Mitigating the Table-Overflow Attack in Software-Defined Networking

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Abstract—Software-defined networking (SDN) is a promising network paradigm for future Internet. The centralized controller and simplified switches replace the traditional complex forwarding devices, and make network management convenient. However, the switches in SDN currently have limited ternary content addressable memory to store specific routing rules from the controller. This bottleneck provokes cyber attacks to overload the switches. Despite existing some countermeasures for such attacks, they are proposed based on simplified attack patterns. In this paper, we review the table-overflow attack using a sophisticated attack pattern. In the attack pattern, attack flows are targeted at their middle hops instead of endpoints. We first define potential targets in the network topology, then we propose three specific traffic features and a monitoring mechanism to detect and locate the attackers. Further, we propose a mitigation mechanism to limit the attack rate using the token bucket model. With the control of token add rate and bucket capacity, it avoids the table overflow on the victim switch. Extensive simulations in different types of topologies and experiments in our testbed are provided to show the performance of our proposal.

Index Terms—Software-defined networking, OpenFlow, communication system security, table-overflow attack.

I. INTRODUCTION

SOFTWARE-DEFINED Networking (SDN) is considered as one promising next generation network architecture because of its high flexibility in network management. Many companies, such as Google and Amazon, have deployed SDN devices in their backbone and data center [1], [2]. The key concept of SDN lies in the decoupling of the data plane and the control plane [3]. In SDN, the switches are free from rigid routing computation and can be focused on packet forwarding. The centralized controller now is in charge of the routing rule computation and assignment.

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Since the switches become highly primitive, the assigned routing rules from the controller are expected to be precise. Currently, OpenFlow [4] is the most widely used control link protocol owing to its fine-grained routing rules (i.e., flow entries) and abundant flow statistics. To support OpenFlow protocol better, the switches have to use ternary content addressable memory (TCAM) to store flow entries. However, considering the high cost and highpower consumption [5], the current OpenFlow-enabled switches usually have limited flow table, which supports a few thousand flow entries [6], [7]. For example, without the external TCAM, the NoviSwitch 2150 [8] can only store 16,384 flow entries.

As a result, how to use such limited cache efficiently and safely has been an active field of research. To help the switches store more flow entries without adding TCAMs, several proposals attempt to split the workload between the switches [9], [10] or aggregate redundant flow entries [11], [12]. Although these proposals are useful for normal users, they could be inefficient when attackers attempt to exhaust the switches. We call such attacks the table-overflow attack in this paper. Many recent studies [13]–[15] have paid attention to the table-over flow attack due to its significant negative impact, including higher energy consumption, flow table overflow and normal communication breakdown.

While the awareness of the table-overflow attack has been raised, existing studies [13]–[17], [32] mainly consider the attack with simplified attack patterns. In the simplified attack patterns, only one or a few attackers attempt to overload a target switch using lots of unmatched attack flows. Moreover, the table-overflow attackers are assumed to be brute-force. It means that, the attackers choose their common ingress or egress (physically attached) switch as the target. Based on the simplified cases, a few security suggestions and countermeasures [18], [32] are proposed in the literature.

However, in the real world operation, a sophisticated attack pattern is more attractive to the cyber attackers. In the sophisticated attack pattern, a group of attackers launch the table-overflow attack to a same target switch. And the target switch is a middle hop switch instead of their physically attached switches. Since when attackers launch the table-overflow attack to their physically attached switch, they risk exposing themselves. Besides, the flow table consumption on the target switch (we call these consumption the attack payment) causes the same amount of flow table consumption on their physically attached switches (we call these consumption the attack cost). Therefore, the table-overflow attack is more

likely to be launched by a group of attackers with the purpose of splitting the attack cost on their physically attached switches and hiding themselves.

In the sophisticated attack pattern, the attackers tend to choose a hot switch which has fewer vacancies in the flow table as the target switch. Their attack flows use the target switch as the middle hop instead of the endpoints, because when lots of abnormal flows share the same traffic feature, such as the destination IP, these flows trigger an alarm in the existing security mechanisms [18], [19]. To identify a hot switch, an attacker may seek to use some common social engineering attacks to the network manager, or use route trace tools, or even invade the central controller to obtain the network topology to locate a hot switch.

Knowing the basic characteristics of the sophisticated table-overflow attack, the objective of our work is to defend against it in SDN. Given an SDN topology, we first build a mathematical model to formulate the flow table consumption and the attack. Based on it, we define the potential targets. Then we propose three traffic features and a monitoring mechanism to detect the table-overflow attack and locate the attackers. Further, we propose a mitigation mechanism to limit the rate of attack flows using the token bucket model. It controls the token add rate and the bucket capacity with the consideration of the current flow table vacancy on the victim switch. Both the monitoring and mitigation mechanisms are embedded into the original routing process of SDN. Extensive simulations and experiments are conducted to evaluate our proposal. Here we summarize the main contributions of this paper.

- Most of the related studies investigate the table-overflow attack using simplified attack patterns. In this work, we consider a sophisticated attack pattern and propose a countermeasure to the sophisticated table-overflow attack.
- We build a practical mathematical model to formulate the flow table consumption and the attack. We provide a way to define the potential targets of the table-overflow attack.
- Three specific traffic features and a monitoring mechanism are proposed during the original routing process of SDN. It detects the attack and locates the attacker attached switches.
- A mitigation mechanism is proposed using the token bucket model. Given the current flow table vacancy on the victim switch, it limits the rate of attack flows and avoids the table overflow under different attack rates.

