SDFW: SDN-based Stateful Distributed Firewall

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Abstract—SDN provides a programmable command and control networking system in a multi-tenant cloud network using control and data plane separation. However, separating the control and data planes make it difficult for incorporating some security services (e.g., firewalls) into SDN framework. Most of the existing solutions use SDN switches as packet filters and rely on SDN controllers to implement firewall policy management functions, which is impractical for implementing stateful firewalls since SDN switches only send session’s initial packets and statistical data of flows to their controllers. For a data center networking environment, applying a Distributed FireWall (DFW) system to prevent attacker’s lateral movements is highly desired, in which designing and implementing an SDN-based Stateful DFW (SDFW) demand a scalable distributed states management solution at the data plane to track packets and flow states. Our performance results show that SDFW achieves scalable security against data plane attacks with a marginal performance hit $\sim 1.6\%$ reduction in network bandwidth.

Index Terms—Software Defined Networking (SDN), Distributed Firewall (DFW), Connection Tracking

I. INTRODUCTION

Software Defined Networking (SDN) simplifies networking management by decoupling control plane and data plane. The SDN controller can dynamically configure multiple physical or virtual network switches. The lack of built-in security in the SDN limits its adoption, as reported some campus adopters [2]. Although the centralized design is an import characteristic of SDN framework, we designed a scalable stateful firewall (SDFW) to provision granular security in a scalable fashion. Using an SDFW architecture, the distributed firewall can be easily managed in a cloud network.

With these security challenges and design goals, discussed above in mind, and realizing the need for an automated-security management framework, we designed SDFW. The key contribution of this research work are as follows:

- The SDFW firewall in our framework is utilized to construct OpenFlow rules, which are implemented on the switches using a stateful distributed firewall (SDFW) framework. Using the SDFW scales well on a large network with limited performance impact $\sim 1.6\%$ reduction in network bandwidth.
- SDFW identifies the lateral movement of the attacker and implements SDN based security countermeasures to prevent the attack propagation in a multi-tenant cloud network.

II. BACKGROUND AND MOTIVATION

A. SDN and OpenFlow

![OpenFlow Rule Format](image-url)
We define the flow rule using tuple \( r = (p_i, \rho_i, h_i, a_i, s_i) \), where \( p_i \) denotes rule priority, \( \rho_i \) is the protocol of incoming traffic (TCP/UDP), \( a_i \) is the action associated with the rule, \( s_i \) is the statistics associated with the rule.

The flow rule header space \( h_i \), consists of physical port of incoming traffic \( \delta_i \), source and destination hardware address, i.e., \( \alpha_{s_i}, \alpha_{d_i} \), source and destination IP address, \( \beta_{s_i}, \beta_{d_i} \), source and destination port address, \( \gamma_{s_i}, \gamma_{d_i} \). Packet header can be defined by the tuple \( h_i = (\delta_i, \alpha_{s_i}, \alpha_{d_i}, \beta_{s_i}, \beta_{d_i}, \gamma_{s_i}, \gamma_{d_i}) \). Rule statistics \( s_i \) comprises of both flow duration and number of packets/bytes for each flow rule \( s_i = (d_i, h_i) \).

The flow rules, generally presented in the Figure 1 can be used to block traffic from a network segment, using SDN based centralized firewall architecture [9]. However, the attacks originating in data-plane which rely on connection information, go undetected using the centralized firewall architecture.

### B. Need for Stateful-Distributed Firewall

**Firewall:** is a collection of components, interposed between two networks, that filters the traffic between them according to some security policy. If we consider the modern data-centers as a use-case, the scope of security enforcement offered by a traditional firewall is limited to north-south traffic, i.e., firewall serves as a sentry between trusted and untrusted networks. Once the attacker has managed to breach the security restrictions at the network edge, he can laterally move inside the network (east-west traffic), exploiting key resources, virtually unchecked. The volume of east-west traffic in the data center environment is around 76%, as compared to north-south traffic - 17% [11].

