Abstract—Attack-awareness recognizes self-awareness for security systems regarding the occurring attacks. More frequent and intense attacks on cloud and network infrastructures are pushing security systems to the limit. With the end of Moore’s Law, merely scaling against these attacks is no longer economically justified. Previous works have already dealt with the adoption of Software-defined Networking and Network Function Virtualization in security systems and used both approaches to optimize performance by the intelligent placement of security functions. However, these works have not yet considered the sequence in which traffic passes through these functions. In this work, we make a case for the need to take this ordering into account by showing its impact. We then propose a reordering framework and analyze what aspects are necessary for modeling security service function chains and making decisions regarding the order based on those models. We show the impact of the order and validate our framework in an evaluation environment. The effect can extend to multiple orders of magnitude, and the framework’s evaluation proves the feasibility of our concept.

I. INTRODUCTION

Today’s network attacks rely on massive bot networks. Their attacking power rises as the number of online devices rapidly grows in times of Internet of Things (IoT). The ending of Moore’s Law (promising doubled resources every two years) limits the opportunity to throw in additional resources to fight attacks. Moreover, booking additional resources on demand is very costly, especially considering that the owners of bot networks do not have to pay for their attack resources.

IT systems providing services via a network offer various attack vectors. For each type of network attack, there are dedicated security functions to defend the system. Multiple security functions together form Security Service Function Chains (SSFCs) to protect a system against a set of attack types. For most systems, there is a direct correlation between consumed resources and the number of processed packages. In contrast, security functions (and therefore SSFCs) stand out, as they drop packets deemed as malicious causing lower load on subsequent security functions.

Figure 1 shows an SSFC with three different security functions. In most current security architectures, those SSFCs are hard-wired or interconnected using a fixed order via Software-defined Networking (SDN).

If the setup is under standard load without an attack occurring, the SSFC order is not relevant. All packets are benign and, therefore, have to pass through all security functions in the SSFC. Reordering the functions would not change the resource demand generated by the benign packets.

This changes when an attack occurs, that matches one of the security function. With the initial configuration, the traffic passes through all security functions in the SSFC. Thus, it creates resource demand at every step until the last security function stops it. When we put the blue security function at the front of the SSFC, this order leads to the first security function dropping the malicious traffic immediately. Thus, traffic does not pass on to the white and red security functions and creates only resource demands at the blue security function. Table I shows an example scenario which proves that optimal configurations can reduce the total number of required instances.

Related work mainly deals with Network Function Virtualization (NFV) as an enabler for security functions covered SDN either a security risk or feature. To the best of our knowledge, no other works went into analyzing the performance impact of SSFC orders or presented solutions and models for SSFC reordering.

This work introduces the following contributions:

- An analysis of the performance impact of different individual security functions and of security functions in SSFCs with different orders.
- A design, proof-of-concept (PoC) implementation, and evaluation of a framework for dynamic SSFC reordering.

| SSFC number of instances | Ordering       | red | white | blue | total |
|--------------------------|----------------|-----|-------|------|-------|
| red – white – blue       | 10             | 5   | 7     | 22   |
| red – blue – white       | 10             | 7   | 1     | 18   |
| white – red – blue       | 5              | 10  | 7     | 22   |
| white – blue – red       | 5              | 7   | 1     | 13   |
| blue – red – white       | 7              | 1   | 1     | 9    |
| blue – white – red       | 7              | 1   | 1     | 9    |

TABLE I: Example calculation of the resource demand for different SSFC orders of the example SSFC. Throughput per instance: red 100 MBit/s, blue 150 MBit/s, white 200 MBit/s. Load profile: 950 MBit/s malicious traffic matching the blue security function and 50 MBit/s of benign traffic.
 Modeling formalisms for the traffic inside the network, single security functions and SSFCs.

The remainder of this paper is structured as follows: First, Section II and Section III present the required background and related works. We analyze security function and SSFC performance in Section IV and present our SSFC reordering framework in Section V. Section VI introduces modeling approaches for individual security functions and SSFCs, and Section VII provides our conclusion and future work.

II. FOUNDATIONS

For our approach, we use various security functions. Also, SDN and NFV are important underlying technologies.

A. Security Appliances

We use multiple security functions in this work. We mainly focus on DPSs, IDPSes, and firewalls.