The rest of the paper is organized as follows. Some related work is introduced in Section II. The basic concept of SDN and the table-overflow attack is provided in Section III. In Section IV, we build the mathematical model to formulate the flow table consumption and the table-overflow attack. The monitoring mechanism and the mitigation mechanism are proposed in Sections V and VI, respectively. In Section VII, we show the simulation and experiment results of our proposal. Finally, we conclude this paper in Section VIII.

II. RELATED WORK

In this section, we introduce some related work about the table overflow problem of SDN.

A. Table Overflow Avoidance Under Normal Circumstances

For SDN-enabled switch vendors, such as NoviFlow [8] and Pica8 [20], the only mature way to store more flow entries seems to be adding the number of TCAMs. In the literature, to find a better solution, the existing studies mainly go along two directions, i.e., heterogeneous flow entry and cache optimization.

The key concept of heterogeneous flow entry approaches is that not all arrived flows need an individual wildcard flow entry stored in TCAM. For example, DevoFlow [21] classifies flows into two types: the transient mice flow and the persistent elephant flow. It clones the mice flow's packet header to create an exact-match flow entry. Then the exact-match flow entry can be moved from TCAM to RAM. Similarly, Nguyen *et al.* [22] only assign specific rules to the elephant flows, the mice flows are handled by the default rules in switches. CacheFlow [23] only stores the most popular rules in a small TCAM. The rest of rules are cached in software switches using RAM. The rules stored in TCAM have a higher priority than the rules stored in RAM.

Besides, Banerjee and Kannan [24] propose Tag-In-Tag based on their former study about TCAM [5]. They utilize a combination of path tag and flow tag (24 bits in total) instead of the original flow entry (356 bits in total) to match a flow. The path tag exploits the path similarity between different flows. Likely, Huang *et al.* [25] divide flow entries into the universal rules and the local rules. They conduct different partition and allocation algorithms for different kinds of flow entries. In this way, these proposals reduce redundant rules in switches.

In contrast, the key concept of cache optimization approaches is that not all cached flow entries in TCAM need to follow a same and rigid update mechanism. For example, SmartTime [26] sets the idle timeout dynamically according to its observation of the repeated flow and the real time TCAM occupation. It aims to improve the utilization of TCAM (i.e., use a smaller idle timeout) while ensuring that TCAM miss does not increase (i.e., fewer flows are repeated). Similarly, MWFP [27] adjusts the idle timeout of flows with the consideration of the average interval between packets. It reduces the TCAM updates by setting a bigger idle timeout for the long-distance and unstable flow.

Besides, FDRC [28] aims at fine-grained cache management. It sets a timer for each flow entry to estimate the time of next hit. The rarely hit rules have a larger timer value and will be evicted once TCAM is full. Likely, MMS [29] cleans the rarely used or obsolete flow entries. It resides in the SDN controller and monitors the activity of applications. To free TCAM in the switches, MMS evicts the flow entries once their applications in the controller are terminated.

B. Table Overflow Avoidance Under DoS Attacks

The aforementioned proposals improve the accommodation of flow entries in SDN, however they are inefficient to handle malicious flows from cyber attackers. It has been proven that the limited flow table space can be easily exhausted by table-overflow attackers [16], [17]. To deal with such security issues, several mechanisms are proposed recently.

Fig. 1. SDN's routing process: global network view establishment, routing rule calculation and routing rule assignment.

TABLE I
THE CAPACITIES OF MOST USED SWITCHES

Context	Capacity
Commercial switches [6, 20]	2,000~8,000
OpenvSwitch [33]	15,000~20,000
NoviSwitch 2150 [8]	16,384
NoviSwitch 2128, 2122, 1248 [8]	1,000,000
Simulation settings in related studies [16, 32]	1,500~8,000

During this routing process, the new arrived flow not only leads to flow entry installations on its ingress switch S_{src} and egress switch S_{dst} , but also on the middle hop (logically attached) switch S_{mid} .

B. The Table-Overflow Attack in SDN

Currently, the switches in OpenFlow-based SDN usually have limited cache for flow entries. Table I shows the cache sizes of different OpenFlow-enabled switches. We can see that the OpenFlow-enabled switch generally can hold a few thousands of flow entries. Such bottleneck provokes cyber attackers to overload the switches. By generating lots of unmatched flows in a short time, the attackers trick the controller into assigning flow entries to a target switch intensively. Once the cache of the target switch is full of these flow entries, the target switch will be paralysed and the legitimated flows will be delayed or even dropped.

We note that the NoviSwitch 2128, 2122 and 1248 can support 1 million of flow entries using large TCAMs. Such amount of cache definitely can withstand most of the table-overflow attack in the simplified model [13]–[17], [32]. In the simplified attack model, the attack flows use the target switch as their ingress or egress in their routing paths, e.g., S_{src} or S_{dst} in Fig. 1. Such attack flows can be easily aggregated by the target switch according to their common ingress or egress. Unless the brute-force attacker targets a switch with fewer vacancies in the cache, the attacker has to generate attack flows at a very high rate.

However, in the sophisticated attack model, the attack flows use the target switch as their middle hop in their routing paths, e.g., S_{mid} in Fig. 1. Using different paths with a same middle hop, the attackers can accumulate useless flow entries on the middle hop. In the real world operation, the switch serves as a middle hop frequently in the network. This makes lots of available routing paths for the attackers. More importantly, such attack flows are difficult to be aggregated according to their common middle hop. To overflow a switch using large TCAMs, the sophisticated attack can utilize more routing paths and share the attack cost accordingly.

Besides, adding the number of TCAMs in the switch is an efficient way to improve the reliability of switch but not security. Especially for the sophisticated table-overflow attackers, adding cache may provoke more intense attacks. Therefore, the motivation of this paper is to keep the limited or finite cache from the sophisticated attackers.

