switches is OpenFlow. The controller also provides APIs to write network management applications [1].

One of the controller's duties is to perform an accurate, secure and near real time topology discovery to provide management applications with an up-to-date view of the network topology. However, all current SDN controllers perform topology discovery using OpenFlow Discovery Protocol (OFDP), which is far from being secure and efficient [3]. Figure 1 shows how OFDP works; To discover the unidirectional link s1 → s2, the controller encapsulates a LLDP packet in a packet-out message and sends it to s1. The packet-out contains instruction for s1 to send the LLDP packet to s2 via port p1. By receiving the LLDP packet via port p2, s2 encapsulates it in a packet-in message and sends it back to the controller. Finally, the controller receives the LLDP packet and concludes that there is a unidirectional link from s1 to s2. The same process is performed to discover the link in the opposite direction s2 → s1 as well as for all other switches in the network.

In highly dynamic networks like large virtualized data centers and multi-tenant cloud networks, keeping an up-to-date view of the topology is a critical function; Switches join and leave the network dynamically, creating changes in the topology which affects routing decisions that the controller has to make continuously. To stay up-to-date, the controller needs to repeat the process described in figure 1 periodically. The period between two discovery rounds, we will refer to as the discovery period, must be chosen carefully based on the dynamicity, size and capacity of the network.

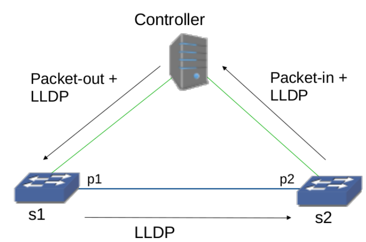


Fig. 1: Discovering a unidirectional link in OFDP

An inefficient, vulnerable or buggy topology discovery mechanism can affect routing logic and drastically reduce network performance. This paper extends our previous work on OFDP limitations [3] by detailing the design of a secure and efficient alternative protocol that we call $sOFTDP$ (secure and efficient OpenFlow Topology Discovery Protocol).

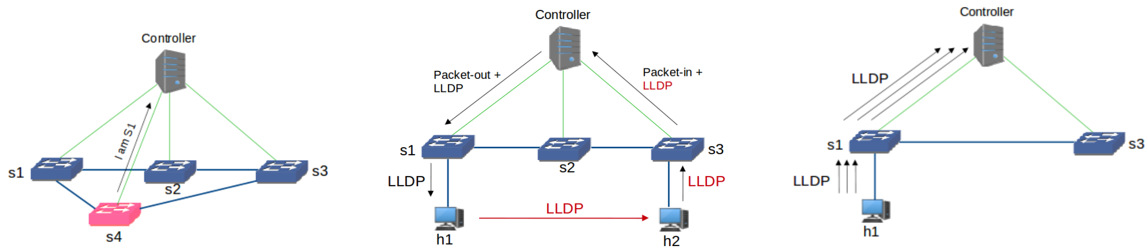
The remainder of this paper is organized as follows: In section II we show why the de-facto $OFDP$ shouldn't be implemented in production networks. We introduce our alternative protocol $sOFTDP$ in section III and evaluate its performance in section IV. Related work is discussed in section V and section VI concludes the paper.

II. Why OFDP shouldn't be implemented in production networks

In this section, the security and efficiency issues of $OFDP$ are briefly recalled in order for this paper to be self contained. We refer to [3] for a more thorough discussion.

A. OFDP is not secure

Current OpenFlow controllers that we have tested (ONOS [8], OpenDaylight [9], Floodlight [10], NOX [11], POX [11], Beacon [12], Ryu [13] and Cisco Open SDN Controller [14]) implement default $OFDP$ using clear and unauthenticated $LLDP$ packets. $OFDP$ is vulnerable to a number of attacks



(a) Switch spoofing attack (b) Link fabrication attack (c) LLDP flooding attack

Fig. 2: Attacks on OFDP

including switch spoofing, link fabrication, controller fingerprinting and LLDP flooding.

Switch spoofing. LLDP packets in OFDP have two mandatory TLVs: $ChassisSubtype$ and $PortSubtype$ to track packets. Most controllers we have tested set $chassisSubtype$ value to the MAC address of the local (or internal) port of the switch. In figure 2a, the malicious switch s4 intercepts LLDP packets from s1 containing s1's local port MAC address and then use it to connect to the controller as s1.

