SDN based Network Function Parallelism in Cloud

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Abstract—Network function virtualization (NFV) based service function chaining (SFC) allows the provisioning of various security and traffic engineering applications in a cloud network. Inefficient deployment of network functions can lead to security violations and performance overhead. In an OpenFlow enabled cloud, the key problem with current mechanisms is that several packet field match and flow rule action sets associated with the network functions are non-overlapping and can be parallelized for performance enhancement. We introduce Network Function Parallelism (NFP) SFC-NFP for OpenFlow network. Our solution utilizes network function parallelism over the OpenFlow rules to improve SFC performance in the cloud network. We have utilized the DPDK platform with an OpenFlow switch (OVS) for experimental analysis. Our solution achieves a 1.40-1.90x reduction in latency for SFC in an OpenStack cloud network managed by the SDN framework.

Index Terms—Software Defined Network (SDN), Service Function Chaining (SFC), Queuing Model, OpenFlow, Network Function Parallelization (NFP)

I. INTRODUCTION

The real-time ad-hoc provisioning of SFC in a multi-tenant cloud network is a challenging task. Software Defined Network (SDN) allows orchestration and centralized management of a multi-tenant cloud network. SDN separates data plane and control plane in a network, so that network switches become simple forwarding devices. There are several security features such as firewall, network address translation (NAT), deep packet inspection (DPI), intrusion detection and prevention system (IDPS) which can be deployed efficiently in an SDN based cloud network.

These security and network functions can be virtualized using network function virtualization (NFV) approach. Instead of a dedicated hardware resources such as routers, firewalls, and switches, the NFV [3] allow software-based implementation of various security network functions called virtual network functions (VNF’s). Service Function chaining (SFC) provides an ordered list of VNF’s to act in serial or parallel order providing optimal security in SDN enabled cloud network.

There are research works that consider the implementation cost, throughput [10] and mean response time [2] for deployment of VNF’s for Optimal SFC. A VNF intrusion detection system (IDS) before VNF firewall is sub-optimal since the firewall can filter out part of traffic, which needs to be mirrored for intrusion detection thus reduce traffic volume to be mirrored for intrusion detection. Additionally, some network functions such as IDS and network-probe involve only mirroring or passive monitoring of network traffic. Since they involve no modification to the packet header, they can be operated in parallel. This reduces the performance hit induced by serial processing of VNF’s. Current works, however, fail to identify opportunities of parallelization of VNF which have a non-overlapping match and action sets in SFC environment.

In this research work, we compile the network functions into OpenFlow rules in order to check the overlap between a match and action fields of network traffic. SFC-NFP achieves gain in performance by up to 48% [4]. VNF’s operate in parallel using data path development kit (DPDK) [2] based Openflow [3] switches. Our experimental results show packet processing performance enhancement by 2.5x times [1]. We make use of flow aggregation and network function parallelism for performance optimization and security enforcement in the SDN based cloud network.

The key contribution of this research work are:-

1) Identification of overlap between match and action fields of various service functions in cloud network.
2) Performance optimization by in SFC using network function parallelism. This will ensure reduced SFC latency and higher throughput which is critical for security in a cloud network.

II. BACKGROUND

In a multi-tenant cloud network, different tenants can have different security requirements, e.g., Tenant 1 in Figure 1 can have a security requirement of firewall at the gateway of the network in order to ensure users outside the cloud network cannot directly communicate with cloud virtual machines (VM 1, VM 2). Similarly, communication across two different tenants (Tenant 1, Tenant 2) as shown in Figure 1 distributed geographically may require a company mandated virtual private network (VPN).

We consider all such security features as VNF’s. The SFC in effect creates an overlay between network nodes (VM’s) independent of network topology. This scheme allows connection of a large number of VNF’s in NFV environment. These connections are ad-hoc and can be setup or torn on a need basis. A Service Function Forwarder (SFF) is a layer forwarding provider to deliver packets from SFC to destination nodes in the network.

The OVS for each tenant acts as SFF in Figure 1. Service Function Path (SFP) is the VNF’s traversed by network traffic for packet delivery from source to destination node in cloud network. In Figure 1 SFP for communication between external users (Ext-NET) and virtual machines of Tenant 1 is Ext-NET → IDS → Firewall → VM 1.
Consider the VNF IDS for Tenant1 - Rule 1 in Table I where any traffic from Ext-NET coming to an internal network (10.1.0.0/24) needs to be examined for distributed denial of service (DDoS) attack pattern. Also the VNF firewall rule on Tenant1 blocks any traffic from external users on port 80 i.e., web service hosted on Tenant1 VM’s can only be accessed by internal users. The IDS will, however, inspect web traffic as well for DDoS attack pattern. Since firewall rule already blocks that traffic, it is redundant to examine web traffic by IDS, if the SFP is instead Ext-NET → Firewall → IDS → 10.1.0.0/24, this is much more efficient from a performance perspective.