IV. SYSTEM MODEL AND PROBLEM DESCRIPTION

In this section, we build a mathematical model to formulate the above mentioned table-overflow attack. When switches

AVANT-GUARD [30] is a security mechanism embedded in the SDN-enabled switches. It consists of a connection migration module and an actuating trigger module. The connection migration module is designed to monitor TCP session failures. The actuating trigger module is used to activate several predefined routing rules when lots of TCP session failures are observed. In this way, it protects the controller and switches from the SYN flooding attack.

Dong *et al.* [31] propose a detection method for the DDoS attack to the controller and switches. Such a DDoS attack utilizes a large number of low-traffic flows to exhaust SDN's routing system. The low-traffic flows have fewer packets than the normal flows, and they can lead to significant resources consumption in both the data plane and the control plane. In the proposal, the authors use SPRT (Sequential Probability Ratio Test) to control the false negative and false positive rates.

The most related work to this paper is the QoS-aware mitigation strategy [32]. It prepares the idle flow table resources in the data plane for the table-overflow attack. By redirecting attack flows from saturated switches to idle switches, it makes SDN more resilience to such an attack. However, since the redirection action cannot limit the attack rate, its performance relies on the amount of idle flow table resources, and it may be unsatisfactory when there are no adequate idle switches or the attack rate is high. Moreover, the effectiveness of this approach relies on the identification of the attack. Since the authors did not provide a proper attack monitoring method, the effectiveness of their proposed solution is somewhat limited.

III. PRELIMINARY KNOWLEDGE

In this section, we introduce the original routing process of OpenFlow-based SDN and the table-overflow attack.

A. The Routing Process of OpenFlow-Based SDN

According to OpenFlow protocol, the SDN-enabled switch has to register its configuration and status before it can forward packets in the network. During this process, the controller builds a topology of the entire network. As shown in Fig. 1, when an unmatched flow arrives at S_{src} , S_{src} sends a request to the controller. Then the controller traces the endpoint S_{dst} and finds the middle hop S_{mid} in the established topology. To make sure that the arrived flow is continuously transmitted, all switches in the routing path have to install a flow entry.

Fig. 2. Classification of the flow table consumption.

finish their registration, the global view in the network controller can be viewed as an undirected and unweighted graph $G = (S, L)$, where S represents the switch set and L is the physical link set. We use N to denote the number of switches. Then we formulate the flow table consumption in a discrete time model, where the time horizon consists of a series of time slots. We use l to denote the length of the time slot.

During a time slot t , the flow entries assigned to S_i are viewed as a set R_i^t . Then we define the flow table consumption of S_i in time slot t as

$$C_i(t) = \text{card}(R_i^t), \quad (1)$$

where $\text{card}(R_i^t)$ is the cardinality of set R_i^t . To give a further view of $C_i(t)$, we divide R_i^t into two parts: the local flow used set $R_i^{t,L}$ and the foreign flow used set $R_i^{t,F}$. The local flow of S_i uses S_i as the ingress or egress switch, the foreign flow of S_i uses S_i as the middle hop. For example, as shown in Fig. 2, the users' flow is a local flow for S_1 and S_4 , and it is a foreign flow for S_2 and S_3 . It is obvious that $R_i^{t,L}$ and $R_i^{t,F}$ have the following properties:

$$\begin{cases} R_i^{t,L} \cup R_i^{t,F} = R_i^t \\ R_i^{t,L} \cap R_i^{t,F} = \emptyset. \end{cases} \quad (2)$$

Then we define the local flow consumption (i.e., $C_i^L(t)$) and the foreign flow consumption (i.e., $C_i^F(t)$) as

$$\begin{cases} C_i^L(t) = \text{card}(R_i^{t,L}) \\ C_i^F(t) = \text{card}(R_i^{t,F}). \end{cases} \quad (3)$$

Therefore, the flow table consumption $C_i(t)$ is

$$C_i(t) = C_i^L(t) + C_i^F(t). \quad (4)$$

We use $\langle S_i \cdot S_j \rangle$ to denote the routing path between S_i and S_j (flows from S_i to S_i are not considered in this paper). For the normal flows on the path, we formulate them as the generally used Poisson process [32]. Considering the fact that different paths have different amount of traffic. We use $\lambda_{i,j}$ to denote the unmatched flow arrival rate of path $\langle S_i \cdot S_j \rangle$ and set it randomly for different paths. All symbols and variables used in this paper are summarized in Table II.

When the table-overflow attackers choose S_i as the target switch, they generate flows on different paths which include S_i as the middle hop. These attack flows lead to a huge foreign flow consumption $C_i^F(t)$ during the attack.