Link Fabrication. Link Fabrication attacks have two forms: *(i)* Link Fabrication by LLDP relay where the adversary has control over two end-hosts h1 and h2 connected to switches s1 and s3 respectively. h1 sends the LLDP packets received from s1 to h2 through an out-of-band connection (a tunnel over s2 for example), and h2 replicates them to s3 (figure 2b). *(ii)* Link Fabrication by fake LLDP injection. If the adversary has control only over h1, but knows the Data Plane Identifier (DPID) of s3 then he still can fabricate a unidirectional link between s3 $\rightarrow$ s1 by injecting fake LLDP packets into s1 [4], [6]. As discussed in [3], authenticating LLDP packets using a static or dynamic key-Hash Message Authentication Code (HMAC) does not prevent the link fabrication by relay attack.

Controller fingerprinting. The LLDP packets' content and frequency is different from one controller to another, which allows fingerprinting attacks on SDN controllers. An adversary (h1 in figure 2b) matches the LLDP content he/she receives from s1 (LLDP packets originating from the controller) against a controller signature database to detect which controller is managing the network. Such information is very useful to launch specific and precise attacks on the controller [15].

LLDP Flooding. An adversary can exhaust the controller's resources and congest links connecting switches to the controller by generating enough fake LLDP packets. In figure 2c, h1 generates a large number of LLDP packets and sends them to s1 which has a rule to forward every LLDP packet to the controller. Basic countermeasure methods such as port blocking or packet filtering may not be effective, especially in the case of very dynamic environments (e.g. multi-tenant cloud) since connected hosts and switches change frequently which may result in preventing legitimate LLDP packets from reaching the controller.

B. OFDP is not efficient

By using OFDP, the controller periodically sends multiple packets to every switch in the network, which could result in performance decrease of the data plane. Experiments made on different controllers [16] show that starting from a certain network size (i.e. number of switches), running only the discovery module results in significant increase of the controller's CPU usage and decrease in performance.

C. OFDP is not scalable

Other issues with OFDP include that it may not reliably work for heavily loaded links, because discovery packets might get dropped or delayed. Moreover, when using OFDP in a multi-controller SDN network (e.g. running several tenant controllers in a virtualized network through FlowVisor), discovery cost increases linearly as more controllers are added.

III. Introducing sOFTDP: Secure OpenFlow Topology Discovery Protocol

In a dynamic data center SDN, the controller needs to be updated whenever a topology change occurs in order to make the suitable routing decisions for the new topology. Topology changes typically occur as a consequence of two events: *(i)* a new link is added to the network or *(ii)* an existing link is removed from the network. Both events are the result of either adding a new switch, removing an existing switch or adding/removing a link between two existing switches (the latter include link and switch failures). sOFTDP design assumes that the controller has **no prior knowledge** of the occurrence of such events and it is expected to dynamically update its topology map and adapt its routing decisions accordingly.

Network as a Service (NaaS) platforms are good examples where the controller has no prior knowledge of upcoming events. This is the case for example, of a public Cloud provider that offers customers the possibility to create their own networks, including hosts and SDN switches in virtual machines. The consumer (or tenant) can create hosts and switches and link them on the fly using a web interface, while the provider's controller manages the network and ensure the connectivity. In this way, the tenant can add, remove, place or move host and switch instances without worrying about the underlying configuration.

In the remaining of this section we first identify some fundamental requirements for topology discovery in the context of dynamic virtualized data center networks, then we detail the sOFTDP design choices.

A. Fundamental requirements for topology discovery

Topology discovery is a critical process that is required to be:

- **Error free:** a topology error leads to wrong routing of flows. The impact can be very harmful if the error is in the routing core (core routers and links)
- **Secure**: a discovery protocol must be secure, preventing the introduction of fake links and information leakage (including topology information).
- **Efficient:** a discovery protocol must not flood the controller with redundant information and only transmit the topology events information when they occur.

