A Survey of Securing Networks using Software Defined Networking

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***Abstract*—Software Defined Networking (SDN) is rapidly emerging as a new paradigm for managing and controlling the operation of networks ranging from the data center to core, enterprise and home. The logical centralization of network intelligence presents exciting challenges and opportunities to enhance security in such networks, including new ways to prevent, detect and react to threats, as well as innovative security services and applications that are built upon SDN capabilities. In this paper we undertake a comprehensive survey of recent works that apply SDN to security, and identify promising future directions that can be addressed by such research.**

***Index Terms*—software defined networking, OpenFlow, network security, threat detection, threat remediation, network verification, anonymization, data offloading, network functions virtualization.**

I. Introduction

Computer networks typically consist of hosts interconnected by switches and routers providing data forwarding and routing functionality. These forwarding devices are usually black boxes that run proprietary operating systems and vendor-specific protocols that have to be individually configured in a tedious process in which network operators translate high-level network policies into device-specific low-level commands, manually input using command-line interfaces. The lack of unified network control makes network management challenging, and the painstaking error-prone configuration process is the leading cause of network faults, bugs, and security lapses [1] [2]. Furthermore, due to this inflexibility, network innovation has essentially stagnated, contributing to what some term the Internet "ossification" [3] phenomenon.

The recently emergent Software Defined Networking (SDN) paradigm [4] addresses this challenge by separating the packet forwarding functionality of the forwarding devices, i.e. the *data plane* from the control element, the *control plane*. This decoupling enables a radical new network architecture: switches in the network are reduced to basic packet forwarding devices containing *flow tables* populated with localized flow rules. These rules describe how incoming packets will be handled based on matching fields (such as packet header content, incoming port, etc.), and are managed by a remote 'controller' entity, which communicates securely with switches potentially using a standard and open interface, such as the OpenFlow protocol [4]. To reconfigure a switch as per new policy, the controller modifies relevant entries in the flow tables. This may also be done reactively, i.e. a specific packet may arrive at the switch necessitating that existing flow rules be modified or new ones be specified, and the controller updates relevant flow table entries in real-time.

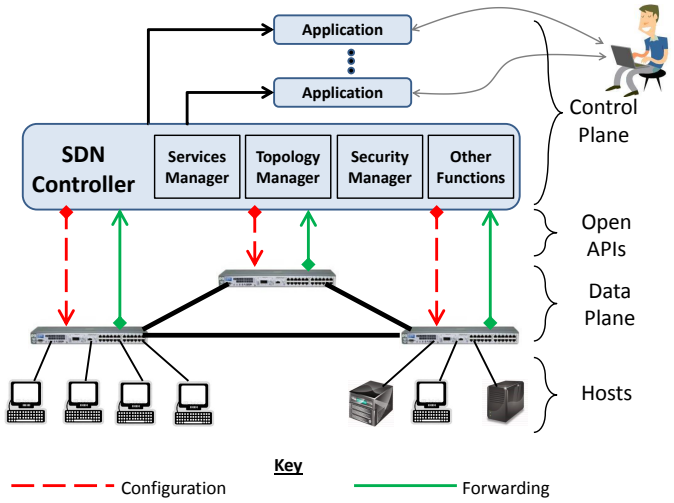

Fig. 1. The SDN architecture

This new architecture where control and forwarding elements in the network are disassociated, allows for a range of considerably more flexible and effective network management solutions. Compared to a purely distributed control plane, a logically centralized controller not only enables the implementation of consistent policy across the network in a dynamic and scalable manner, but also provides application developers with a unified programmable interface on which to deploy software and higher level applications. This abstraction is analogous to that of an *operating system* [5] in which the controller acts as the OS kernel which abstracts the forwarding hardware of the network. In such a case, network operators no longer need to enforce complex policies manually on individual switches and routers, instead they can specify high-level declarative policies for the network as a whole which an application running on the controller translates and installs in switches in the form of localized flow rules. A high-level view of this scenario is depicted in Fig. 1.