**Stateful Firewall:** is responsible for packet filtering by tracking the state of network connections. The TCP connections have three major states, connection establishment, usage, and termination. The firewall normally utilizes a state-table to track the bidirectional connection between hosts and blocks the packets that deviate from expected state [12]. The application firewall that performs fine-grained analysis such as stateful protocol analysis and deep-packet-inspection (DPI), has not been considered in SDFW framework in its current version.

### Scenario 1: Stateless-centralized Firewall

Figure 2 shows three OpenFlow switches connected to centralized SDN controller, with Firewall functionality. The traffic between certain VMs across the networks has been allowed, using OpenFlow rules shown in the flow table. Suppose if there is a security vulnerability on Web1, DB1, and, DB2, and the attacker is located on VM1. Although the network traffic is allowed between VM1-Web1, the stateless firewall cannot inspect the state of the network connection. Using a stateless firewall alone, the connection information used by an attacker to mount a multi-hop attack will remain undetected.

### Scenario 2: Stateful centralized Firewall

If the SDN controller decides to inspect every single packet, all the network connection traffic will be redirected to SDN controller, as shown in Figure 2. The SDN controller may be quickly overwhelmed. Additionally, the attacker can launch control plane saturation attacks if the connection tracking is enforced on the SDN controller, as highlighted by AVANTGUARD [13].

### III. System Architecture and Data Flow

The SDFW architecture in Figure 3 is primarily divided into three planes, i.e., *application plane*, responsible for user-
interface, through which the user can enter higher-level security policies, and visualize the state of a distributed firewall. The control plane consists of modules, responsible for the translation of higher level security policies, into OpenFlow rules, and identifying any conflicts between OpenFlow rules, and security policies. The data plane consists of OpenFlow switches, with state-tracking capability, each OpenFlow switch acts as a firewall module for inspecting traffic between the hosts connected to the switch, and the traffic between switch and control plane.

SDFW Manager: checks the status of individual virtual firewalls connected through Network Information Base as shown below, and accepts the security policies through the UI written in the PHP-laravel framework.

Network Information Base (NIB): acts as a middleware between the application plane implementing distributed firewall policy and local event listeners on each switch. NIB notifies the local-agents on each switch about any new application security policies and maintains synchronization between different agents. NIB has been implemented using Zookeeper [14].

Policy-Graph-Creator: checks the dependencies between requirements of different security policies, and creates end-to-end conflict-free Policy-Graph to direct traffic between different hosts in a data-center. The control plane utilizes this Policy-Graph to modify the flow rules of OpenFlow tables, using OpenFlow message `ofp_flow_mod()` and creates an end-to-end traffic flow. This module checks the dependencies between requirements of different policies. The end result of this process is Policy-Graph.

Traffic Statistics: The controller consists of TopoChangeEventListener, which listens on the events such as port status (UP/DOWN), switch status, port information of hosts connected to switches. If there is any topology change, the event listener utilizes a PUSH notification to notify the application plane, which in-turn updates the visualization and traffic statistics.

IV. DESIGN OF STATEFUL DISTRIBUTED FIREWALL

The most popular software switch used by OpenFlow protocol Open vSwitch has a capability to track the connection-state of the packet, as well as the features to define the virtual routing domains in the Linux kernel. Some important fields, of the conntrack module, which we will use in the illustrative example have been defined in the Table 1 below.

In our distributed firewall design, we leverage the information stored by the OpenFlow table and connection tracking table to identify security violations. We use a Local DFW Event-Listener, which keeps track of all the stateful connection events, that happen on the conntrack module. The event listener can inspect if the activities are malicious or benign, and take corresponding countermeasures to mitigate the security threats. The Figure 4 shows the stepwise handling of security incidents such as TCP SYN-Flood attack. Consider the attacker located on the source IP address 10.0.0.1, sends traffic to the victim on the destination IP address 10.0.0.2, port 80 - Step (1).

