SUPC: SDN enabled Universal Policy Checking in Cloud Network

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Abstract—Multi-tenant cloud networks have various security and monitoring service functions (SFs) that constitute a service function chain (SFC) between two endpoints. SF rule ordering overlaps and policy conflicts can cause increased latency, service disruption and security breaches in cloud networks. Software Defined Network (SDN) based Network Function Virtualization (NFV) has emerged as a solution that allows dynamic SFC composition and traffic steering in a cloud network. We propose an SDN enabled Universal Policy Checking (SUPC) framework, to provide 1) Flow Composition and Ordering by translating various SF rules into the OpenFlow format. This ensures elimination of redundant rules and policy compliance in SFC. 2) Flow conflict analysis to identify conflicts in header space and actions between various SF rules. Our results show a significant reduction in SF rules on composition. Additionally, our conflict checking mechanism was able to identify several rule conflicts that pose security, efficiency, and service availability issues in the cloud network.

Index Terms—Software Defined Network (SDN), Service Function Chaining (SFC), Network Function Virtualization (NFV), Security Policy Conflicts

I. INTRODUCTION

Service Functions (SFs) comprise a class of middleboxes, such as Firewall, Intrusion Detection System (IDS) and Deep Packet Inspection (DPI), that examine and modify the traffic and flows in a sophisticated fashion. The SFs at the network level is known as Network Functions (NFs) [3]. Network Function Virtualization (NFV) proposes replacement of hardware middleboxes with flexible and programmable software middleboxes, which is referred to as Virtual Network Functions (VNFs) [4]. Lack of a common protocol standard among middleboxes makes it hard to debug the configuration errors. In case of any middlebox failure, network administrators rely on ad-hoc rules to resolve the issue, which lacks a comprehensive view of the overall network and are error prone [1]. Current Service Function Chaining (SFC) solutions that consider VNF policy ordering and policy compliance [5], [3] do not analyze the policies at the granularity of the packet header. The policy specifications of SF and actual implementation on the network are often quite different, and without a common standard to interpret various SFs, the ordering mechanism is hard to be verified. Network-wide policy enforcement solution for middleboxes discussed in FlowTags [2] may not scale well on a large cloud network since tracking of tags across various VNFs and backtracking in case of SF failure can be quite difficult. The policy composition mechanisms such as PGA [8], implement SFs multiple times in order to achieve the desired security objectives, however, there is a significant overlap in the packet header and actions of SFs, which slows down the SF performance. The solutions that focus exclusively on security enforcement in SFC [9], [11] do not consider the overlap between the packet header and the associated actions in SFC, which can cause policy level conflicts.

SDN has the capability of dynamically managing VNF connections and data plane flows as discussed by Trajkovska et al. [10]. SDN utilizes OpenFlow [6] (programmable network protocol) for interacting with forwarding plane of network devices [6]. In the SUPC framework, we reduce all SF configuration to OpenFlow rules in order to have a global view of the network. This SDN controller OpenDaylight in our framework provides end-to-end visibility to help resolve misconfiguration related failures. SUPC framework utilizes an OpenFlow format to identify conflicting scenarios across different SFs. The presence of common rule format also helps in automatic verification of security policies across various SFs. The key contributions of this research work are as follows:

- SUPC utilizes packet header fields and traffic steering of SFs and to composes a set of OpenFlow rules with no duplicates. We incorporate correct service ordering by assigning priority to flow rules derived from SFs with higher precedence. We were able to achieve a significant reduction in the number of rules to be processed and the flow composition time in our experimental analysis.
- SUPC identifies four major type of rule conflicts based on important network and security properties. We identified 100s of conflicts in our SDN cloud dataset with 25k OpenFlow rules, which can cause security conflicts and network service failures.

II. RELATED WORK

Security in SFC has been modeled in SICS [11]. The authors consider rule composition, header space mapping, order and priority of various requirements specified as part of SFC. The algorithm is however based on simple predicate logic, which doesn’t allow deductive reasoning to make some inference about rule conflicts as in case of our work. Network security defense pattern (NSDP) based on multiple objectives such as security, minimal resource wastage, fault tolerance has been
proposed by Sendi et al. [9]. Authors use mechanisms such as decomposition, composition, location and zone awareness for service chain composition. Our work uses a constrained set of OpenFlow rule representation which will be more cost efficient in terms of SFC latency compared to this solution. Policy Aware SFC has been discussed by Joseph et al. [5]. Authors separate policy from reachability in SFC in order to ensure correctness and flexibility. FlowTags [2] extends SDN architecture for adding tags to outgoing packets. This provides a necessary context for policy enforcement. These works do not, however, consider possible overlaps between network policies based on packet header match. Works that focus on policy safety and efficiency of SFC like SDN based virtual firewall discussed by Brew [7] consider issues like semantic consistency, and scalability but their application is limited to the firewall SF.