B. sOFTDP design

sOFTDP [1] is designed to satisfy the above requirements. The main idea is to move a part of the discovery process from the controller to the switch. By introducing minimal changes to the OpenFlow switch design, sOFTDP enables the switch to autonomously detect link events and notify the controller. We also implement the necessary logic in the controller to handle switch notifications. The key ingredients of sOFTDP design are: Bidirectional Forwarding Detection (BFD) as port liveness detection mechanism, asynchronous notifications, topology memory, FAST-FAILOVER groups, ”drop lldp” rules and hashed LLDP content. In the following we describe each of these mechanisms.

1) BFD as Port Liveness Detection mechanism: sOFTDP uses BFD (Bidirectional Forwarding Detection [17]) as port-liveness-detection mechanism to quickly detect link events. Instead of requesting topology information by sending periodic $LLDP$ frames, the controller just listens for link event notifications from switches to make topology updates. Hence, the switch needs a mechanism to autonomously and quickly detect link events and report them to the controller.

BFD is a protocol that provides fast routing-protocol-independent detection of layer-3 next hop failures. BFD establishes a session between two preconfigured endpoints over a particular link, and performs a control and echo message exchange to detect link liveliness. sOFTDP implements BFD in asynchronous mode: once a session is set up with a three-way handshake, neighbor switches exchange periodic control messages to confirm absence of a failure (presence of link) between them. Note that sOFTDP only relies on BFD to detect link removal events. For link addition events, sOFTDP uses OFPT_PORT_STATUS messages to update the topology as we will detail in the next subsection. The reason for using BFD instead of OFPT_PORT_STATUS messages in detecting link removal is to include link failures that do not originate from administratively shutting down ports, e.g., failure of the underlying physical link or switch failure, etc.

[1]We interchangeably use the name sOFTDP for the topology discovery protocol and for the topology discovery application implementing it

BFD detection time of link events depends on the control packet transmission interval T_i and the detection multiplier M[17]. The former defines the frequency of control messages and the latter defines how many control packets can be lost before the neighbor end-point is considered unreachable. In the worst case, failure detection time is given by equation 1

$$T_{det} = M * T_i \tag{1}$$

The transmit interval T_i is lower-bounded by the RTT of the link. Note that a transmit interval of $T_i = 16.7ms$ and a detection multiplier of $M = 3$ are sufficient to achieve a detection time of $T_{det} = 50ms$. Also, $M = 3$ prevents small packet loss from triggering false positives. Furthermore, a such session generates only 60 packets per second.

2) Asynchronous notifications: sOFTDP enables the switch to inform the controller about port connectivity events. In case of administrative changes to port status (port turned up or down), the switch reports it via a OFPT_PORT_STATUS message defined in OpenFlow switch specifications. But, in the case of link failure or the remote port going down, OpenFlow doesn’t provide any mechanism for the switch to inform the controller. sOFTDP adds this functionality to the switch by defining a new switch-to-controller message BFD_STATUS.

3) Topology memory: sOFTDP keeps track of topology events and builds a database of potential backup links besides the actual link database. When a new link is added, sOFTDP computes the local topology (relative to the added link). If the new link forms a shorter path between two switches and no traffic engineering application decides otherwise, the new path will be used for forwarding and the previous one will be saved as potential backup. sOFTDP installs OpenFlow FAST-FAILOVER groups [18] on the switches of the new link and marks the link as ’safe to remove’ since it has at least one potential backup. Note that potential backup links are not considered backup links until all traffic engineering applications agree. Traffic engineering applications must communicate with sOFTDP to prevent interference in selecting primary paths and backups.

4) FAST-FAILOVER groups: OpenFlow groups enable OpenFlow to abstract a set of ports as a single forwarding entity allowing advanced forwarding and monitoring at the switch level. The group table contains group entries; each group entry is composed of a set of action buckets with specific semantics dependent on the group type. When a packet is sent to a group, the actions in one or more action buckets are applied to it before forwarding to the egress port. Groups buckets can also forward to other groups, enabling to chain groups together.

The following four types of group tables are provided:

- **All:** used for multicast and flooding
- **Select:** used for multipath
- **Indirect:** simple indirection
- **Fast Failover:** use first live port

Different types of group tables are associated with different abstractions such as multicasting or multipathing. In particular, the Fast Failover Group Table monitors the status of ports and applies forwarding actions accordingly. When the monitored port goes down, the Fast Failover Group Table switches to the first port alive without consulting the controller [18].

sOFTDP enables seamless removal of switches and links while preserving connectivity. In order to accomplish that, when a link removal event occurs, sOFTDP uses OpenFlow FAST-FAILOVER groups (optional in OpenFlow 1.1+) to watch switch ports and perform fast switchover to backup links. Hence, switches concerned by the link removal start forwarding flows through the backup link and do not have to wait until the controller receives the topology event and installs new rules.