In addition, the controller polls flow statistics from network devices periodically, thereby compiling a centralized real-time view of network state. This state can be exposed via open APIs, allowing developers to automate the control process,

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enabling dynamic and efficient network management. Examples of innovative network management applications include dynamic load balancing [6], advanced threat mitigation [7], and virtual machine mobility [8].

SDN has captured the imagination of the research community and industry alike and the movement towards adoption has gained considerable momentum. Universities are actively building SDN deployments and testbeds [9], [10]. Google has already deployed SDN in-house for datacenter backbone traffic and reports an unprecedented network utilization of up to 95% [11]. There is significant interest from industry vendors: major commercial switch vendors including Cisco, IBM, Hewlett-Packard, Dell, Juniper Networks, Brocade Communications and others have announced intent to support or have already launched switching products that support the OpenFlow protocol. Industry and vendors have also launched collaborative efforts such as the Open Networking Foundation (ONF) [12] and the OpenDaylight project [13] to promote SDN standardization and innovation, and the IETF and IRTF have also set up SDN working groups. Market analysts agree that the SDN market will grow at a phenomenal rate: IDC predicts it will be worth $3.7 billion by 2016 [14]. ACG Research estimates that the service-provider SDN market (for 'live' SDN deployments) will reach $15.6 billion by 2018 [15].

The ability to view network state in real-time, and programmatically control network behavior, opens up exciting possibilities for network security. Security has assumed critical importance in recent years due to a number of reasons. As adoption rates for disparate networked devices such as mobile phones, tablets, and sensors skyrocket, networks face a 'crisis of trust' [16] and reports indicate that security threats continue to grow and evolve very rapidly [17], [18]. Furthermore, critical and aging infrastructure, such as automation systems, factory equipment, and traffic controls, are being brought online without adequate security and safeguards [19], amid growing fears of 'irrational' hackers [20]. In this paper we examine how SDN offers new ways to tackle these concerns.

We categorize current SDN-based security research into two branches, research geared towards protecting the network, and providing security as a service. The first direction, reviewed in Section II, deals with **security configuration** and **threat detection, remediation and verification** using SDN. The consolidation of policies at the central controller enhances consistency of configuration, helping prevention of attacks. The centralization of network state makes it easier to detect intrusions and anomalies, and to react in an agile and coherent way to isolate or neutralize the attack. As examples, a Denial of Service attack can be inferred from current network state, and a threat mitigation application may dynamically reprogram switches at the network perimeter to drop malicious traffic flows; a malware outbreak in one section of the network can be contained by instructing select switches to restrict traffic flows to that section; and a user on an infected machine can automatically be routed to a web-server issuing a quarantine notification. An analogy may be drawn to the 'immune system response' [21] where a centralized intelligence collects information from network elements and dispatches the appropriate response to the infected part.

The second branch of SDN-related security research, reviewed in Section III, develops innovative security capabilities that can be instantiated on-the-fly, thereby offering **security as a service**. For example, user identity such as IP address may be anonymized, affording privacy from targeted advertising or government surveillance; sensitive data may be offloaded securely within an enterprise network or across organizational boundaries; and management of security threats may be outtasked to specialized third parties. These security capabilities need not be always on, they may be selectively invoked on a need basis for specific traffic flows, thereby permitting an elastic cost model for the value-add services.

We believe that research in SDN-based security is still in its early days, and there are several areas in which SDN can play a pivotal role. In Section IV we discuss the major challenge of securing SDN itself, and promising new directions, which include the use of SDN to federate heterogenous networks, couple overlay networks with hardware, and for service chaining using network functions virtualization.

II. Protecting the Network

In this section we survey the basics of security configuration using SDN, and discuss new techniques for threat detection, remediation, and network verification.