On the other hand VNF IDS - Rule 2 which is applicable for traffic between Tenant1 and Tenant2. The SF followed by SFP is 10.1.0.0/24 → VPN → IDS → 192.168.1.0/24. The IDS rule 2 in Table I should ideally examine traffic from Tenant1 to Tenant2 for buffer overload attack patterns. However, since VNF VPN encrypts traffic between both tenants, the IDS will not be able to check the payload and packet headers of the traffic. Thus, traffic needs to be mirrored to IDS before being encrypted by VPN VNF. The desired SFP for security provisioning is 10.1.0.0/24 → IDS → VPN → 192.168.1.0/24.

We utilize the flow rule compilation of VNF ruleset so that VNF’s can be expressed in the common OpenFlow rule format. The OpenFlow rules are checked for match and action set overlap in our framework. Once the flow rules are aggregated, we use DPDK based parallelized packet processing for fast packet processing and security provisioning.

SDN architecture relies on OpenFlow protocol [3] for communicating with OpenFlow enabled network switches. An OpenFlow switch consists of one or more flow tables for packet lookup and forwarding. Each table of the OpenFlow switch consists of entries - match fields, counters, and instruction set that apply to the matching packet. The packet processing in the current Open vSwitch (most commonly used OpenFlow switch) architecture occurs using daemon *ovs-vswitchd* which lies in kernel space. This poses two main issues, both of which slows down throughput and limit the scalability of the architecture.

1) System calls are required for context switch when flow matching and action operations take place in OpenFlow network.

2) Packet processing occurs in serial i.e., dedicated queue for every network interface card (NIC).

The DPDK drivers make use of Non-unified memory architecture (NUMA), which avoids dedication of a separate CPU core for transmission (TX) and reception (RX) of network packets on a NIC [1]. Each NIC can have multiple TX/RX queues which allow us to perform SFC for various security VNF’s in parallel.

### A. SFC Parallelization Model

For each security operation like IDS, firewall, etc. we utilize one $M/M/c$ queue for a theoretical estimate of parallel packet processing. The parameters $M$ represents the packet arrival rate $\lambda$ and packet service rate $\mu$. The parameter ‘c’ represents the number of servers handling the packets. Since each TX/RX buffer allows parallel packet processing, we can have up to ‘c’ serving threads for each security operation. The packet arrival rate $\lambda$ is modeled using Poisson’s distribution in $M/M/c$ model and the packet service rate $\mu$ is modeled using exponential distribution.

We explore the parallelization between network functions by checking the order of dependency between functions. For DROP action associated with one network function firewall can affect the functionality of the subsequent network function Load Balancer. Since the packet processing of most security functions depends on either read/write operations on header or packet payload, we identify these dependencies while constructing parallel packet processing queues. There can be following relations between network functions - Read after Read (RAR), Write after Read (WAR), Read after Write (RAW) and Write after Write (WAW). The network functions $SF_1$ and $SF_2$ can be parallelized if dependencies between them are Read after Read (RAR) or Write after Read (WAR). The table below shows operations on packet header and payload by various VNF’s.

As can be observed from Table I, probe, and NAT operations are RAR for packet header. Also, IDS and Firewall operations are WAR, so these VNF’s can be parallelized. Whereas the operations that involve WAW on packet header or payload such as load balancers and IPS cannot be parallelized.

We implement service function chaining (SFC) algorithm at application plane using ODL controller. The virtual network functions such as group-based policy (GBP), Firewall, deep...
packet inspection (DPI), etc. are stitched as a part of the service function queue using optimized service function chaining algorithms discussed in next sections.