The OpenFlow Table sends the packet to Conntrack Module - Step (2). The conntrack module, is responsible for creating and updating connection tracking table - CT Table - Step (1). The rule with ID ‘1’, is used by CT table to assign a state=+trk to the new connection, corresponding to the SYN packet (syn=100). Additionally, the OpenFlow module, sends back the SYN-ACK - rule ID ‘2’, to notify the attacker, about the intent for establishing the TCP connection, using response (syn=100,ack=200).

The attacker, however, instead of sending ACK=201 corresponding to the (syn=100,ack=200), sends a huge volume of networking traffic as shown using `sendp()` command above. These half-open connections, saturate the network bandwidth of victim ‘10.0.0.2’.

Local DFW-Event-Listener also receives the event-notification about the connection state from the CT Table. The module, checks the difference in the Stats column for the

### Table 1

| Field       | Description                                                                 |
|-------------|-----------------------------------------------------------------------------|
| cf_state    | State of the connection tracking module, +/- is used for specifying set, unset. Examples - +new, +established, +trk. |
| cf_zone     | Independent connection tracking context, set by action.                     |
| cf nw_src, cf nw_dst | Source and destination IP of connection.                                   |
| cf tp_src, cf tp_dst | Source and destination port of connection.                                 |
| commit      | Commit the connection to the connection tracking module.                   |

![Fig. 4. Local State Tracking and Security Analysis, TCP SYN-Flood Attack mitigation.](image-url)
rules with ID '1', and '2' (syn=100 to syn=300), in the figure above, and the absence of ACK from the attacker, which is necessary to establish the TCP full connection, and inserts a rule in OpenFlow Table - Step 5, to drop the communication from attacker corresponding to the half-open connections - rule ID '3'.

A. SDN Managed Container Environment: Case Study

The Linux Containers have gained popularity in recent times, since they allow quick provisioning of applications, and are easy to manage using the lxc daemon. We created an environment, with about 100 Linux containers of type Ubuntu:16.04 and CentOS 6, which downloads the lxc images for OS, creates the containers and assigns the IP address to containers.

```python
import lxc
import sys

def createContainers():
    for i in range(1,100):
        os.system('lxc-create -t download -n u'+str(i)+''
                    ' dist ubuntu -release bionic -arch amd64')

def setVMIP():
    for i in range(1,100):
        os.system('sudo lxc-stop —name u'+str(i)+''
                    ' daemon')

def printContainers():
    for container in lxc.list_containers(as_object=True):
        print(container.name, container.state, container.
                        get_ips(),
                        container.get_cgroup_item("memory.
                                          max_usage_in_bytes"))

createContainers()
setVMIP()
printContainers()
```

We modified the configuration files of each container to attach the containers' port to the Linux bridge 'br100', which we used for the analysis of the target environment as shown below. The 'ovsup' and 'ovsdow' scripts were utilized for attaching and detaching the containers to ovs-bridge when the container is started or stopped. The default configuration option linking the containers to Linux bridge is commented out.

```
êm config
# Distribution configuration
lxc.include = /usr/share/lxc/config/ubuntu.common.conf
lxc.arch = linux64

# Container specific configuration
lxc.rootfs = /var/lib/lxc/ul/rootfs
```

Each OpenFlow switch runs a Local DFW-Event-Listener, a python module, which keeps track of events related to stateful connections. For instance, we used TCP SYN-Flood.py module, which simulates SYN-Flood attack on the container with u2 - IP (10.0.3.102) to try and send a huge volume of traffic to container u3 - IP (10.0.3.103). With the connection tracking in place, we check the OpenFlow rules, present on the OVS-bridge br100 connecting both hosts.

```
(1) cookie=0x0, duration=355.095s, table=0, n_packets=1400, n_bytes=75600,
    nw_src=10.0.3.102, nw_dst=10.0.3.103, reset_counts
    priority=50, ct_state=trk,
tcp.in_port=vethNNE99K actions=ct(table=0)
(2) cookie=0x0, duration=492.169s, table=0, n_packets=1400, n_bytes=75600,
    nw_src=10.0.3.102, nw_dst=10.0.3.103, reset_counts
    priority=50, ct_state=new,
tcp.in_port=vethNNE99K actions=ct(commit), output:
        vethMFMXS7
(3) cookie=0x0, duration=72.178s, table=0, n_packets=0, n_bytes=0,
    nw_src=10.0.3.102, nw_dst=10.0.3.103, reset_counts
    priority=50,
    ct_state=est, tcp.in_port=vethNNE99K actions=output:
        vethMFMXS7
```