A. Security Configuration using SDN

1) Centralizing the Control Plane: The original vision for software defined network security management is spelt out by Casado et. al in **SANE** (Secure Architecture for Network Enterprise) [22], a clean-slate security solution for enterprise networks. Enterprises today face a barrage of ever-evolving security threats and have little choice but to rely on a combination of security solutions that are complicated, distributed, and limited in scope. Security policies are typically implemented as complex, topology-dependent access control lists. Trust is distributed across multiple components, such as switches, DNS servers, authentication services (such as Kerberos [23] and RADIUS [24]) and each of these individual components need to be protected in turn. If a network element is compromised, an attacker may be able to identify vulnerabilities and obtain sensitive information about the network itself, such as the topology, the location of critical servers, etc. Furthermore, security enforcement at higher layers may be undermined by unsecured access at the lower layers.

In SANE, all connectivity in the network is mediated by a single protection layer that is overseen by a logically centralized controller in charge of all routing and access control decisions. High-level declarative policies can thus be specified in terms of services and principals that are independent of topology, e.g. *Alice can contact service ftp* or *users in group bobs-friends can access bob's streaming-audio server*, and the controller accordingly configures encrypted access routes across switches and routers. Security is enforced at the link layer and cannot be undermined by lower layers. The controller is the sole trusted entity in the network and it restricts network access for unauthorized parties.

Deploying SANE, however, requires a complete upgrade to the entire network infrastructure and modifications at the hosts. To ease deployment issues specifically, the authors extend their original work and propose **Ethane** [25]. Ethane retains SANE's primary vision of a centralized controller and introduces the additional element of Ethane Switches, which consist of basic forwarding hardware with minimal memory able to track flows in-progress. Ethane Switches can be deployed alongside Ethernet switches in the enterprise, and the controller ensures seamless traffic flow across them, thereby allowing enterprises the option to upgrade their networks incrementally. Furthermore, Ethane does not require modification at the hosts.

However, Ethane suffers from a critical shortcoming, pointed out by Levin et al. [26], that transitional deployment using Ethane switches cannot guarantee rigorous enforcement of network policy (including security) on legacy devices. The authors note that the real-world process of upgrading is slow, typically undertaken in stages due to budget restrictions, but that it is possible to realize the benefits of SDN in large enterprise networks using a very small number of SDN switches, provided that every network source-destination path includes at least one SDN switch. In their solution **Panopticon** [27], this fundamental requirement is modelled as a constraint in an optimization problem to determine optimal upgrade sites in the network in a cost-aware manner. VLAN technology (commonly available on enterprise switches) is then used to isolate network hosts and route network traffic through SDN-upgraded switches, ensuring that network policy is rigorously enforced. The technical challenges encountered using this approach are detailed in [28] and simulation results indicate that for large campus network topologies (> 1500 switches) by upgrading as low as just 0.6% of the existing switches, it is possible to operate more than 80% of the network as an SDN.

2) Flexible Policies: Software defined networking also allows network administrators to define intelligent and dynamic policies that strike a cost-effective balance between users' convenience and network protection. A popular example is that of Ballarat Grammar [29], a school in Victoria, Australia. The school, catering to over 1400 students, sought a campus-wide network security solution to facilitate WiFi access for personal devices, such as laptops and tablets, and would not be restrictive on students and staff. The school installed OpenFlow firmware on its switches and used Hewlett-Packard's Sentinel Security SDN application [30] to route DNS queries through an intrusion prevention system. This approach effectively filters for malware on user devices without having to install and manage specialized software on individual users' devices.

Administrators at Ballarat Grammar report a further advantage: previously when a machine would be infected, a user would report it to the IT department which would initiate diagnosis and repair, a process spanning several days to weeks. After deploying SDN, however, infections and malicious activities are detected and logged in detail by the Sentinel application, significantly aiding with trouble-shooting and reducing downtime.

B. Threat Detection

The SDN paradigm offers a new level of visibility into the network which is ideally suited for traffic monitoring applications. The controller can program forwarding devices in the network to conduct fine-grained packet inspection on traffic passing through the devices. These statistics, periodically collected by the controller, afford a centralized real-time view of network state which is exposed via open APIs, allowing for automation. Developers can write applications utilizing data mining and machine learning techniques to enable rapid intelligent identification of threats.