### III. Network Function Parallelism M/M/c Queue Model

We use a queuing model for the M/M/c queue for optimizing the service function allocation for every service function chain (SFC). We define key parameters for an M/M/c queue in the table below.

| Variable | Description                          |
|----------|--------------------------------------|
| n        | Number of service functions          |
| \( p_n \) | Packet arrival rate                  |
| \( \lambda \) | \( n \) VNFs' probability          |
| \( \mu \) | Packet service rate                  |
| \( \rho \) | Mean of servers                     |
| \( c \)  | Equilibrium Probability for zero VNF's |
| \( W \)  | Mean wait time for VNF in queue      |

The mean length of queue is calculated using equilibrium probability

\[
E(L^q) = \sum_{n=0}^{\infty} n p_{c+n} = \frac{p_c}{1-\rho} \sum_{n=0}^{\infty} n(1-\rho)^n \tag{6}
\]

The queue length will give an estimation of network functions waiting to be processed thus new VNF can be chained based on mean waiting time. We can make use of Little’s Law to obtain mean waiting time for a virtual network function in SFC.

\[
E(W) = \Pi_{c+1} \frac{1}{1-\rho} \frac{1}{c\mu} \tag{8}
\]

The real-time security provisioning will need minimal waiting time for critical services such as Intrusion Prevention System (IPS), as opposed to Quality of service (QoS). The mean waiting time estimated using queuing model has been used in the experimental analysis for comparing flow optimization performance gain against mean waiting time when VNF’s are parallelized using dependencies of read/write between them discussed in Section II-A. We discuss prioritized network function provisioning algorithm in the next subsection. This algorithm optimizes the processing of functions in an SFC.

#### A. Network Function Parallelization

The algorithm Network Function Parallelization (NFP) checks the action list of each flow rule line 4. If the action associated with flow rule involves forwarding (fwd) for the matching traffic, \((fwd, fwd)\) or \((fwd, flow_mod)\) line 6. The parallelization between network functions related to action, e.g. conntrack and NAT is possible, however, if flow_mod operation occurs before forward in two actions for a traffic match or \((flow_mod, flow_mod)\) for two actions occurs for a particular flow rule - line 8, the network functions are required to be operated in serial order, e.g. NAT and Intrusion Prevention System (IPS) for a flow match will occur in serial order.
Algorithm 1 Network Function Parallelization

1: procedure NETWORK FUNCTION PARALLELIZATION($F$)
2: \[ F \leftarrow \text{current flow rules} \]
3: for \( i \in \{1, n\} \) do
4: \[ \text{actions} \leftarrow f_i.\text{actions()} \]
5: for \( j, k \in \{1, n\} \) do
6: \[ \text{if } a_j, a_k \in (\text{fwd}, \text{fwd}) \text{ or } (\text{fwd}, \text{flow_mod}) \text{ then} \]
7: \[ \text{Parallelize } (a_j, a_k) \]
8: \[ \text{else if } a_j, a_k \in (\text{flow_mod}, \text{fwd}) \text{ or } (\text{flow_mod}, \text{flow_mod}) \text{ then} \]
9: \[ \text{Serial } (a_j, a_k) \]

IV. Implementation and Evaluation

We utilized an OpenStack based cloud network comprising of two Dell R620 servers and two Dell R710 servers all hosted in the ASU data center. Each Dell server has about 128 GB of RAM and 16 core CPU. The SDN controller OpenDaylight-Carbon has been used for network management and orchestration. The Openstack version Ocata was utilized for implementation of DPDK enabled architecture. The script networking-ovs-dpdk was incorporated in neutron component of Openstack to enable support for DPDK. The OVS version 2.8.90 was used on compute nodes for Openstack cloud and datapath was modified to use netdev driver. We utilized the following security, virtual network functions and corresponding software shown in Table IV for experimental evaluation. We created a multi-tenant network in an OpenStack cloud environment for experimental evaluation. The Ubuntu Mini OS was used for guest VM’s that were connected to the OVS in each compute node allow the guest VM to become a part of SDN network.

| Security Function | Software |
|-------------------|----------|
| Probe             | nmap     |
| NAT               | netfilter|
| Firewall          | netfilter|
| IDS               | Snort    |
| Load Balancer and Proxy | nginx |
| VPN               | openvpn  |
| DPI               | OpenDPI  |

Table IV

Service Functions and Softwares

A. SFC Latency

We measured the latency for the qperf tool to evaluate the end to end latency when NAT, Firewall, and IDS are used as security VNF’s on top of OVS. The experiment evaluates the effect of using NFP SFC-NFP for providing VNF’s as opposed to VNF’s in serial SFC-Serial which assumes that support of OVS-DPDK is missing in the deployment of VNF’s for SDN cloud network. The formula for theoretical estimates of multi-core architecture latency SFC-Theoretical using M/M/c queuing model has been discussed in Section III. We increase the number of CPU core from 2 to 8 for the experiment as shown in Figure 3. Additionally, we estimate the theoretical value of the mean delay between two network endpoints using the M/M/c queue model for validation of experiment when using multi-core architecture. The latency values calculated are mean of five runs of each algorithm on a network of varying size.