Based on the observation of flow rules, we can see that the attacker, only sends only SYN-packets, ct_state = +new - rule (2) in the output above, the field n_packets = 1400 indicates a huge volume of TCP traffic directed towards the victim. The host 10.0.3.103, sends SYN-ACK, but the attacker, doesn’t send back ‘ACK’, which can lead to state-transition, i.e., ct_state = +est, thus leading to full TCP connection. We can observe that the OpenFlow rule (3) has n_packets = 0.

\[
\frac{\text{Flow}(ct\text{\_state} = +new, n\text\_packets} = 1400)}{\text{Flow}(ct\text{\_state} = +est, n\text\_packets} = 0)} \geq \delta \quad (1)
\]
The SDFW Local DFW-Event-Listener, realizes that the threshold set for DDoS detection $\delta$ has been exceeded as shown above, and installs a new Flow rule with higher priority than the existing rule which allows TCP SYN packets, as shown below.

```bash
ovs-ofctl add-flow br100 "table=0, priority=51, nw_src=10.0.3.102,nw_dst=10.0.3.103,tcp actions=drop"
```

The malicious devices can also send a connection request to the switching software in the data plane. If the switch consists of flow rule entry corresponding to the traffic pattern, traffic is forwarded out of the specific switch port. If the entry is missing (table-miss packets) the request is sent to the controller. A class of DoS attacks - data to control plane saturation attacks as discussed by Gao et al [10] can forge the OpenFlow fields with random values, that will lead to table-miss event in the switch. When a large volume of forged table-miss flows is sent to the controller as packet_in messages will consume a large amount of switch-controller bandwidth and controller resources (CPU, memory). SDFW helps in the detection and mitigation of such attacks using state-based traffic analytics as discussed in the case study above.

V. IMPLEMENTATION AND EVALUATION

A. Experimental Setup

We utilized an OpenStack based cloud network comprising of two Dell R620 servers and two Dell R710 servers all hosted in the data center. Each Dell server has about 128 GB of RAM and 16 core CPU. The SDN controller OpenDaylight-Carbon was provided network management and orchestration in our framework.

| Component                      | LOC/Version | Language / Framework       |
|--------------------------------|-------------|-----------------------------|
| SDN Controller                 | OpenDaylight Carbon | Java, REST APIs |
| Local DFW-Event-Listener       | 500         | python                      |
| Policy-Graph                   | 500         | python with Flask APIs      |
| Flow Conflict Analyzer         | 700         | python, networkx            |
| Flow-Visualizer                | 250         | python, d3, REST APIs       |
| Data-Plane                     | 200         | Linux container, LXC-3.0    |
| Frontend/UI                    | 400         | php-lavarel                 |

TABLE II

SDFW COMPONENTS USED IN IMPLEMENTATION

In addition to these components - Table II, we used the latest version of Open vSwitch (OVS 2.9.0), with conntrack module enabled to support the data plane connection tracking.

B. SDFW Scalability Analysis

We conducted a scalability analysis to check the performance of SDFW when handling the TCP-SYN Flood attack. We conducted two separate experiments, one on a single switch topology, and one on a tree topology.

Flat Topology: We utilized python script to run DDoS script from host H1 - 10.0.3.1 to perform TCP SYN-Flood on host H100 (10.0.3.100) - Figure 5(a). The experimental results show that once attack pattern is detected by SDFW, the attack-mitigation is enforced using OpenFlow rule on corresponding OpenFlow switch. We have currently utilized countermeasure to `DROP' traffic flows for malicious traffic pattern, however other possible countermeasures include 'Rate-Limiting' the traffic flow, or redirecting to a honeypot for performing fine-grained packet analysis.