1) Distributed Denial-of-Service (DDoS) Protection Systems: One of the most popular mechanisms to mitigate DDoS attacks is SYN Cookies. It is readily available for services running on top of mainline Linux kernel, and therefore is widely adopted. A SYN flooding attack exploits the limited size of the TCP buffer which is a critical resource for establishing new connections. SYN cookies are a Transmission Control Protocol (TCP) standard compliant way of eliminating the need for buffer entries related to half-open connections. Generally, the data stored in the buffer is necessary to check if a received ACK packet belongs to previous SYN and SYN+ACK packets and whether the client received the server’s initial sequence number correctly. The idea of SYN cookies is to not store this information locally, but to encode it into the sent SYN+ACK packet and to retrieve this information from the ACK response.

2) Intrusion Detection and Prevention Systems (IDPSes): Intrusion Detection and Prevention Systems (IDPSes) combine Intrusion Detection Systems (IDSes) and Intrusion Prevention Systems (IPSes). IDSes can detect attacks and provide additional defense mechanisms, whereas, IPSes are capable of actively defending against incoming attacks. IDPSes can be classified based on the type of Monitored Platform, Attack Detection Methods used, Monitoring Method and Deployment Architecture. In this work, we focus on network-based, misused-based, real-time and non-distributed IDPSes. A network-based IDPSes is placed strategically on the network to detect any attacks that originate from outside the network. Misuse-based IDPSes primarily target singular attacks that usually are carried out in a single step [1] to exploit a selected vulnerability. Here, an IDPSes uses signatures containing the features of the exploit for its detection. Real-time IDPSes intercept the packets before they reach the target system and work synchronously to the traffic flow. Non-distributed IDPSes are deployed at a singular (central) position inside the network.

3) Firewalls: Firewalls can be defined [2] as an intermediate system that is plugged between the network and the Internet to establish a controlled link, and to erect an outer security wall or perimeter. The aim of this perimeter is to protect the network from network-based threats and attacks, and to provide a single choke point where security and audit can be imposed. Most common firewalls work on the third layer of the OSI-Stack, also known as the network layer. These firewalls filter the incoming packets based on a pre-defined set of rules and check whether a packet matches against these rules or not. The rules rely on the information available in the packet headers such as protocol numbers, source and destination IP addresses. Another type of firewall is the so-called proxy servers (e.g., SYNPROXY). These servers require authentication before the individual services can be accessed. If the authentication is successful, the proxy forwards packets between the server and the client.

B. Software-defined Networking (SDN)

SDN takes on the challenges posed by the increasing number of participants in the network and the associated exponential rise in cost due to the directly correlated growth in resource demands. The objective of SDN was to achieve greater scalability, flexibility, automation, and independence from hardware manufacturers to reduce acquisition and operating costs. SDN relies on four basic principles:

The separation of control and data planes divides the switching process into the control plane, using routing algorithms to decide on packet forwarding, with the data plane, technically handling the packet. SDN allows influencing the forwarding process externally to communicate with the switch allowing the switch to change its behavior at runtime without having to replace the hardware components.

The central control instance, called the controller, enables the configuration and administration of the network. For reasons of availability or load distribution, it can be deployed as a physical or virtual replica.

The behavior of a switch can be changed using software, enabling the installation from algorithms or other applications from different manufacturers - independent of the hardware producer. This feature also allows applications to operate above the network layer, i.e., at the application level, regardless of the switch model or the OS.

SDN brings together areas that are traditional handled separately via four essential APIs. The Southbound API connects the control and data layer. OpenFlow is the most popular open protocol for the Southbound API in SDNs. OpenFlow (OF) can be used to configure and evaluate the statistics of a network device, usually a switch. The Westbound API is used to communicate different control layers of different domains. The Northbound API exchanges information between the application and control layers. The Eastbound API provides a contact surface for non-SDN components.

C. Network Function Virtualization (NFV)

NFV is a new paradigm for networks. Typically deployed on proprietary specialized hardware in the past, these functions are replaceable by software solutions running on commodity hardware [3], [4]. Typical examples of such functions are switching, routing, load balancing, and firewalls. The implementation of a function usually is referenced as a Virtualized
Network Function (VNF) as it is commonly deployed inside a Virtual Machine (VM) to allow for higher flexibility and scalability. Not every function is suitable for conversion into a VNF. The use of multiple resources having optimized processors or FPGAs still can be advantageous for real-time requirements. VNFs depend on performance in several ways. First, the network adapters limit the number and the speed of available ports. Second, the I/O subsystem between the network card and the application can affect the performance. Also, the resources provided for the application (such as memory, and Central Processing Unit (CPU)) can become a bottleneck. Many NNF solutions are implemented usually in conjunction with specialized Operating Systems (OSs) or drivers to minimize bottlenecks. Mapping the network functions in the software separates the data and control layers, one of the central goals of SDN.