TABLE II
VARIABLES AND NOTIONS

Notations	Description
G	Undirected and unweight graph, $G = (S, L)$. S is the SDN-enabled switch set, $S = \{S_i i = 1, 2, \dots, N\}$, L is the physical link set
$\text{card}(A)$	The cardinality of set A, e.g. $\text{card}(\{1, 2, 3, 5\}) = 4$
$\mathbb{P}$	The probability
$\mathbb{E}$	The mathematical expectation
D_i	Degree of S_i
d_i	Virtual degree of S_i , i.e. the number of paths which include S_i as the middle hop
l	Length of each time slot, e.g. time slot t
R_i^t	Set of flow entries assigned to S_i during time slot t
$R_i^{t,L}$	Flow entries for local flows in R_i^t
$R_i^{t,F}$	Flow entries for foreign flows in R_i^t
$C_i(t)$	Flow table consumption of S_i in time slot t
$C_i^L(t)$	Local flow consumption of S_i in time slot t
$C_i^F(t)$	Foreign flow consumption of S_i in time slot t
$\langle S_i \cdot S_j \rangle$	The routing path between S_i and S_j
$\lambda_{i,j}$	Flow arrival rate of path $\langle S_i \cdot S_j \rangle$
λ_p	Flow arrival rate of path $\langle S_i \cdot S_j \rangle$ in the simplified traffic model
$\lambda_i^{F,j}$	The arrival rate of flows which use S_i as the middle hop and S_j as the ingress or egress
λ_i^F	Foreign flow arrival rate of S_i , $\lambda_i^F = \sum_{S_j \in S, j \neq i} \lambda_i^{F,j}$
λ_i^L	Local flow arrival rate of S_i , $\lambda_i^L = \sum_{S_j \in S, j \neq i} \lambda_{i,j}$
λ_i	Flow arrival rate of S_i , $\lambda_i = \lambda_i^F + \lambda_i^L$
λ_G	Flow arrival rate of G , $\lambda_G = \sum \lambda_{i,j}$

However, not all switches are attractive for attackers. As shown in Fig. 2, the instinct of the attackers makes them choose a hot switch (e.g., S_2) instead of S_1 as the target, since S_2 is responsible for more normal flows and has fewer vacancies than S_1 . Therefore, before we monitor and further mitigate the table-overflow attack, we should identify the potential targets in a given graph G .

V. MONITORING THE TABLE-OVERFLOW ATTACK

In this section, we first define the potential targets according to their common feature. Then we design three traffic features to monitor the attack for the potential targets. Finally, we show how our monitoring mechanism is embedded into the routing process of SDN.

A. Definition of Potential Targets

To find potential targets in a given graph G , we can first exclude some switches that are secure from the table-overflow attack. Since the attackers generate attack flows on different paths which include the target as the middle hop. Switches that only act as the ingress or egress are not the candidate of potential target. For example, as the graph G shown in Fig. 3(a), S_1 , S_4 and S_5 are not middle hops in any routing paths in G , and their foreign flow consumption $C_i^F(t) \equiv 0$ since their degree $D_i = 1$. Therefore, we select potential targets from switches which satisfy $D_i > 1$.

We use Algorithm 1 to build virtual graphs for switches with $D_i > 1$. As shown in Fig. 3(b) and Fig. 3(c), each virtual graph consists of a central switch S_i and several virtual neighbors. The virtual neighbors are the paths in graph G , which include the central switch as the middle hop. When flows traverse in

Fig. 3. An example of building virtual graphs using G , in the virtual graphs, the paths in G represent virtual neighbors.