There is also the advantage of flexibility and scale: Microsoft has revealed that it uses a homegrown SDN solution to capture and analyze the huge volumes of traffic in its Internet-facing and cloud services data centers [31]. Data centers typically consist of thousands of 10 Gigabit Ethernet links, and traditional packet capture mechanisms such as port mirroring and SPAN, which require an immense number of physical ports, are infeasible from a scale and cost perspective. On SDN-compatible switches, virtual ports can be defined with ease for packet monitoring purposes. Furthermore, network operators can define software policies to create service chains, diverting flows through multiple analysis and inspection points. This obviates the need to insert dedicated middleboxes at traffic chokepoints in the physical network.

1) Denial-of-Service Attack Detection: Security solutions provider Radware has recently developed **DefenseFlowTM** [32], the first commercial SDN application that addresses denial-of-service (DoS) attacks. Radware has furthermore contributed a simplified open source version of DefenseFlow, Defense4All, to the OpenDaylight project [33].

DefenseFlow directs the network controller to collect specific flow statistics from forwarding devices in the network at a per second resolution. The application measures baseline traffic flows and then monitors for patterns suggestive of a DoS attack. In the event that a threat is detected, a traffic diversion mechanism programmatically redirects suspicious traffic to a dedicated scrubbing center (running Radware's DefensePro network behavioral analysis system) for detailed traffic inspection, signature analysis, and threat neutralization.

2) Traffic Anomaly Detection: SDN-enabled distributed traffic inspection functionality also has application to anomaly detection solutions. Anomaly detection mechanisms running on Internet core routers cannot process adequately the high volumes of traffic flowing through at line rates, and, additionally, these mechanisms generate a large number of false positives, which cannot be dealt with practically in the network core.

Mehdi et al. [34] make the novel suggestion that the user home gateway device is ideally positioned to run anomaly detection mechanisms. The advantage of the home gateway is that residential data rates are low enough to enable anomaly detection at line rate, false positives can be screened more efficiently, and specialized security policies can be managed on the device by a remote controller.

The authors implement four anomaly detection algorithms for the NOX SDN controller [5] (and these implementations

have been made publicly available). These include the Threshold Random Walk with Credit Based Rate Limiting (TRW-CB), Rate Limiting, Maximum Entropy Detector, and NETAD algorithms. Experiments are undertaken with real-world traffic datasets, into which the authors inject portscans and DoS attacks at varying rates, and perform anomaly detection at three points in the network: the edge router of an ISP, a home network router, and a switch in a small office. Results indicate that the algorithms are unable to satisfactorily identify anomalies at the ISP level but prove highly accurate running at the home and small office level.

C. Threat Remediation

In traditional networks, the only possible response to a threat has been to drop offending traffic. SDN, however, with on-the-fly programmatic capabilities, makes possible a richer variety of dynamic responses, including emergency alarms, dynamic quarantine solutions, traffic redirection for forensics, and entrapment mechanisms such as tarpits and honeypots.

FRESCO [7], proposed by Shin et. al, is an application development framework facilitating design of sophisticated threat detection and mitigation modules. FRESCO provides a scripting API and basic reusable modules, which can be assigned relevant parameters and stitched together into a desired security configuration. At compilation, these modules produce flow rules which are overseen by FortNOX [35], a specialized security enforcement kernel which is embedded in the network controller.

The authors provide two case studies to demonstrate the power and range of FRESCO: first they build Reflector Net, an application to detect and entrap malicious scanners. If an attacker initiates a large number of failed TCP connections, the ScanDetector module is triggered, prompting the ActionHandler module to redirect the traffic to a remote honeypot. The attacker therefore receives valid responses from the honeypot machine, under the impression that it is still communicating with the original target. In the second example, the authors demonstrate how FRESCO can be integrated with legacy security applications: monitoring tools such as BotHunter [36], in the event that they detect a threat, can invoke security applications written in FRESCO script to quarantine infected hosts on the network.

The FRESCO Application Layer prototype is implemented in Python and operates as an OpenFlow application on NOX. The kernel, FortNOX, is implemented directly into NOX as a native C++ extension. However, the architecture and methodology can easily be ported to other SDN designs and controllers. Modules are implemented as Python objects. The research team has built 16 commonly used modules (including a FRESCO Scan Deflector, an adapted version of the Botminer [37] application, and a P2P malware detection service) with plans to build more and release to the research community.