III. RELATED WORK

We provide a compressed overview of works regarding SDN for security and security for SDN. We further present works on NFV deployment, application, and the whitepaper that motivated our research.

SDN creates “a very fascinating dilemma” [5] — it offers a wide range of benefits for security implementation while introducing new security challenges. The research demonstrated that different attacks can affect not only the functioning of the targeted component but also the availability and confidentiality of each layer and interface of the SDN stack. Scott-Hayward et al. [6] presented a detailed analysis of these security challenges and categorized them by the affected SDN layer/interface.

In addition to traditional Denial-of-Service (DoS) attacks, the intelligence centralization and vertical split into three main functional layers that expand the attack surface and inspire new techniques for each layer. An Application Layer DoS Attack directly targets an application to consume all of the resources allocated to it and to cause a DoS. A Control Layer DoS Attack can arise by targeting any of its components, (e.g., forcing different applications to generate many conflicting flow rules may lead a controller to an unpredictable state). In Infrastructure Layer DoS Attacks, bottlenecks in OF switches and the southbound Application Programming Interface (API) are exploited. Moreover, generating fake flows fills the flow tables and prevents rules for normal network flows to be stored [7].

SDN provides opportunities to revisit old security concepts and to introduce new techniques as SDN features [5] to enhance network resilience. Network-wide knowledge facilitates the validation of security policies and enables quick identification and resolution of any conflicts [8]. As a result, consistent security policies can be built and maintained. In addition, SDN supports software-based traffic analysis that opens the door for innovative ideas, and Chi et al. [9] present different concepts on how to integrate the Snort IDS into an SDN-based network.

Barbette et al. [10], as well as Gallemmueller et al. [11], provide a detailed comparison of various NFV development kits and frameworks, including the recently proposed XDP framework [12]. In the context of the performance evaluation of software-implemented network functions, [5] provides an extensive list of best practices and caveats. A detailed network security investigation related to the use cases of SDN and NFV is presented in the survey by Lorenz et al. [13], and Farris et al. provide an extensive overview of emerging SDN and NFV security mechanisms in the context of the Internet of Things [14].

In addition to introducing the possibilities for dynamic SSFC, SDN also allows augmenting them with traffic and application awareness [15]. Many solutions rely on SDN and NFV in the context of DDoS resiliency. Multiple open topics are discussed by various authors that include 1) rule anomalies [16], 2) intelligent positioning [17], and 3) effective provisioning [18].

Security Function Chaining (SFCing) is a significant component of this work and essential for complex NFV security frameworks. The first inspiration for this work was the Cloud Security Alliance (CSA) “Security Position Paper: Network Function Virtualization” paper by Milenkoski et al. [19] that proposes six NFV security challenges: 1) Hypervisor dependencies, 2) Elastic network boundaries, 3) Dynamic workloads, 4) Service insertion, 5) Stateful versus stateless inspection, and 6) Scalability of available resources. The authors detail an enterprise-grade architecture for a NFV security framework that reduces deployment and management resources as well as adapt the SSFC ordering of its security appliances depending on an incoming attack. This work inspired our efforts.

IV. IMPACT OF SECURITY FUNCTION CHAIN ORDERING

We claim that that the SSFC order of security functions influences the performance of the SSFC. In this section, we will evaluate security functions and SSFCs with different orders to assert our claim. At first, we present the used evaluation environment. We then measure the performance of three different security functions in a stand-alone deployment. The measured security functions are a firewall, a DPS, and an IDPS. Then, we put these security functions in SSFCs with two service functions and vary their order. Last, we discuss the results and the conclusions that we must consider for the reordering framework and the decision-making in the following sections.

A. Evaluation Environment

To evaluate security function performance, we designed a testbed (Figure 2) that can incorporate benign and malicious workloads using single functions and composite SSFCs with modifiable function order and different server applications.

1) Hardware Components: We use a total of six physical servers. These play the roles of 1) a client and attacker, 2) an application server (the protected application), 3) a DDoS Protection System (DPS), 4) a firewall, 5) an Intrusion Detection and Prevention System (IDPS), and 6) an SDN, Experiment and Function Chaining Controller. For all servers,
we use a four-core (8 threads) Intel Xeon E3-1230 V2 CPU at 3.30 GHz equipped with 16 GB RAM. The client & attacker machine is serving two roles and, therefore, also uses one link for each role. Two standard non-programmable 1 GBit/s HPE switches provide the connectivity for the backend and controller network and HPE 5130 24G 4SFP+ EI SDN switches span the network for the experimentation data. The switches provide sufficient backplane switching capacity to ensure that this setup does not become a bottleneck.