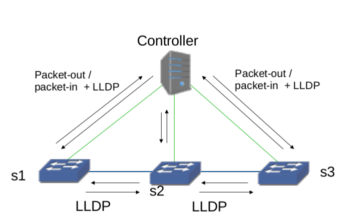
5) "drop lldp" rules: The switch has a rule "drop lldp" to drop every LLDP packet to prevent LLDP flooding attacks (see figure 2c). In a SDN running OFDP, traditional Denial of Service (DoS) mitigating methods like placing firewalls or Intrusion Detection Systems (IDSs) to filter out LLDP packets are not effective because it is hard to distinguish between legitimate LLDP packets (generated by the controller and forwarded by switches) from the fake ones (generated by the attacker and also forwarded by switches to the controller). By removing periodically broadcasted LLDP packets, sOFTDP eliminates the possibility that malicious LLDP packets get forwarded to the controller and hence prevents it from being flooded.

6) Hashed LLDP content: The controller sends encrypted LLDP packets only when it receives a OFPT_PORT_STATUS with the flag $PORT\_UP$ set to 1 indicating the port went from down to up status. The LLDP packets are sent only to the concerned switches along with OpenFlow rules to forward them to the controller. These rules must have a higher priority than "drop lldp" rules and their $hardtimeout$ values are set to $500ms$. The purpose of the LLDP packets here is to learn added links as shown in figure 3b and detailed in subsection III-C. Finally, $500ms$ is a small arbitrary value to ensure that potential malicious LLDP packets generated exactly during this time window will not significantly affect the controller.

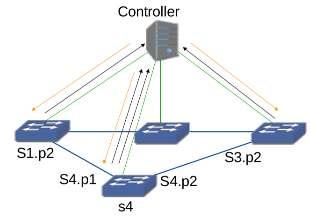
C. How sOFTDP works

Figure 3 shows how sOFTDP works. To bootstrap, the controller sends LLDP packets to all connected switches like in traditional OFDP (figure 3a). The main difference is that we do not use clear MAC addresses as switch DPIDs. Instead, we use hash values of them to prevent all information discloser and switch spoofing attacks. We also hash *system_description* field value to prevent controller fingerprinting [15].

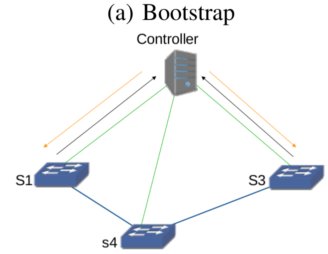
When a new switch joins the network, it starts by establishing a connection with the controller: The switch and the controller exchange $hello$ ($OFPT\_HELLO$) messages that specify the latest OpenFlow protocol version supported by the sender. Then, the controller sends the switch a $feature\ request$ message asking its capabilities. The switch responds with a $feature\ reply$ message, which includes the local MAC address (that corresponds to the internal port of the switch) in the $switch\ datapath\ ID$ field and that's how the controller keeps track of connected switches. The $feature\ reply$ message also includes ports status which are all down initially. In figure 3b, when switch $s4$ joins the network and new links are established, switches s1, s3 and s4 send $PORT\_STATUS$ messages to inform the controller that involved ports s1.p2, s4.p1, s4.p2 and s3.p2 went up and are connected. The controller 'c' then sends LLDP packets to be forwarded only through those ports: $c \rightarrow s1.i \rightarrow s1.p2 \rightarrow s4.p1 \rightarrow s4.i \rightarrow c$, $c \rightarrow s4.i \rightarrow s4.p2 \rightarrow s3.p2 \rightarrow s3.i \rightarrow c$, $c \rightarrow s3.i \rightarrow s3.p2 \rightarrow s4.p2 \rightarrow s4.i \rightarrow c$ and $c \rightarrow s4.i \rightarrow s4.p1 \rightarrow s1.p2 \rightarrow s1.i \rightarrow c$. With i indicates internal port.