III. BACKGROUND

SDN based SFC: We consider the multi-tenant cloud network as a use case to highlight some of these issues in detail. In this example, we consider two Compute nodes with four SFs namely Classifier (C), IDS, VPN and Load Balancer (LB). We discuss a few ordering and placement strategies and highlight the shortcomings below. Our SFC has the following requirements:

1) Traffic coming into the network should be classified into different categories based on source IP address using Classifier SF.
2) Any traffic not part of data network security domain should be processed via Intrusion Detection System.
3) Data network traffic and SDN controller traffic should go through Load balancing SF.
4) Control plane traffic from SDN controller should be encrypted using public key encryption scheme.

![Figure 1. Service Function Chaining Example in Cloud Network](image)

The nodes in an SFC architecture can be SFs or Service Function Forwarders (SFFs). An SFF is responsible for forwarding traffic packets or frames received from a particular network segment to associated SFs using the information encapsulated in the packet. In the Figure 1 the Open vSwitch (OVS) bridge acts as SFF.

The Service Function Path (SFP) is the actual path traversed by the packet/frame from source to destination in SFC after application of granular policies and operational constraints in SFC. For instance in the Figure 1, there are three SFPs - \( SFP_1 \), \( SFP_2 \), \( SFP_3 \) corresponding to Data Net, Public Net and SDN controller traffic.

**Strategy 1 Order:** \( C \rightarrow VPN \rightarrow IDS \rightarrow LB \).
**Issue:** SDN controller traffic needs to go through both VPN and IDS as per policy, placing VPN first (incorrect order) violates security objective. Thus, IDS should precede VPN, since VPN encrypts the traffic and IDS can operate only on the raw traffic.

**Strategy 2 Order:** \( C \rightarrow LB \rightarrow IDS \rightarrow VPN \).
**Issue:** The traffic from SDN controller and data network has to go through classifier and load balancer. Malicious traffic could have been filtered out using IDS policy resulting in less impact on QoS offered by the load balancer. The incorrect placement leads to an efficiency issue. In order to preserve both security and efficiency constraints, we design better placement and ordering as shown in Fig. 1 - Strategy 3.

**Strategy 3 Order:** \( C \rightarrow IDS \rightarrow VPN \rightarrow LB \).

**Efficient Placement** is obtained in this strategy since unwanted traffic is filtered at IDS and load balancer has to deal with only legitimate traffic from Data-Net and SDN Controller.

**Correct Ordering** is obtained for SDN controller traffic. The traffic is passed in raw (un-encrypted) format through IDS, and later through VPN thus IDS has complete visibility.

**SDN Controller Traffic Needs:**
- SDN controller traffic needs to go through both VPN and IDS and SDN controller traffic.

![Figure 2. Packet Header space Overlap](image)

Creation of SFC can lead to several options. We observed that current deployments of SFs in current works lack following desirable properties, which leads to the presence of redundant and conflicting rules in SFC:

(i) **SF Rule Ordering and Composition**: Figure 2 shows that the packet header space of Firewall, IDS, and Load Balancer in SFC overlap with each other. Inefficient placement of SFs can incur communication cost on the network. For instance, if IDS was placed before Firewall, IDS would have to analyze traffic which may be dropped by Firewall in the current arrangement. (ii) **SF Conflict Analysis**: We identified several conflicting scenarios in security and traffic processing policies in SFC after the composition of SF rules into OpenFlow format due to partial or full overlap in packet match and action fields of SF rules. These conflicts can cause security policy violations due to conflicting actions and service disruption...
IV. SFC COMPOSITION AND CONFLICT CHECKING

The possible overlap in packet header provides scope for policy composition and traffic steering in an efficient fashion. We automate flow rule match (layer 2-4 headers) and action set composition to OpenFlow rules at each middlebox in SFC.

A. Flow Composition

To illustrate the flow composition problem we take example of traffic manipulation and access control policies of some SFs and their corresponding translation into OpenFlow rules. In OpenFlow specification [6], each flow rule is a tuple of three sets, i.e. - match, action (A) and priority (P). We define each flow rule $R_i = \{\text{match}_i, A_i, P_i\}$. The match field for each rule $R_i$ consists of several sub-fields such as source MAC address $l_2s_i$, destination MAC address $l_2d_i$, source IP address $l_3s_i$, destination IP address $l_3d_i$, source port $l_4s_i$, destination port $l_4d_i$, protocol $\rho_i$. We consider seven sub fields for our conflict detection model. Thus, $\text{match}(R_i) = \{l_2s_i, l_2d_i, l_3s_i, l_3d_i, l_4s_i, l_4d_i, \rho_i\}$.