2) Software Components: a) Traffic Generator (benign): On the first 10 GBit/s interface of the client & attacker server, we generate benign Hypertext Transfer Protocol (HTTP) traffic. For this purpose, we use HTTP Load Generator [20]. b) Traffic Generator (malicious): We use the second 10 GBit/s interface of the client & attacker server to create malicious packets. We create SYN, User Datagram Protocol (UDP), and IDS floods using Cisco’s Trex generator. For the chosen attacks, we use only the stateless mode. To generate HTTP floods, we employ BoNeSi — a BotNet Simulator. c) IDPS: The IDPS host runs the Snort IDPS in version 2.9.7. Snort is a popular, open-source IDPS developed by Cisco and also is the foundation of Cisco’s commercial IDPS solutions. d) Firewall: Like the IDPS, the Firewall uses one interface for incoming and one for outgoing traffic. We interconnect both interfaces using a Linux bridge, and Netfilter/iptables rules accomplish the packet filtering. e) DPS: As a DPS, we use a modified version of TCP Handshake Remote Establishment and Dynamic Rerouting using SDN (THREADS) [21]. THREADS is a DPS VNF against SYN flood attacks. It handles SYN requests and only for successful requests establishes a connection with the server and triggers an SDN reconfiguration. Thereby, it eliminates many shortcomings of SYNPROXY and SYN

cookies. f) Protected Service: The target server runs TeaStore, a micro-service reference and test application emulating a basic online store [22]. g) SDN Controller: We use Ryu as the SDN controller. The ryu.app.ofctl_rest module provides a REST-based interface for deploying flows.

3) Monitoring and Metrics Collection: The testbed measures and records the following metrics from various sources: a) the CPU usage of each server in various states: user, iowait, softirq, system, b) the total number of sent and successful benign HTTP requests, and c) the average Internet Control Message Protocol (ICMP) and TCP SYN latency and packet loss between sender and receiver. Telegraf collects CPU usage statistics and sends them to an InfluxDB running on the experiment controller. We use Grafana to visualize the gathered data. The HTTP traffic generator reports the number of total and successful requests during the run. The ping command allows measuring the latency and packet loss between the sender and receiver. We measure the SYN latency and packet loss using hping3. For ICMP and SYN latency and packet loss, we run an attack of intensity $x$ for a time $t$ and ping and establish TCP connections during that time.

B. Single Security Function Performance

Before evaluating the impact of the SSFC order on performance, it is necessary to establish a baseline that establishes a realistic maximum performance that is attainable by the service host. Figure 3 visualizes that the service scales linearly and beginning with 16000 requests/second the number of successful requests stalls. There is even a small decrease in throughput afterward which is probably attributable to queuing, swapping, and context switching effects. At that point, for the Direct Chain (both servers directly connected to the same switch), the target service has reached its limit. The first data row in Table IIa shows very low latency and no packet loss. These results serve as a baseline for evaluating how the appliances impact the latency and data loss.

We repeat the same experiment with each single security function present and Figure 3 shows that the security functions...
perform 2000 benign HTTP requests/second for one minute and scale the HTTP flood attack in 1000 requests/second steps up to 14000 requests/second and the malicious sources. We scale the HTTP flood attack in defending security function and blocks HTTP requests from creating a high compute load. The firewall is the issuing HTTP requests either in high frequency or by targeted attack. This attack aims to exhaust a service’s resources by each attack and switch their ordering for comparison. We simulate attacks and combine pairs of security functions for proceeding to combinations of security functions. We create loss for either ICMP or SYN packets.

The firewall, that reduces this time. No configuration creates packet additional hops. For the SYN response the sole outlier is the connects via a single extra switch, while the firewall and the switches the packets must travel through. Here, the DPS assumption that this effect roots in the number of necessary response. These results and further experiments lead us to the realize, that the firewall and the IDPS increase the ICMP response packet loss response packet loss.

To assert the performance for benign workloads. We measure metrics – other than the throughput – at 5000 requests/second flood strength. We compare the following two SSFC orders: a) IDPS→Firewall, and b) Firewall → IDPS.