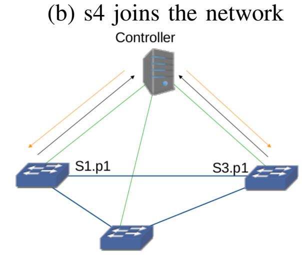
(a) Bootstrap



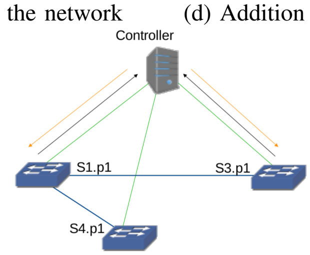
(b) s4 joins the network



(c) s2 leaves the network



(d) Addition of link $s1 \leftrightarrow s3$



(e) Removal of link $s3 \leftrightarrow s4$

Fig. 3: How sOFTDP works

Once all LLDP packets are received, the controller identifies the new links and store them in the Topology Map. Note that by using $PORT\_STATUS$ messages as trigger to learn new links, the controller doesn't need to periodically send discovery packets and switches do not need to be too smart to determine the new links (as in [19]) or to store them locally.

Once the new topology is computed, the controller detects multiple paths between pairs of switches. Independently of traffic engineering applications running on the same controller, the sOFTDP topology module tags shortest paths as primary paths and longer paths as secondary paths or potential backups (e.g., $s1 \leftrightarrow s2$ is a primary path and $s1 \leftrightarrow s4 \leftrightarrow s3 \leftrightarrow s2$ is a secondary path). Then, if not specified otherwise by any traffic engineering application, the controller installs fast-failover group rules on the switches of the shortest path. This ensures continuity of connectivity in case of topology events. In the example shown in figure 3b, there are two similar paths, in term of number of hops, between $s1$ and $s3$. The controller arbitrary tags $s1 \leftrightarrow s4 \leftrightarrow s3$ as primary path and installs fast-failover group rules on switches $s1$ and $s3$ to watch ports $s1.p1$, $s1.p2$, $s3.p1$ and $s3.p2$.

When a switch leaves the network ($s2$ in figure 3c), neighbor switches detect and report link events to the controller: BFD session on $s1.p1$ detects the link $s1.p1 \leftrightarrow s2.p1$ failure and sends a BFD_STATUS message to the controller. In the case of link removal, the controller doesn't need to send LLDP packets and just removes the link from the topology map. The same process applies to link $s2.p2 \leftrightarrow s3.p1$. Switches s1 and s3 automatically switch traffic through the path s1 $\leftrightarrow$ s4 $\leftrightarrow$ s3 using the fast-failover group rules installed previously.

When a link is added between two existing switches ($s1 \leftrightarrow s3$ in figure 3d), the involved ports $s1.p1$ and $s3.p1$ send $PORT\_STATUS$ messages to the controller with "port up" flags set. The controller then sends LLDP packets to be forwarded only through $s1.p1$ and $s3.p1$: $controller \rightarrow s1.internal \rightarrow s1.p1 \rightarrow s3.p1 \rightarrow controller$ and $controller \rightarrow s3.internal \rightarrow s3.p1 \rightarrow s1.p1 \rightarrow controller$. After the new topology is computed, the controller tags $s1 \leftrightarrow s3$ as the shortest path and $s1 \leftrightarrow s4 \leftrightarrow s3$ as a potential backup path and installs fast-failover group rules on $s1$ and $s3$ (in this particular example, the same rules already exist)

When an existing link is removed ($s3 \leftrightarrow s4$ in figure 3e), the involved ports $s3.p2$ and $s4.p2$ detect loss of connectivity very quickly using BFD and report it to the controller via BFD_STATUS messages. The controller then drops the link $s3 \leftrightarrow s4$ from its topology map without the need to send LLDP packets. Finally, the controller removes the tag from the remaining path.

IV. Evaluation

A. Emulation Testbed

To evaluate sOFTDP, we implemented sOFTDP topology module on Floodlight. We conducted experiments on an emulated testbed using Mininet [20]. The emulated testbed is composed of four virtual bridges based on Open vSwitch [21] and controlled by Floodlight controller from a different physical machine. We upgraded existing Open vSwitch (of mininet v2.2.1) to the newer version 2.3.1 that supports the BFD protocol and fast failover groups. Then we added a simple patch to Open vSwitch to send BFD_STATUS to the controller upon BFD events (see section III-B2). BFD detection time is set to $1ms$.