We have identified four types of conflicting scenarios that can lead to security violations, i.e., Intersection, Subsumption, Transitivity and Symmetry as shown in Figure 4. The algorithm 2 presents the details of conflict analysis in current OpenFlow rules composed from SFs.

Algorithm 1 Flow Rule Composition

1: procedure FLOW RULE COMPOSITION($R_s$, $S$)
2: $R \leftarrow \text{HashSet}$
3: $S \leftarrow \text{service function rules}$
4: $s \in S \triangleright \text{All Netfilter, proxy, IDS rules in S}$
5: $i \in \{1, n\}$
6: $P_{FW} \leftarrow \text{Priority Set}$
7: for $s_i \in S$ do
8: $R_i$.match().prot() $\leftarrow s_i$.prot()
9: $R_i$.match().ipSrc() $\leftarrow s_i$.ipSrc()
10: $R_i$.match().ipDst() $\leftarrow s_i$.ipDst()
11: $R_i$.match().sPort() $\leftarrow s_i$.sPort()
12: $R_i$.match().dPort() $\leftarrow s_i$.dPort()
13: $R_i$.action() $\leftarrow s_i$.action()
14: if $s_i \in S$.Netfilter() then
15: $R_i$.match().hwSrc() $\leftarrow s_i$.hwSrc()
16: $R_i$.match().hwDst() $\leftarrow s_i$.hwDst()
17: $R_i$.prior() $\leftarrow \text{rand}(1,65535)$
18: $P_{FW}.add(R_i.prior())$
19: else if $s_i \in S$.IDS() then
20: $R_i$.prior() $\leftarrow \text{rand}(max(P_{FW}, 65535))$

Because some symmetric traffic flows require configuration changes for incoming and outgoing traffic.

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Algorithm 2 Conflict Checking Algorithm

1: procedure RULE CONFLICT CHECKING(R)
2: \( R \leftarrow \) current flow rules
3: \( R = \{match(R_i), A(R_i)\}\)
4: \( C \leftarrow \) Conflict Set
5: for \( i \in \{1,n\} \) do
6: for \( j \in \{1,n\} \) do
7: if \( match(R_i) \cap match(R_j) \neq \emptyset \) then
8: \( C.add(Intersection) \)
9: else if \( match(R_i) \subseteq match(R_j) \) OR \( match(R_j) \subseteq match(R_i) \) then
10: \( C.add(Subsumption) \)
11: else if \( P(Symmetry) \rightarrow \{match(R_i), A(R_i)\} \cup \{match(R_j), A(R_j)\} \) then
12: \( C.add(Transitivity) \)
13: if \( P(Symmetry) \) then
14: \( C.add(Transitivity) \)
15: if \( match(R_i) \cap match(R_j) \neq \emptyset \) then
16: \( C.add(Symmetry) \)

Figure 5. SFC Rule Conflict Scenarios

are either same or different. For instance the rules 1 and 2 in Figure 5, \( l3s_2 \subset l3s_1 \) and \( l3d_1 \subset l3d_2 \), \( A(R_1) = A(R_2) \). Therefore, \( \{match(R_1) \cap match(R_2)\} \neq \emptyset \). Similarly, for rules 1 and 3, \( l3s_3 \subset l3s_1 \) and \( l3d_3 \subset l3d_2 \), \( A(R_1) = A(R_3) \). The match fields for rules 1 and 3 have \( \{match(R_1) \cap \) match\( (R_3)\} \neq \emptyset \). So rules 2 and 3 have Intersection conflict with rule 1.

Subsumption refers to class of conflicts where head match of one rule is completely subsumed by another rule, and the actions are similar or dissimilar. For the rules 1 and 4, \( match(R_4) \subseteq match(R_1) \) and \( A(R_4) = A(R_1) \). Another scenario of Subsumption is for the rules 1 and 5, i.e., \( match(R_5) \subseteq match(R_3) \), whereas \( A(R_5) \neq A(R_3) \). We classify all such conflicts in the class Subsumption.