Figure 4 presents the throughput results. Both systems handle the benign workload and a small attack load of 1000 requests/second well. At higher attack load levels, the number of successful benign requests drops for the IDPS→Firewall SSFC and from 10000 requests onwards settles just above 20000 successful requests. Meanwhile, the Firewall→IDPS SSFC is hardly affected by the attack load and remains close to the maximum attainable level and always stays significantly above the other SSFC order’s level.

Table IIa shows further metrics for the two SSFC orders. Considering these values, both SSFC orders perform similarly. When considering the CPU load measurements (not shown), we see that the IDPS is at maximum load for both SSFC orders. However, when the firewall is not in front, at the beginning, a clear overload is visible. The firewall resides at very low load levels and shows to have significant reserves.

2) SYN Flood: As a second benchmark, we perform a SYN Flood attack. This attack aims at exhausting a server’s buffer for half-open TCP connections. The DPS is the defending security function. For each run, we increase the SYN flood strength by 500 Mbit/s, up to 6500 Mbit/s. We generate a load of 2000 benign HTTP requests/second for one minute to evaluate the successful requests during a SYN flood. We measure metrics other than the successful requests at 5000 MBit/s.

Fig. 4: Successful requests during an HTTP flood attack.

After evaluating the single security functions, we now proceed to combinations of security functions. We create simulated attacks and combine pairs of security functions for each attack and switch their ordering for comparison.

1) HTTP Flood: The first benchmark is an HTTP flood attack. This attack aims to exhaust a service’s resources by issuing HTTP requests either in high frequency or by targeted requests creating a high compute load. The firewall is the defending security function and blocks HTTP requests from the malicious sources. We scale the HTTP flood attack in steps of 1000 requests/second up to 14000 requests/second and perform 2000 benign HTTP requests/second for one minute to assert the performance for benign workloads. We measure metrics – other than the throughput – at 5000 requests/second flood strength. We compare the following two SSFC orders: a) IDPS→Firewall, and b) Firewall → IDPS.

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Table IIa shows further metrics for the two SSFC orders. Considering these values, both SSFC orders perform similarly. When considering the CPU load measurements (not shown), we see that the IDPS is at maximum load for both SSFC orders. However, when the firewall is not in front, at the beginning, a clear overload is visible. The firewall resides at very low load levels and shows to have significant reserves.
and combinations. The Firewall→DPS SSFC offers a faster ICMP response while the DPS→Firewall SSFC yields a faster SYN response. The relative difference for the SYN response is larger than for the ICMP response. Both configurations do not yield packet losses.

The Firewall→DPS SSFC impacts the load during the attack. The background load (e.g., OS operations or filesystem journaling) in the user and system state is forced out by the actual load of the firewall application. This application load appears in the softirq level, where the CPU spends 100% of its time. When reversing the SSFC order, no noticeable load shows in the softirq state, and the background loads remain in the user and system state. Thus, this SSFC order eliminates all load on the firewall.

3) Intrusion Flood: The intrusion flood attack aims at abusing vulnerabilities inside a service. We use UDP packets containing a signature that matches the IDPS rules to create the flood and perform the intrusion flood up to 5000 MBit/s scaling in steps of 500 MBit/s. Further, we measure further metrics at an attack load of 1000 MBit/s and compare the same SSFC orders as for the HTTP flood.

Figure 6 shows the number of successful requests for both SSFC orders. Already at a flood strength of 500 MBit/s the Firewall→IDPS chain drops to 31732 successful requests. At 1000 MBit/s flood strength this chain further drops to 7238 successful requests and from thereon stays at similar or lower levels. The reverse chain’s performance drops later, starting at 1000 MBit/s with a drop to 43442 MBit/s. It then continues to slowly fall and finally aligns with the firewall-headed chains throughput at 4000 MBit/s. Between the beginning of attacks at 500 MBit/s and the alignment, the IDPS→Firewall SSFC outperforms the other chain.

The IDPS→Firewall SSFC about doubles the response time compared to its counterpart (see Table II). It also introduces a packet loss rate of about one third of packets. This result surprises, since the higher throughput of the IDPS-headed chain did not hint at this behavior. However, a way of getting higher throughput might lie in accepting packet losses. Putting the firewall first creates user and system load for both systems. While the firewall is not in an extremely high load situation, the IDPS is in overload. Changing the SSFC order results in taking away the load from the firewall and the system load from the IDPS but heavily overloads the IDPS. The firewall spends most of its time the softirq state, when it is first in the chain. However, when the IDPS heads the chain, only a small peak appears at the beginning.