B. Experiments and results

As previously explained, to handle link removal, sOFTDP uses BFD protocol to detect port events at the switch level, then the switch triggers a notification the the controller (BFD_STATUS message) and finally the controller removes the link from the topology map. To handle link addition, sOFTDP listens for OFPT_PORT_STATUS messages triggered by the ports going up then the controller sends a LLDP message to the concerned switches to confirm the added link and finally adds it to the topology map. Accordingly, two scenarios are implemented and evaluated:

Scenario one: Link $s1.p1 \leftrightarrow s3.p1$ is added (figure 3d). We measure the $learning\ time$ the controller takes to know about the added link as given in equation 2.

$$T_{learn}(i,j) = max_{d \in \{i,j\}}(T_{pstatus}(d)) + RTT_{LLDP}(i,j) \tag{2}$$

$$RTT_{LLDP}(i,j) = T_{delv}(c,i) + T_{delv}(i,j) + T_{delv}(j,c) \tag{3}$$

$$T_{learn}(\{i,j\}) = max(T_{learn}(i,j), T_{learn}(j,i)) \tag{4}$$

Where: $T_{learn}(i,j)$ is the time necessary to learn unidirectional link (i,j) $T_{pstatus}(i) = T_{trsm}(i,c)$ is the time OFPT_PORT_STATUS message takes from switch i to the controller. $RTT_{LLDP}(i,j)$ is the round trip time that a LLDP packet sent from the controller takes to go through switch i then switch j and back to the controller. $T_{learn}(\{i,j\})$ is the time necessary to learn bidirectional link $\{(i,j),(j,i)\}$ and finally $T_{delv}(x,y)$ is the packet delivery time from node x to node y. Figure 4a shows the average of 50 performed experiments and 95% confidence interval yielding learning times of $5.68 \pm 0.85ms$

To further demonstrate sOFTDP performance, we also measure the overall $adaptation\ time$ when a new link is added (see figure 3d) to the network. $adaptation\ time$ includes learning the new link, installing fast-failover group rules in the switches and the actual switchover time. Figure 4b depicts the result averaged from 50 conducted experiments. The average and 95% confidence interval are of $6.12 \pm 0.7ms$.

Scenario two: Link $s3.p2 \leftrightarrow s4.p2$ is removed (figure 3e). We measure the $learning\ time$ the controller takes to learn the change in the topology. The link is brought down upon the first BFD_STATUS message of either of its endpoints.

The $learning\ time$ in this case is:

$$T_{learn}(i,j) = min(T_{bfd}(i), T_{bfd}(j)) \tag{5}$$

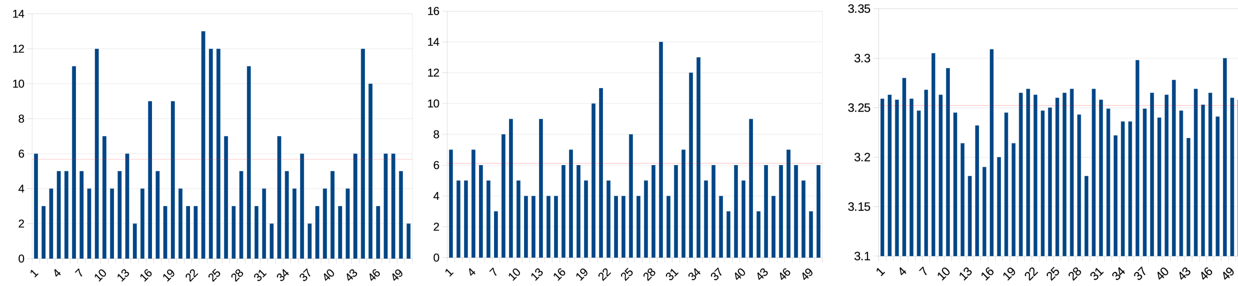
Where $T_{bfd}(x)$ is the BFD detection time on the involved port of node x. Computed as follows:

$$T_{bfd}(x) = T^x_{det} + T_{delv}(x,c) \tag{6}$$

Where T^x_{det} is $BFD\ detection\ time$ given in equation 1 and $T_{delv}(x,c)$ is $packet\ delivery\ time$ from node x to the controller.