Algorithm 1: Building Virtual Graphs

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Input: graph  $G$ 
Output: virtual graphs
 $S_{target} = \emptyset$   $PathInG = \emptyset$   $VirtualNeighbor_i = \emptyset$   $d_i = 0$ ;
for each pair of switches  $(S_x, S_y)$  do
     $\langle S_x, S_y \rangle = ShortestPath(S_x, S_y)$ ;
     $PathInG = PathInG \cup \langle S_x, S_y \rangle$ ;
end
for  $i = 1; i \leq N; i++$  do
    if  $D_i = 1$  then
         $\mathbb{E}[C_i^F(t)] = 0$ ;
    end
    if  $D_i > 1$  then
        while all paths in  $PathInG$  are checked  $\neq true$  do
            if  $S_i \cap \langle S_x, S_y \rangle \neq \emptyset$  &&  $S_i$  is the middle hop then
                 $d_i = d_i + 1$ ;
                 $VirtualNeighbor_i = VirtualNeighbor_i \cup \langle S_x, S_y \rangle$ ;
            end
        end
    end
end

```

graph G , the controller finds the shortest (in terms of hop, delay or some commercial cost) path between its ingress and egress switches. In this paper, the least number of hops is the shortest path. Then we use d_i to denote the virtual degree of S_i , and the virtual degrees of S_2 and S_3 are 3 and 5, respectively. Then the question becomes whether we can simply treat all switches with $D_i > 1$ as the potential targets in G . For small scale graphs, this definition may be workable since there are a few switches in the topology. While for large scale graphs this is not sufficient and can lead to lots of potential targets. Meanwhile, it should be note that, the virtual neighbors of the switch with small d_i may also belong to the switch with large d_i . For example, in Fig. 3(b) and Fig. 3(c), two thirds of the S_2 's virtual neighbors are also belong to S_3 . It indicates that, for large scale graphs, even attackers try to overload a switch with small d_i , some switches with large d_i are also involved into the attack. And due to the fact that switches with large d_i usually has fewer flow table vacancy than the ones with small d_i , switches with large d_i will be overloaded first.

It's obviously hard to draw a clear line between switches with large d_i and small d_i , and make sure switches with small

d_i will not exhausted before the rest under any rates of table-overflow attacks.

Therefore, we narrow the range of potential targets with the consideration of a simplified traffic model in graph G . In this simplified traffic model, each path has the same flow arrival rate λ_p . It should be noted that we do not use this model to monitor the table-overflow attack, what we do is to provide a possible way to narrow the range of potential targets in graph G . Then the expected local flow consumption during a single time slot is

$$\mathbb{E}[C_i^L(t)] = (N-1)\lambda_p l. \quad (5)$$

And the expected foreign flow consumption during a single time slot is

$$\mathbb{E}[C_i^F(t)] = \begin{cases} 0, & D_i = 1 \\ d_i \lambda_p l, & D_i > 1 \end{cases} \quad (6)$$

according to (3). To define the potential targets, we use the foreign-local ratio as following,

$$\frac{\mathbb{E}[C_i^F(t)]}{\mathbb{E}[C_i^L(t)]} = \frac{d_i \lambda_p l}{(N-1)\lambda_p l} = \frac{d_i}{N-1}. \quad (7)$$

It reflects the topology feature of S_i in graph G . When the foreign-local ratio is bigger than 1, i.e., $d_i > (N-1)$, switch S_i has more paths for its foreign flows than its local flows, and it may have less flow table space than the rest switches. In this paper, we denote the switch with $d_i > (N-1)$ as the potential target. For example, as shown in Fig. 3, S_3 is the potential target while the rest switches are not. As discussed, its hard to draw a clear line between switches with large d_i and small d_i , we do not indicate that switches with $d_i \leq (N-1)$ (like S_2 in Fig. 3) are free from the table-overflow attack. In contrast, we believe that some of the excluded switches can be added as the potential targets by other definitions with different viewpoints. And as for the numerous switches with $d_i \leq (N-1)$, the passive detection method [34] can be a more proper way to monitor the table-overflow attack.

B. Traffic Features

Knowing the potential targets, we propose the following traffic features to monitor the attack: growth of foreign flow consumption ($GFFC$), deviation of flow amount (DFA) and commonness of flow entry (CFE).

1) *Growth of Foreign Flow Consumption (GFFC)*: Although the attackers can hide themselves by splitting the attack cost, to exhaust the flow table in the target switch S_i , the attack payment $C_i^F(t)$ must be noteworthy. Therefore, $GFFC$ is defined as

$$GFFC_i(t) = \frac{C_i^F(t)}{l} = \frac{card(R_i^{t,F})}{l}. \quad (8)$$

During the table-overflow attack, $GFFC_i(t)$ increases linearly with the attack rate. A larger $GFFC_i(t)$ indicates a burst of foreign flow consumption in S_i .

2) *Deviation of Flow Amount (DFA)*: The burst of foreign flow consumption may also be caused by a sudden increase of normal flows. In order to differentiate the table-overflow attack

from the normal flow burst, we propose *DFA*. The burst normal flows are usually related to special events, such as popular live matches and sudden news. These flows from distributed users rarely share the same middle hop in the network. In contrast, the attack flows have a strong directionality, they are clustered at the d_i paths of the target switch. Therefore, *DFA* is defined as

$$DFA_i(t) = \frac{\mathbb{P}\{FA_{d_i} = \text{card}(R_i^{t,F})\}}{\mathbb{P}\{FA_G = \frac{1}{2} \sum_{i=1}^N \text{card}(R_i^{t,L})\}}, \quad (9)$$

where variable FA_{d_i} and variable FA_G represent the arrived flow amount of the d_i paths and the whole network in time slot t , respectively. We use λ_i^F and λ_G to denote the flow arrival rate of the d_i paths and the whole network, then variable FA_{d_i} follows $Poisson(\lambda_i^F l)$ and variable FA_G follows $Poisson(\lambda_G l)$. During the table-overflow attack, all the burst attack flows are clustered at the d_i paths, and they make $DFA_i(t)$ decrease greatly. During the normal flow burst, only part of the burst flows are accidentally clustered at the d_i paths, and they make $DFA_i(t)$ change slightly.

3) *Commonness of Flow Entry (CFE)*: To locate the attackers, we measure the switches presented in the virtual graph using *CFE*. When S_j is the attacker attached switch and S_i is the target, the number of common flow entries between $R_j^{t,L}$ and $R_i^{t,F}$ increases greatly. Therefore, *CFE* is defined as

$$CFE_j(t) = \frac{\text{card}(R_j^{t,L} \cap R_i^{t,F})}{\lambda_i^{F,j} l}, \quad (10)$$