D. Discussion

Section IV-B shows that even under benign workloads, the different security functions perform with significant differences. While the firewall can protect a service without reducing the throughput, the DPS and the IDPS reach their limits far before the protected service. Also, both systems (the IDPS more than the DPS) show that their performance can further drop when the load increases further.

Section IV-C confirms our assumption that the SSFC order has a significant impact on SSFC performance. When considering the throughput, we see different behaviors when comparing different attacks. Those behaviors share one commonality – placing the security function that defends against the attack first yields the most successful benign requests. In some cases, the right SSFC order significantly prolongs the load level at which performance drops and slows the drop. Still, at some point, both SSFC orders converge to similar results.

We show that the SSFC order has a significant effect on the throughput, other metrics and the CPU load. For the selected attack combinations, we also find that there is no optimal SSFC order for all attacks. While for HTTP flood, the firewall performs best before the IDPS, the reversed chain is superior during an intrusion flood. In general, putting the security function dedicated to protecting against the current attack first, yields the best results. Therefore, we require different SSFC orders depending on the current attack state of the system. This finding confirms our claim that dynamic SSFC reordering can improve the performance of SSFCs. We will follow the realization of this concept in the following sections.
V. A FRAMEWORK FOR ATTACK-AWARE SECURITY FUNCTION CHAIN REORDERING

In this section, we will present an architecture for an attack-aware dynamic SSFC reordering framework and provide a PoC implementation. We then evaluate this implementation and its capabilities and discuss the results and further challenges.

A. Architecture

The attack-aware SSFC reordering framework consists of multiple components, as depicted in Figure 7. A generic SDN-enabled network connects the external network and the service protected by our security system. All relevant security functions connect to that network as well. We deploy so-called security function wrappers alongside the security functions to gather metrics about them and their attack and report them to the Function Chaining Controller (FCC). The FCC collects data from the wrappers and optionally other sources. It forms a decision whether an SSFC reordering is necessary and in that case sends the new SSFC order to the SDN controller which enforces the new order inside the SDN-enabled network.

The Security Function Wrapper is a program running on the security function hosts and communicates with the FCC. It is responsible for registering the security function at the FCC, deleting it on graceful shutdowns, keeping a connection to the FCC to allow the management of security functions through the FCC, and finally, offering an interface for the security function to report detected attacks to the FCC over the wrapper. At first, the security function wrapper validates and loads its configuration. If everything is loaded correctly, it registers with the FCC and receives a token for further communication. In a keep-alive loop, the security function wrapper periodically sends a keep-alive message to the FCC and receives an updated token. In its main loop, it reports attacks registered by the monitored security function after performing a validation (e.g., a machine on a 1GBit/s interface could not report a valid attack with a strength of 5 GBit/s) to the FCC. Upon shutdown, it deregisters with the FCC.

The Function Chaining Controller runs in a centralized location reachable from all security functions. A webpage showing attack statistics and the current and standard configuration is part of the FCC. Additionally, the webpage contains a form to change the routing configuration manually based on the available groups of security functions. The controller needs to handle the requests from the wrapper instance, namely registration, delete requests, attack alerts, and keep-alive requests, as shown before. The FCC must keep a list of the security function groups and their respective attack rate to calculate the new optimal routing configuration reactively. After calculating the new routing configuration, the FCC sends it to the SDN controller, which then applies it to the switches and, therefore, the network. In this section, we use a simplified approach putting the security function group with the most attacks at the front. After successfully changing the routing configuration, the FCC changes the stored current configuration to the new routing configuration and resets the reported attacks.

B. Evaluation

1) Implementation and Evaluation Environment: The complete framework uses Python 3 with four non-standard Python libraries: Flask, PyJWT, requests, and netifaces. In general, this framework supports every SDN controller offering a Representational State Transfer (REST) API for flow modification. To ensure the absence of side effects from the SDN controller, we implemented a minimalistic SDN controller ourselves. For this PoC evaluation and the following evaluation, we limit our framework to use Open vSwitch only. This SDN Controller consists of two Flask applications: the actual controller and a switch wrapper running on the Open vSwitch machines.

We use a testbed environment similar to the one presented before for the SSFC order evaluation. However, we replace the physical switches with Open vSwitch instances.

2) Manual Reordering: At first, we evaluate that our system is able to correctly apply reordering decisions.

a) Experiment Description: We test all six SSFC orders possible for the three security functions. Therefore, we automated the process to test these routing configurations in the network based on the standard configuration. After starting the system and registering the security functions, the client sends an ICMP echo-request to the server. Next, we started tcpdump on each security function logging the traffic. From these logs, we construct the path, a packet takes through the network.

b) Results: The results show that our framework applies every permutation of the default configuration correctly. When reordering, it is possible to traverse through more security functions than there are in the network. This issue is a result of changing the routing configuration while traffic passes through the system. The following packets go through the desired function chain. Although packet loss is theoretically possible, the new routing configurations are applied instantly for the
retransmissions. Also, while theoretically possible, no attack completely skipped a security function.