Transitivity is a class of conflicts where the flow rule is not defined explicitly but the combination of two flow rules leads to an inferred flow rule. If the inferred flow rule can be in a state of conflict with a predefined flow rule for same header match. Consider rules 1, 6 and 7. actions for match fields \( l3s_1 = 192.168.1.0/24 \) and \( l3d_1 = 192.168.2.0/24 \) is ALLOW. The action for rule 6, i.e. \( A(R_6) \) for match fields \( l3s_1 = 192.168.1.0/24 \) and \( l3d_1 = 192.168.1.0/24 \) is ALLOW. The action for rule 6, i.e. \( A(R_6) \) for match fields \( l3s_1 = 192.168.1.0/24 \) and \( l3d_1 = 192.168.1.0/24 \) is ALLOW. The action for rule 6, i.e. \( A(R_6) \) for match fields \( l3s_1 = 192.168.1.0/24 \) and \( l3d_1 = 192.168.1.0/24 \) is ALLOW. We can infer a new rule from these two rules, i.e., \( R_1 \rightarrow R_6 \) is \( R_x \). For the rule \( R_x \), the traffic between source 192.168.1.0/24 and destination 192.168.3.0/24 should be allowed by transitivity. Considering inferred rule \( x \) and rule 7, the match fields, \( match(R_7) \subseteq match(R_3) \), however the action for rule 7, i.e. \( A(R_7) \) is in conflict with action for the rule inferred - \( A(R_3) \neq A(R_7) \). We classify all such scenarios into a class of transitive conflicts.

**Symmetry** is a required property for some applications that require bi-directional connections to maintain a persistent session. For example, a stateful firewall SF requires 3-way handshake ‘SYN’ from source to destination, ‘SYN-ACK’ from destination to source and ‘ACK’ from source to destination. If the source address \( l3s \) is 192.168.1.12 and destination address \( l3d \) is 192.168.2.10, the property - symmetry is satisfied iff \( R_1 \) and \( R_8 \) are working together, i.e., \( P(Symmetry) \rightarrow R_1, R_8 \). However if we check rule 9, the action for rule 9 conflicts with the action of rule 8. The \( P(Symmetry) \) implies \( \{match(R_i) \cup match(R_j)\} \) and \( A(R_1) = A(R_8) \). However, \( match(R_8) \cap match(R_9) \neq \phi \) and \( A(R_8) \neq A(R_9) \). Thus, rule 9 violates the symmetry property.

V. IMPLEMENTATION AND EVALUATION

A. Flow Composition Analysis

We implemented Bro IDS and Linux Firewall (Netfilter) as SFs on two separate Ubuntu 16.04 VMs, between source and destination. The SFC classification policy was configured in a way that data plane traffic of the communicating machines was required to pass through the SFs. The second column in the Table I denotes number of Netfilter and IDS rules combined that are invoked in SFC source \( \rightarrow \) Netfilter \( \rightarrow \) IDS \( \rightarrow \) destination. It can be observed that the header fields of most of the signature-based rules present in these SFs overlap with each other and result in same OpenFlow rules. There was about 97% reduction in number of rules (\( \frac{54}{2056} \times 100 \approx 3\% \)) if the SF rules are composed into OpenFlow rules. As the time increased, from 5s to 25s, the number of SF rules invoked increase from 2056 to 13472, but the number of distinct OpenFlow rules only increase from 54 to 201. Thus, Flow composition can lead to a significant gain in terms of performance on a network with large number of SFs.

1) Composition Time Comparative Analysis: We performed a comparative analysis of composition time for our algorithm 1 against policy composition time of PGA [8] and SICS framework [11]. We use rules as a generic term to define PGA nodes, SICS rules, and OpenFlow rules, and to have a common comparison format. We observed that SUPC achieves faster composition time - 20s for 10k rules, and 25s for about 12k rules. The composition time for SICS was

| Time (s) | IDS + Netfilter Rules | Flow Rules |
|---------|-----------------------|-----------|
| 5       | 2056                  | 54        |
| 10      | 4014                  | 85        |
| 15      | 7166                  | 104       |
| 20      | 9286                  | 127       |
| 25      | 12241                 | 179       |
| 30      | 13472                 | 201       |

Table I

IDS AND NETFILTER OPENFLOW RULE COMPOSITION
VI. CONCLUSION AND FUTURE WORK

The paper presents SUPC, an automated SF composition and conflict analysis framework. SUPC translates traffic and security policies of various SF into common OpenFlow format. This helps in elimination of redundant policy rules, networkwide policy enforcement using SDN controller, and conflict identification across heterogeneous SFs each having their own policy specification language. Our experimental results on the dataset of Netfilter firewall rules and Bro IDS achieved a significant reduction in matching rules ~ 97% due to Flow Composition, which leads to performance gain in SFC. We also identified four class of conflicts among the rules of various SFs which can cause security violations and service disruption. Our experiments for Flow Conflict analysis on the dataset of an order of 1000s of rules is able to identify different possible conflicting cases.

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