where $R_j^{t,L} \cap R_i^{t,F}$ represents the common flow entries between S_i and S_j . We use $\lambda_i^{F,j}$ to denote the arrival rate of unmatched flows that use S_j as the ingress of egress and S_i as the middle hop. Then $\lambda_i^{F,j} l$ is the expected number of common flow entries in $R_j^{t,L} \cap R_i^{t,F}$. During the table-overflow attack, since the attacker sends lots of flows through its physically connected switch S_j , these attack flows can make $CFE_j(t)$ increase greatly and become larger comparing with the normal switches.

C. Embedding the Monitoring Mechanism

To make our traffic features practical and meaningful, we propose a monitoring mechanism which can be embedded into the original routing process of SDN. Considering the fact that the control link of SDN is limited and unsuitable for heavy statistics applications [35], our monitoring mechanism utilizes the existing interactions between the switches and the controller as shown in Fig. 4.

When SDN-enabled switches finish their registrations, our monitoring mechanism views the established topology in the controller as the graph $G = (S, L)$. Using Algorithm 1, the potential targets in G can be identified. During this step, the controller gets the λ_i^F , λ_G and $\lambda_i^{F,j}$ according to the flow arrival rate $\lambda_{i,j}$ of each path and the network topology. Next, for example S_{mid} is a potential target and an unmatched flow uses S_{mid} as the middle hop in its flow path, after the controller assigns the flow entries to each hop, the monitoring mechanism updates the local flow consumptions of S_{src} and S_{dst}

Fig. 4. Embedded monitoring steps in the SDN routing process.

and the foreign flow consumption of S_{mid} . Based on this, our proposed traffic features can be calculated without getting data plane statistics from the SDN-enabled switches. With enough traffic feature samples under normal circumstances and table-overflow attacks, our monitoring mechanism can recognize such an attack and locate the attacker attached switches.

VI. MITIGATE THE TABLE-OVERFLOW ATTACK

In this section, we propose a mitigation mechanism for the table-overflow attack using the token bucket model. Our mitigation mechanism aims to keep the user's transmission rate while limiting the attacker's transmission rate.

A. Flow Entry Token Bucket

The classic token bucket is a model used to control the packets' average transmission rate and burstiness in computer networks. In that model, the token is added into the bucket at a fixed rate and the bucket has finite capacity. When a packet is transmitted, a token is removed from the bucket. Therefore, the token add rate decides the average transmission rate of packets and the bucket capacity determines the burstiness of the packet transmission.

Given the location of attacker by our monitoring mechanism, we build an FETB (flow entry token bucket) for the attacker attached switch to limit its transmission rate of attack flows. When a flow from the attacker attached switch tries to use the victim switch as the middle hop, a token is removed from the FETB. To control the average transmission rate of the attack flows, the fixed token add rate (denoted by *TAR*) is defined as

$$TAR = \lambda_i^{F,j}, \quad (11)$$

when S_i is the victim switch and S_j is the attacker attached switch.

Meanwhile, we set the bucket capacity (denoted by *BC*) with the consideration of the current flow table vacancy on the victim switch. It should be noted that, given *BC* and *TAR*, the attack time (denoted by *T*) and the attack rate (denoted by *AR*) satisfy that

$$T = \frac{BC}{AR - TAR}, \quad AR > TAR. \quad (12)$$

Fig. 5. The working process of the flow entry token bucket.

Since the attacker always sends non-repeating unmatched packets, the flow entries for the attack flows are removed by the idle timeout. Denoting the idle timeout value as IT , we can calculate the maximum table consumption of the attack (denoted as MTC) by

$$MTC = \begin{cases} T \cdot AR + (IT - T) \cdot TAR = BC + IT \cdot TAR, & T < IT \quad (\Leftrightarrow AR > \frac{BC}{IT} + TAR); \\ IT \cdot AR, & T \geq IT \quad (\Leftrightarrow \frac{BC}{IT} + TAR \geq AR > TAR). \end{cases} \quad (13)$$

For different attack rates, we note that the maximum value of MTC is $(BC + IT \cdot TAR)$. Since the current flow table vacancy (denoted by FTV) on the victim switch can be acquired by the controller using the Controller-to-Switches Messages [4], and the attacker attached switch's proportion is $\frac{\lambda_i^{F,j}}{\lambda_i}$, to prevent the attacker overloads the victim switch, the maximum value of MTC should satisfy

$$BC + IT \cdot TAR \leq FTV \frac{\lambda_i^{F,j}}{\lambda_i}. \quad (14)$$

Therefore, the bucket capacity of the FETB is

$$BC = \lambda_i^{F,j} \left(\frac{FTV}{\lambda_i} - IT \right). \quad (15)$$

B. Embedding the Mitigation Mechanism

To make our work practical, we embed the mitigation mechanism into the original routing process of SDN shown Section III. As the example shown in Fig. 5, when the monitoring mechanism detects a table-overflow attack against S_{mid} and locates the attacker at S_{attack} , it activates the mitigation mechanism. The mitigation mechanism uses the Controller-to-Switch Messages [4] to make sure the current FTV of S_{mid} . Based on this, the FETB for S_{attack} is established, and its BC and TAR can be calculated according to (15) and (11).

After this, when a flow from S_{attack} tries to use S_{mid} as the middle hop, S_{attack} sends the routing request to controller. The controller removes a token from the FETB and assigns routing rules to each switch in the flow path. If there are no tokens in the FETB, the flow is cached or discarded at S_{attack} . Since the burstiness in the FETB model is determined by BC , and we

have set BC with the consideration of the current flow table vacancy, the transmission rate of attack flows can be limited at S_{attack} . In contrast, the flow from S_{normal} can be transmitted without a token.

However, attackers may repeat their attack flows in time to avoid attack flows being evicted by the idle timeout. In this case, despite limiting the attack rate at S_{attack} , the fixed token add rate may let the attackers occupy the victim switch slowly. Therefore, we use a dynamic token add rate, once the number of flow entries caused by the attacker attached switch exceeds their expected value $FTV \frac{\lambda_i^{F,j}}{\lambda_i}$. The token add rate is determined by the rate of Flow Removed Message [4] from S_i . When a flow from the attacker attached switch is finished at S_i , its Flow Removed Message from S_i makes a token added into the bucket. In this way, FETB protects the switch against such repeated attack flows.

VII. SIMULATION AND RESULT

In this section, we first present simulations to demonstrate the performance of our monitoring mechanism in WAN, LAN and data center scenarios. Then we present experiments in our testbed to demonstrate the performance of our mitigation mechanism for the table-overflow attack.