3) Reaction to Simulated Attacks: Next, we analyze how the system reacts to simulated attacks.

a) Experiment Description: This experiment validates whether the FCC correctly changes the routing configuration based on the attacks reported by the security functions. The main idea that led to the development of the framework is to change the routing configuration dynamically. As described before, the security functions report detected attacks via the co-located security function wrapper instance to the FCC. We simulate attacks on each VM, to show that the attack reporting works and the routing configuration changes depending on the attack reports. The simulated security functions send attack reports with a changing probabilities. We configured a threshold of 100 attacks in the FCC. Only if the attack count exceeds this threshold, the FCC calculates and — if necessary — applies a new routing configuration. Additionally, we define an imminent threshold three times larger than the regular threshold checked every ten seconds.

b) Experiment Results: Figure 8 illustrates the imminent attack functionality. The first modification of the routing configuration occurs at almost three minutes into the experiment. The SSFC order changes from DPS-Firewall-IDPS to Firewall-IDPS-DPS. This change could not originate from the regular check as it occurs before the five-minute mark.

A further change proves the regular functionality of the FCC. The routing configuration takes effect approximately 12 minutes after the start of the experiment. The SSFC order changes from Firewall-IDPS-DPS to IDPS-Firewall-DPS. Here, it becomes visible that for one ping, the packets did not traverse every security function, posing a potential security risk.

Further reorderings work as desired. The FCC resets the configuration to the standard configuration if reported attacks of all security functions are below the configured threshold. This reset to default allows users to select a default configuration that best fits the average attack on the system.

4) Discussion:

a) Functionality: In summary, the developed framework is working as expected. Small issues like packet loss may occur during the application of new routing configurations. The generation of routes and their application works as desired. We also showed that the framework is indeed attack-aware and successfully changes the routing configuration of the network based on the reported attacks from the security functions. After attacks fade out, the framework then switches back to the default configuration.

b) Security Issues During Reconfiguration: Three undeclared events can occur during reconfiguration: i) packets get dropped because the framework has not installed the required flow yet, ii) packets traverse through more than once through one or more security functions, and iii) packets do not traverse through all required security functions.

The first and second issues pose only Quality of Service and Quality of Experience concerns. However, the third issue is relevant to security. If packets can skip security functions, single malicious packets can reach the receiver. This issue is of little concern for flood attacks, but for intrusions, a single packet might be enough to trigger a vulnerability and cause a severe security breach.

To avoid this issue, we propose several solutions: i) A second set of security functions. Reconfigurations would then use this second set for the SSFC. Once all packets clear the security functions in the first chain, those functions become the spare functions for the next reconfiguration. ii) To model the stay of packets inside the security function, by adding short-lived flows with artificial delays that ensure, that no packets are inside the functions when executing the reordering. However, this requires detailed knowledge of all security functions inside the chain, especially regarding their queuing behavior. iii) To force the security functions to drop all packets before executing the reordering. This solution fixes the second and third problems but moves the affected packets and others to the first issue. iv) To use the options field in the Internet Protocol (IP) header. We create a counter field in the options and increment it for every reconfiguration. The inbound switch has a rule that modifies incoming packet headers to contain the current counter value, and all created flows match against the current counter. Older flows expire after some time.

Depending on the use-case, there are different optimal solutions for the security system architecture. We have not yet implemented these solutions but will do so in the future. For the PoC, the presented implementation is sufficient.

VI. MODELING SECURITY FUNCTION CHAINS

Here, we will develop a precise model. First, we take a look at how to model a single security function based on the incoming traffic. We then use this knowledge and combine multiple security function models into a single SSFC model.

A. Modeling Single Security Functions

1) Modeling Traffic: Different security functions show a different behavior under different types of traffic. Thus, we need a model that takes both benign traffic and the various
attack types into account. To this end, our model of the arrival rate must consider the content and the composition of the traffic. Therefore, we model the traffic as different workload classes. For every workload class, we record the rate of packets and the used bandwidth. We model the traffic composition for the link from an external network to the first security function, every connection between security functions, and the link from the last security function to the protected system.