D. Network Verification

A popular area of research is the use of automated techniques to verify network consistency in SDNs. Human operators are prone to make errors: security professionals attending the DEF CON 18 conference recently reported encountering poorly configured networks "more than three quarters of the time" and they were in strong agreement that badly configured networks are the main cause of network breaches [1]. A Gartner study predicts that in the period 2010 to 2015, 80% of network outages impacting mission-critical services will be due to 'people and process issues', and more than 50% of these stemming from configuration modifications and updates and hand-off problems [2].

In software defined networks, such problems may be encountered when network controllers are shared by different users or applications, or multiple controllers operate in the same domain, leading to conflicting rules, violation of policy, or network faults, such as loops, black holes, access control violations, etc. Malicious parties may even bypass security policies by defining strategic flow rules to re-label and redirect traffic. Furthermore, in the case of large networks potentially comprising hundreds of switches, where multiple applications are able to program the network and SDN controllers have the capability to install approximately 50k new flows per second [38], there needs to be quick and efficient mechanisms to ensure security compliance, fault tolerance and fast failover.

Formal reasoning techniques are a powerful tool in this regard. The SDN paradigm simplifies the traditional network in two very important ways: first the network no longer consists of disparate elements running proprietary protocols but instead comprises uniform switching hardware with standard functionality and interfaces, communicating using a single open protocol. Second, network control is no longer purely distributed over several elements but restricted to the controller. The state and behavior of the network therefore is the logical outcome of configuration commands dispatched by the controller, and these can easily be modeled using formal techniques. This allows administrators to fault-check networks, verify network properties, and build in failsafe mechanisms. Formal techniques are already being applied in designing 'machine-verified' network controllers [39], programming languages for software defined networks (such as Frenetic [40]), and innovative abstractions with verifiable security properties such as isolated network *slices* [41] and security monitoring routing protocols [42].

The earliest work in this area, **FlowChecker** [43] is a property-based verifier solution to identify misconfiguration within the network. FlowChecker encodes switch flow-table configuration using Binary Decision Diagrams to model a state machine describing the behaviour of OpenFlow switches in the network. FlowChecker then uses the model checker technique to validate correctness of the interconnected network by pairwise comparison of each pair of flow table rules in the domain. Network administrators can also use this solution to analyse the impact of new applications on the network prior to installation. For experimental evaluation, the authors randomly generated flow tables of various sizes and overlap, and analyzed them for configuration conflicts. Results show that for a network of 120 switches and flow tables containing 1000 rules, it takes approximately 160 ms to verify correctness.

NICE [44] uses automated model checking to identify errors in SDN applications. The network operator inputs details

about the controller, network topology specification, number of switches, hosts, etc. NICE tests applications on this schematic by automatically generating specific traffic flows that study the network for a variety of different events, and identify property violations. NICE checks for specified 'correctness properties' which include no forwarding loops, no black holes, direct paths, no forgotten packets, etc. and operators may craft modules to code other properties. A key innovation here is that the authors utilize symbolic execution to bypass the rapid expansion in state space that typically arises when model checking is undertaken. Instead of exploring all possible states in the network, NICE models the impact of a subset of packets which are representative of all the different packet classes.

The authors prototype NICE using Python for the NOX controller to test three real applications (a MAC-learning switch, a Web server load-balancer, and energy efficient traffic engineering) and uncover several bugs. Experimental results indicate that NICE is five times faster than existing model checkers. The advantage of this approach is that finite-state modelling is a relatively simple verification technique which can be applied to various types of applications. However, there are limitations is that in applications with infinite states, this approach, even while identifying errors, cannot definitively prove that no errors exist. Furthermore, it is problematic to scale this approach to large networks in the real world.