Figure 4c shows sOFTDP learning time average (taken over 50 performed experiments) and the 95% confidence interval resulting in $3.25 \pm 0.008ms$

sOFTDP $learning\ time$ is independent of the size of the network and depends only on the inter-switch RTT and the RTT between switches and the controller. Figure 5 compares sOFTDP to OFDP and OFDPv2 [7] in term of CPU time.



(a) New link detection time in ms (b) Adaptation time in ms (c) Link removal detection time in ms

Fig. 4: Evaluation of sOFTDP

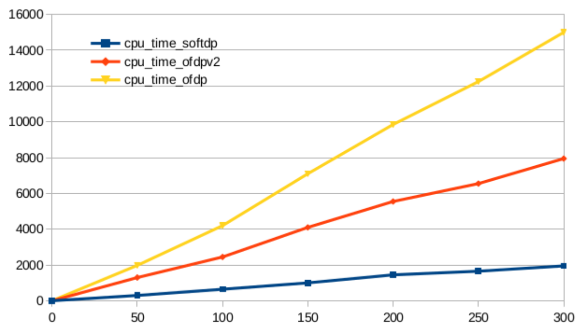


Fig. 5: CPU time (in ms) over number of switches

Each experiment is performed over $200s$ period during which one topology event is generated every second.

V. Related work

Unlike our proposal, most of previous work focus either on security problems or on performance problems in OFDP. In [4], authors identified $link\ fabrication$ attacks on OFDP and proposed to authenticate LLDP packets by adding an optional TLV "HMAC" to ensure their origin and integrity.

The average overhead introduced by this approach differs between the first discovery round and the following rounds, because the HMAC value is computed once and cached for the future construction and validation of LLDP packets. The average overhead accounts for 80.4% of overall LLDP construction time in the first round and accounts for 2.92% in the following rounds. Although this approach prevents link fabrication by fake LLDP injection, it does not defend against link fabrication in a relay manner as discussed in section II. The authors argue that a solution to the link fabrication by a relay could be that the controller monitors ports to detect whether the connected machine is a host or a switch. If the connected machine is a host generating LLDP packets then an alert is triggered. However, a host can easily behave like a switch making this solution unpractical.

A similar approach was proposed in [6] but using HMAC with a dynamic key which is randomly generated for every single LLDP packet. This approach adds an extra 8% of in CPU load.

OFDPv2 [7] reduces the number of OFDP-related packet-out messages by rewriting LLDP packet headers in the switch. In the traditional OFDP, the controller sends $\sum_{i=1}^{n} p_i$ packet-out messages every discovery round, where n is the number of switches and p_i the number of ports in switch i. The number of packet-out messages shrinks to n by sending only one packet per switch and rewriting copies for different ports at level of the switch. OFDPv2 achieves 50% reduction in CPU load compared to OFDP but obviously requires more logic to be added to the switch. Also, OFDPv2 does not reduce the number of packet-in messages that the controller periodically receives from switches.

In [19] authors implemented the ForCES [22] protocol to communicate the topology information between switches and the controller. Switches acquire neighbor topology information by exchanging LLDP packets as in traditional networks and store it in their device maps. The acquired information is updated periodically as LLDP frames are exchanged. Then, upon receiving a topology change notification from a switch, the controller needs to query the connected switches in order to learn their respective neighbors. The authors measured an average learning time of $12ms$ without considering the LLDP exchange time. In other words, the LLDP time exchange time is not included and it takes $12ms$ for the switch to detect the topology change, send a notification to the controller and then answer the controller's request for the topology information.

VI. Conclusion

In this work, we extended our previous paper on OFDP limitations by introducing and detailing a novel topology discovery protocol for OpenFlow (sOFTDP). We argue that this is the first time major security and performance issues related to the topology discovery process in current SDN controllers, are tackled. Our proposal requires minimal changes to the OpenFlow switch design and is shown to be more secure (by design) than previous workarounds on traditional OFDP. Also, our proposal outperforms OFDP and OFDPv2 by several orders of magnitude which we confirmed by proof of concept experiments. Further experiments on larger physical testbeds are being conducted ad will be included in future work.

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