A. Monitoring the Table-Overflow Attack

1) *Simulation Scenarios and Key Parameters:* In this paper we perform our simulation over three typical types of SDN application scenarios: WAN, LAN and data center. For the WAN scenario, we study the recent simulation instance of software defined WAN [36] and utilize the Barabasi-Albert (BA) model [37] to build the network topologies with the property of scale free. For the LAN scenario, we adopt the real router-level dataset from CAIDA [38]. The dataset is computed by the Internet Topology Data Kit (ITDK) under LAN router-level topologies. For the data center, we utilize the BCube(n, k) model [39] to build the network topologies, where n means the port number of each switch and k means the recursion times. In the BCube model, both switches and servers are able to forward flows while only servers are the endpoints of paths. Users or attackers are only connected with or reside in servers.

We build different scales of topologies for each type of simulation scenario. For the WAN and LAN scenarios, we build the networks with the switch number N varying from 100 to 1000. For the data center scenario, as the related study [36] recommended, we apply BCube(n, k) model with n varying from 8 to 18 when k is 1 and 2. Since the number of switches in the BCube topology is $n^k \cdot (k + 1)$, the switch number N of the data center topology scales from 16 to 972.

In the simulation topologies, as shown in the latter part of this paper, the potential target switch generally holds responsible for hundreds of paths. Considering the traffic characteristics shown in the related studies [5], [40] that the hot switch can receive thousands of new flows per second, we set the average flow arrival rate of each path as about 10 flows per second. Besides, since different path holds different amount of traffic, we further set the flow arrival rate of each path randomly between 1 to 20 flows per second.

Fig. 6. The virtual degree d_i of each switch in the BA and real router-level graphs, $N = 500$.

Fig. 7. From $N = 100$ to $N = 1000$, the number of the potential targets in the BA and real router-level graphs.

Fig. 8. The virtual degree d_i of switches in the BCube graphs, the virtual degree d_i of switches in the $BCube(n, k)$ graph satisfies that $d_i = \binom{n}{2} \cdot n^k$.

Fig. 9. From $n = 8$ to $n = 18$, the number of the potential targets in the $BCube(n, k)$ graphs.

Fig. 10. For a certain target, the switch or server numbers of different entropy features.

2) *Simulation Results:* As aforementioned in Algorithm 1, we define the potential targets using the switches' virtual degrees. Fig. 6 shows the virtual degrees of the switches in BA graph and real router-level graph when their sizes are 500. According to the $d_i = N - 1$ line, there are 12 and 6 potential targets in BA graph and real router-level graph. Since the BA graph is built by adding nodes to a small seed topology, the potential targets of BA graph are mainly distributed in the earlier added nodes. When N varies from 100 to 1000, we get the number of the potential targets shown in Fig. 7. In general, the number of the potential targets increases with the topology size N .

In contrast, as shown in Fig. 8, the switches in the BCube graph have the same virtual degree, which is decided by the parameter n and k and satisfies $d_i = \binom{n}{2} \cdot n^k$, the detail explanation can be found in the Appendix. With the increasing of n , the virtual degree of switch increases exponentially and it deviates from the $d_i = N - 1$ line obviously.

From Fig. 8, we can get some further results. First, due to the dense placement of servers ($n^{(k+1)}$) and the sparse placement of switches ($n^k \cdot (k+1)$), switches in the BCube-based data center face much more forwarding task comparing with the ones in the WAN and LAN scenarios, and they are more likely to be compromised by the table-overflow attack. Second, the heavy forwarding task of switches in $BCube(n, k)$ model (each switch maintains $\binom{n}{2} \cdot n^k$ paths) makes $d_i > N - 1$ a loose definition for potential target. However, since the $BCube(n, k)$ topology is homogeneous (each switch has the same virtual degree), our definition is suitable. Last, the recursive property of BCube makes switches homogeneous in the topology, therefore the

number of potential targets in BCube graph increases linearly with the growth of topology size as shown in Fig. 9.

To evaluate the performance of our monitoring mechanism, we first compare our DFA with the entropy-based traffic feature. It should be noted that, the accuracy of the entropy-based traffic feature depends on the randomness of the flows [18]. However, switches (or servers in the BCube graph) have different numbers of paths which use the target as the middle hop. This affects the randomness of the flows. For a certain potential target, Fig. 10 shows the switch or server numbers of different entropy features. The "positive" switches or servers have fewer paths while the "negative" switches have more paths than the average value. When the attackers send flows through the "positive" devices, the entropy features of the target increase. When the attackers send flows through the "negative" devices, the entropy features of the target decrease.

Fig. 11. DFA and the Src-IP entropy values, attacker attached switches or servers are “negative” devices, $l = 10$ seconds, 10 attackers, the attack rate is 500 flows/s, (a) BA model, $N = 500$, (b) real router-level, $N = 500$, (c) BCube model, $N = 507$.

Fig. 12. DFA and the Src-IP entropy values, attacker attached switches or servers are “positive” devices, $l = 10$ seconds, 10 attackers, the attack rate is 500 flows/s, (a) BA model, $N = 500$, (b) real router-level, $N = 500$, (c) BCube model, $N = 507$.

Fig. 13. GFFC and the average attack rate of attackers.

TABLE III
KEY PARAMETERS OF OUR EXPERIMENTS

parameter	Value
maximum allowed MTC	1500 flow entries
TAR	50/s
IT	10s
AR	100 flow/s; 150 flow/s; 200 flow/s

Using DFA and GFFC, we monitor the table-overflow attack in different types and scales of topologies, and we summarize the results in Fig. 14. According to the Receiver Operating Characteristic (ROC) curves and the Confusion Matrixes, we can see that, our method achieves 100% accuracy with a False Positive (FP) rate ranging from 6.3% to 13.7%. During the simulations, as depicted by Fig. 14(b), Fig. 14(d) and Fig. 14(f), our method archives an accuracy of 96.4% in the BA graphs, an accuracy of 95.1% in the real router-level graphs and an accuracy of 93.4% in the BCube graphs.