2) Security Function Modeling: With a model for the traffic, it is possible to model the behavior of the single security functions. We propose to apply architectural performance models to model security functions. Architectural models capture the semantics, allowing for a plain view on the security functions, in contrast to low-level stochastic formalisms. We model each security function as a software component. However, we also offer simplified approaches to model security functions. It is necessary to model three aspects: i) the effect of the security functions on the traffic composition, ii) the performance behavior of the security function, and iii) tertiary effects like packet-loss.

Based on the distribution of the input traffic of a security appliance, the corresponding output traffic can be derived. We define the distribution of the input/output traffic as \( P_{\text{in/out}}(t_i) \) with \( i \in [1, n] \) for \( n \) different types of traffic.

Exemplarily, for a security function which drops all packets of the traffic type \( k \) the output traffic looks as follows:

\[
P_{\text{out}}(t_i) = \begin{cases} 
P_{\text{in}}(t_i)/(1 - P_{\text{in}}(t_k)) & \text{for } i \neq k \\
0 & \text{for } i = k 
\end{cases}
\] (1)

The current model assumes that a function eliminates all malicious traffic of one or more traffic types.

For performance modeling, the most precise modeling solution would be to use a full-blown model of the software component to model the function’s performance behavior. Such models usually base on the functions source code or are extracted by heavy black-box testing. However, often neither the source code nor the resources are available to perform extensive black-box testing. Still, even when such a model is not possible, for our security functions, we have found two general types of resource demand generation. The first type is a constant demand created per unit (e.g., frame, packet, segment, request). The second type creates a demand correlating to the size of the unit with different correlation types.

There are tertiary factors that can increase the accuracy of the model in certain situations. These factors do not correlate directly with single packets or the traffic distribution but instead with the state of the security. Examples are Queuing Behavior, False Positives and False Negatives, Drop Rate, Overload Behavior, and Short Term CPU Frequency Scaling.

B. Modeling Security Service Function Chains

Based on the model for single security functions, it is possible to model the whole security function chain. Therefore, we model the chain by putting the functions one after the other and feeding the output of the previous function to the next.

When starting with the input traffic, the traffic results from putting it through one function after the other. Figure 9 shows such a development of the traffic for the function described above. Therefore, we use a simplified model without tertiary factors. The traffic starts with a distribution over all traffic types. At every security function, this function removes one or more traffic classes. Thereby the share of the other classes increases. This process repeats itself at every security function until only the benign traffic remains. This combination allows a full model of the chain when knowing the composition at the startup. However, most of the time, this composition is unknown. Still, it is possible to reverse engineer this composition using the reports from the security function wrappers and the switches in the framework.

VII. Conclusion

In this paper, we introduced the concept of attack-aware dynamic Security Service Function Chain reordering. This concept incorporates changing the order of SSFCs to optimize them to most efficiently counter attacks. At first, we described the general idea. The main component is the Function Chain Controller (FCC). It gathers information to model the security systems state, uses this information to compute the desired configuration, and enforces the SSFC order. Next, we developed an evaluation environment for individual security functions and SSFCs. When benchmarking single security functions, we found different types of behavior. For every tested combination, the SSFC order has a significant impact.
on the system’s performance. In general, putting the function that defends against the attack first, yields better performance. The difference can make up two or more SSFC orders of magnitude. For different attacks, we found SSFC orders that contradicted each other. Thus, there is no SSFC order that is optimal for every attack.

Next, we have designed a framework that performs attack-aware dynamic SSFC reordering. All security functions reside inside an SDN-enabled network. A security function wrapper co-located with every security function reports attacks at these functions via a separate management network to the FCC. The FCC computes the desired SSFC order for the security functions and submits it to the SDN controller, which enforces it by creating the necessary flows on the SDN switches. We developed a PoC implementation and show that the framework can enforce all possible SSFC orders. The framework successfully adapted to all attacks and, after the attacks ceased, successfully restored the default configuration. Thus this proved the desired functionality. An issue occurs when reordering, packets can drop or pass through a function twice. We proposed four options to combat this issue for different use-cases.

We model the traffic categorizing it into traffic classes, where benign traffic and every attack type each forms a class. Every security function affects the traffic as a function depending on the traffic composition. The model for an SSFC consists of multiple security function models. Traffic that exits one function continues to the next. Thereby, it is possible to compute the total resource demand.

The work on dynamic SSFC reordering is far from finished. In the future, we plan to evaluate our modeling and test it with various decision-making approaches. We also plan to extend the framework to allow different orders for different traffic types and evaluate its impact on energy consumption.

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