Tree Topology: We conducted a scalability analysis to check the performance of SDFW when handling the TCP-SYN Flood attack. We conducted two separate experiments, one on a single switch topology, and one on a tree topology.

Fig. 5. SDFW Scalability Analysis Experiment

The experimental results - Table III show that there is an 11% drop in the network bandwidth - from when using SDFW, and 9% increase in the latency, i.e., from 8.76 ms to 9.66 ms when utilizing SDFW to inspect the connection state of network hosts. The drop in performance can be attributed to the fact that a single switch is receiving requests from about 100 hosts, and connection state of each host is analyzed using connection tracking module.

Table III

| Hosts | BW-No SDFW (Gb/s) | BW-SDFW (Gb/s) | Latency-No SDFW (ms) | Latency-SDFW (ms) |
|-------|-------------------|---------------|----------------------|-------------------|
| 100   | 42.96             | 37.6          | 8.76                 | 9.66              |

The benefit of distributed firewall can be realized in a network having multiple switches, where each switch can locally track events from the hosts connected directly. We created a tree topology, with depth=2, fanout=8 in second experiment - Figure 5(b).
The experiment results - Table [VI] show that in a network, with each switch checking attack-pattern for DDoS locally, then we have limited drop in performance. The bandwidth is reduced from 35.9 Gb/s to 35.4 Gb/s ∼ 1.6% drop, which is acceptable for a moderate size network. Similarly, the network latency increases from 8.87 ms to 9.2 ms, when using SDFW for detecting the SYN-Flood attack, a ∼ 3.5% increase. This gain in performance can be attributed to the fact, that benefit of distributed firewall implementation is obtained when multiple switches are involved. The experiments prove that, in comparison to a centralized firewall model, the distributed stateful-firewall is able to scale well on a large network.

VI. RELATED WORK

Distributed Stateful-SDN Security is required to deal with attacks originating in SDN data-pane, as discussed by Bosshart et al [16]. The most relevant work to ours is what Openstate [17] extended the OpenFlow switch to define a state-transition variable and extended finite-state-machine (XFSM) table, which is able to handle scenarios such as port knocking and TCP SYN-ACK message verification. The design is however based on centralized firewall architecture. The SDFW presented in this paper captures the recommendations defined in NIST 800-125b [18] for protecting workloads within the data-center using next-generation distributed firewall (NDFW) model. Onix [19] uses distributed control plane design for SDN environment. We have used similar design principles for SDFW such as distributed virtual switch and network information base (NIB). P4 [20] is programming language which allows, protocol independent packet processing, and stateful packet inspection. We plan to extend the current work and develop a programming platform based on distributed firewall architecture.

VII. CONCLUSION AND FUTURE WORK

In this paper, we address the issue of security issues associated with lateral movement of attacker along the east-west plane in a data center, and packet flooding based data plane attacks. One limitation of this work is that we utilize SDFW to showcase defense against layer 4 security attacks. However, a next-generation firewall can also act as an application firewall and Deep-Packet-Inspection (DPI) module. As a part of future work, we plan to extend SDFW and address security attacks at the application layer.

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TABLE IV

| Hosts | BW-No-SDFW (Gb/s) | BW-SDFW (Gb/s) | Latency-No-SDFW (ms) | Latency-SDFW (ms) |
|-------|------------------|---------------|---------------------|------------------|
| 64    | 35.9             | 35.3          | 8.87                | 9.2              |

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The experiment results - Table [V] show that in a network, with each switch checking attack-pattern for DDoS locally, then we have limited drop in performance. The bandwidth is reduced from 35.9 Gb/s to 35.4 Gb/s ∼ 1.6% drop, which is acceptable for a moderate size network. Similarly, the network latency increases from 8.87 ms to 9.2 ms, when using SDFW for detecting the SYN-Flood attack, a ∼ 3.5% increase. This gain in performance can be attributed to the fact, that benefit of distributed firewall implementation is obtained when multiple switches are involved. The experiments prove that, in comparison to a centralized firewall model, the distributed stateful-firewall is able to scale well on a large network.

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