To further locate the attacker attached switches, we calculate CFE when the table-overflow attack is identified. For BA and real topologies, we get the CFE values shown in Fig. 15. The CFE values of the normal switches range in (0.8, 1.2) while the attack attached switches range in (1.5, 1.9). For the BCube, as shown in Fig. 16, the CFE values of the normal servers range in (0.7, 1.4) while the attack attached switches range in (1.8, 2.0).

B. Evaluating the Mitigation Mechanism

1) *Simulation Settings*: To test the performance of our mitigation mechanism, we program the flow entry token bucket as an application in OpenDaylight controller [41] using REST API. We use OpenvSwitch [33] as the SDN-enabled switch. The controller and each SDN-enabled switch are equipped with an Intel Xeon E5606 CPU working at 2.13GHz and an 8G memory chip. They are operated with Ubuntu Linux 12.04.

We use two laptops to send and accumulate flow entries on the middle hop switch. The attack flows are generated in the form of the ICMP ping flood using Hping [42]. The parameters that we used are listed in Table III.

2) *Simulation Results*: To avoid the table overflow on the victim switch, we need to control the bucket capacity with the consideration of the current flow table vacancy. According to the experiment settings and the analysis of (15), the calculation result of the maximum BC is 1000. Based on this, the controller can limit the transmission rate of attack flows.

Using the normalized DFA and normalized Src-IP entropy, Fig. 11 shows the monitoring results when attacker attached switches or servers are “negative” devices. We can see that, both features can differentiate the table-overflow attack, and DFA shows a better sensitivity.

However, when attacker attached switches or servers are “positive” devices, the entropy-based method is not feasible. Fig. 12 shows the monitoring results when attacker attached switches or servers are “positive” devices. We can see that, the Src-IP entropy value increases and leads to a False Negative (FN) error while DFA feature keeps a well sensitivity to the attack.

Then we compare our GFFC with the average attack rate of attackers in Fig. 13. As discussed in Section V, the attackers can hide themselves by splitting the attack cost. We can see that, with the growth of attack numbers, it becomes harder to identify an attack according to their request rate. To launch the 500 flows/s table-overflow attack, the average attack cost of the 15 attackers is only less than 35 flows/s, which can be mistaken for normal traffic fluctuations. However, the attack payment CFFC is noteworthy. As shown in Fig. 13, it grows linearly with the attack rate and is independent with the number of attackers.

Fig. 14. Monitoring performances, (a), (c) and (e) are ROCs of BA model, real router-level and BCube model, (b) (d) and (f) are confusion matrixes of BA model, real router-level and BCube model.

Fig. 15. $N = 500$, 10 attackers, for a certain target, the CFE values of switches in the BA and real router-level graphs.

Fig. 16. $n = 13, k = 2$, 10 attackers, for a certain target, the CFE values of servers in the BCube graph.

Fig. 17. The effect of FETB on the attacker attached switch.

Fig. 18. The effect of FETB on the victim switch.

For different attack rates, we get the rate limiting results in Fig. 17. As can be seen, when the bucket has no tokens, the attack flows' transmission rate is limited by the fixed token add rate. The higher the attack rate is, the earlier the limiting action comes. Over a long run, the number of the attack flows is limited to $BC + t * TAR$.

Since the MTC indicates the maximum allowed table consumption for the attackers, we record the flow table

consumptions of the attackers and summarize them in Fig. 18. We can see that, with the rate limiting and the calculated bucket capacity, the maximum flow table consumption of the attackers is limited to MTC . Over a long run, the flow table consumption of the attackers is $IT * TAR$.

However, attackers may repeat their attack flows in time to avoid attack flows being evicted by the idle timeout. To simulate the effect of repeated attack flows, we force the controller to assign static flow entries for the non-repeat attack

Fig. 19. The effect of FETB on both the attacker attached switch and the victim switch.

Fig. 20. The topology of BCube(4,1), the rectangles represent switches and the circles represent servers, the switches have the same $d_i = 24$.

flows. The static flow entries have infinite idle timeout value, and they will not be removed until we delete them manually. In this case, the performance of FETB is shown in Fig. 19. We use the dynamic token add rate, once the number of flow entries caused by attack flows exceeds 2,000.

Comparing with the recent QoS-aware mitigation strategy [32], which redirects attack flows to the idle peer switch, our mitigation mechanism limits the attack rate at the attacker attached switches. Using the proper bucket capacity and token add rate, FETB avoids the table overflow on the victim switch.

VIII. CONCLUSION

In this paper, we examined the table-overflow attack in SDN with practical considerations and concluded that existing solutions were unable to protect the system under such an attack. To address this issue, we first proposed a monitoring mechanism to detect the table-overflow attack during the original routing process of SDN. Three traffic features were designed to differentiate the attack and locate the attackers. We then proposed a mitigation mechanism to reduce the transmission rate of attack flows on the attacker attached switch. We designed a flow entry token bucket model to avoid the table overflow on the victim switch. Extensive simulations were conducted to evaluate and show the effectiveness of our solution against the table-overflow attack.

APPENDIX

The BCube(n, k) model creates iterative graphs, the smallest iteration unit is BCube₀ and the largest iteration unit is BCube _{$k-1$} . For example, Fig. 20(a) shows the topology of BCube(4, 1). In fact, in such an iterative graph, the switches in different levels are homogenous and can be exchanged. When we exchange the level 0 switches with the level 1 switches in Fig. 20(a), we get Fig. 20(b). The iterative feature of BCube(n, k) model makes the switches have the same d_i .

Since the switches have the same d_i , we only need to find one switch's d_i . The simplest way is to choose a switch in

the highest level k , since only flows between two BCube _{$k-1$} s use it as the middle hop. Then according to the number of servers in each BCube _{$k-1$} (i.e., n^k) and the number of possible combinations of two BCube _{$k-1$} s (i.e., $\binom{n}{2}$), we get the d_i of the level k switch as $d_i = \binom{n}{2} \cdot n^k$.

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