We observe latency of 0.45 for network-size=50 - Figure 3(a). The theoretical estimate of 2-core OVS-DPDK architecture SFC-Theoretical is 0.28s. When using SFC-NFP the end to end latency is 0.23s. This shows a performance gain of 1.21x using our algorithm compared to the normal parallelized packet processing of VNF’s. When the number of CPU cores is increased to 4, the latency for network-size=50 - Figure 3(b) is 0.13s compared to 0.18s latency achieved using SFC-Theoretical.

Similarly, SFC-NFP is able to obtain better latency value compared to serial or parallel methods when the number of CPU cores is increased to 8 - Figure 3(c). The performance gain is 1.21x-1.4x for network-size=50 using SFC-NFP. This performance gain can be attributed to the fact that on flow rule compilation many flow table entries of IDS and NAT can be aggregated, which leads to faster packet delivery from source node to the destination.

We increase the network size from 50 nodes to 250 nodes for each experiment i.e. Figure 3(a)-(c) to check the scalability of SFC-NFP. For 2 core OVS-DPDK network network-size=100 the latency using SFC-Theoretical is 0.67s whereas latency achieved using SFC-NFP is 0.56s - Figure 3(a). When the network-size=200 the latency using parallel packet processing SFC-Theoretical is 4.26s, whereas SFC-NFP has a latency of 2.72s which is \( \sim 1.60x \) performance gain. Similarly, when network-size=250, the performance gain using our method is \( \sim 1.66x \).

Our method of flow optimization scales well as we increase the number of network nodes with change in the number of CPU cores. For 4 core OVS-DPDK architecture - Figure 3(b), when network-size=200, the latency using SFC-Theoretical is 2.96s whereas the latency using SFC-NFP is 1.62s. Similarly, the latency for network-size=250, the latency for SFC-Theoretical is 6.1s whereas SFC-NFP achieves 4.05s latency, which is a \( \sim 1.60x \) performance gain.

The network-size=200 for 8 core OVS-DPDK framework - Figure 3(c) shows slight increase in latency using SFC-NFP 1.82s compared to 1.62s that our algorithms achieved in 4 core architecture - Figure 3(b). This delay increase is due to overhead induced by multiple processors running simultaneously. For network-size=250 our method again performs better compared to SFC-Theoretical. The latency for SFC-Theoretical is 4.1s whereas latency using SFC-NFP is 2.95s, a 1.35x performance gain. Overall, flow compression and aggregation help in reduction of flow table size and eventually latency in SDN enabled cloud network. The average performance gain is 1.40x and maximum gain is \( \sim 1.90x \) in some cases.
V. RELATED WORK

Parallelized packet processing has been introduced by ParaBox [11]. The authors exploit parallel packet processing opportunities across network functions. The output of packet processing after various operations is merged to ensure correct sequential processing of packets. Our approach introduces network function parallelism based SFC for security and performance enforcement on the cloud network.

Prados et al [7] have considered G/G/m based queuing model for checking mean response time for network functions for the 5G environment. The analysis is analytic in nature, comparing theoretical and simulated response time of Virtual Network Functions (VNF’s). We validate our model using M/M/c queue architecture in a cloud network, which was proposed as future work by authors Prados et al [7]. Our framework shows a marked reduction in SFC latency compared to the value predicted by the M/M/c queue model for parallelized packet processing.

Distributed cloud security for SDN cloud has been discussed by Pisharody et al [5], [6]. The authors have identified conflicts in flow rules for SDN clouds. We have used an aggregation of flow rules as part of our SFC, however, there can sometimes be conflicting actions between flow rules when VNF’s are compiled to SDN rules. We have not considered such cases in current work, but this can serve a future work for SFC in SDN enabled cloud network. Sun et al [9] have utilized network function parallelism based on DPDK framework to improve the performance of NFV. Our work focuses on ordering security functions in network function parallelism for performance and security assessment.

VI. CONCLUSION AND FUTURE WORK

Optimal service function chaining is important for security enforcement and performance improvement in a cloud network. SDN allows compilation of various VNF’s into the common format - OpenFlow. There is overlap in packet header space and action fields of various VNF’s when SFC is provisioned in the cloud network. Our framework performs NFP in service function chaining by identifying the dependencies between various VNF's such as IDS and VPN. The service functions with independent action sets can be parallelized in order to reduce the performance overhead. Our framework SFC-NFP is able to achieve up to 1.90x performance gain on a large cloud network compared to parallelization on OVS-DPDK architecture in the absence of flow optimization.

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