In contrast to these solutions which are run prior to network initialization or application installation, **VeriFlow** [45] is a dynamic solution which verifies network correctness as the network evolves in real-time. VeriFlow is situated as a layer between the controller and the switches and checks the validity of network invariants whenever a new forwarding rule is installed. VeriFlow divides the network into a set of equivalence classes on the basis of existing rules. Packets falling into a class undergo the same forwarding decisions throughout the network. When a new rule is to be introduced, the classes that will be altered by such a rule are located and network invariants are verified within those classes. VeriFlow maintains forwarding graphs for the equivalence classes and traverses them to query the invariants. Each flow modification is thus verified in real-time before it is implemented. The VeriFlow prototype implementation, run using a NOX controller managing a simulated OpenFlow network on Mininet, validates that VeriFlow has minimal impact on network performance and can verify network-wide invariants in near real-time, within hundreds of microseconds. However, the authors note that it is not yet feasible to implement Veriflow in a network with multiple controllers because it is hard to obtain a complete view of network state in such a case.

FortNOX [35] is a NOX-based security mediation service that is directly integrated in the NOX controller, and is able to identify conflicting flow rules in real-time. This is done by converting all rules to a representation the authors refer to as 'alias reduced rules' by essentially enlarging the rules' match criterion to include wildcards and set operation transformations. These new rules can then be easily validated. In case of conflicting flow rules, the choice of flow rule is made depending on the relative level of security authorization of the requesting party. In case the flow rule is not implemented, the service returns an error message to the application. The authors simulated large traffic flows in a network and discovered that it takes less than 7 ms to compare a candidate flow rule against 1000 existing flow rules.

FLOVER [46] is another solution to verify compliance of dynamically assigned rules with invariant security policy in real time. FLOVER translates security policies into a set of assertions (referred to as Non-bypass properties) which can be processed and verified using an SMT (Satisfiability Modulo Theories) solver. Whereas this technique resembles the modelling approach taken in FlowChecker and VeriFlow, the authors emphasize a distinct advantage in that they also model and verify *set* and *goto* actions which the earlier works neglected, thereby identifying a potentially wider range of policy violations. We consider a simple example: a typical firewall rule may block traffic specifically originating from Host A that is addressed to Host B. However, an application may dynamically insert new rules into flow tables, enabling intermediate switches to re-label source and destination IP addresses of incoming packets and redirect them to other switches (using set and goto directives) such that traffic flows are routed from hosts A to B without explicitly violating the firewall rule.

FLOVER is able to resolve all intermediate actions during the flow rule verification phase rather than the modelling phase. Experimental results from using a simulated OpenFlow network on Mininet with a NOX controller, indicate that FLOVER can detect coverage and modify violations of up to 200 rules in under 131 ms.

Apart from real time network verification, there is also a need for fast failover mechanisms to cope with network disruptions. Typically, if a network link fails in an OpenFlow network, the switch informs the controller which programs new flow rules for all the affected switches. This process takes some time [47] as the controller will have to compute alternate paths, e.g. run spanning tree protocol, verify that new paths do not violate policies, etc. and during this period running traffic in the network may suffer from inconsistent flow and policy violations.

Newer versions of OpenFlow, however, enable multiple forwarding behaviors to be defined for the same switch, differentiated on the basis of switch state and specific parameters, such as whether a link is up or down. Reitblatt et. al [48] capitalize on this feature to formalize network correctness and fast failover in a high-level declarative application programming language called **FatTire** (Fault Tolerating Regular Expressions). With FatTire, programmers do not need to explicitly program failover forwarding rules, they simply specify policies and the controller precomputes appropriate backup paths and populates the switches with flows and backup flow paths. Now, in case a link or device in the network fails, the controller no longer needs to intervene, the network elements switch automatically to the backup rules.

A FatTire program has three policy components: a security policy (e.g. *all SSH traffic must traverse the IDS*), a fault tolerant policy (e.g. *forwarding must be resilient for a single-link failure*), and a routing policy (e.g. *traffic from the gateway to the switch can be forwarded using select paths*). The system

TABLE I
SUMMARIZED COMPARISON OF SDN NETWORK VERIFICATION SOLUTIONS

Solution	Method	Usage	Comparison
FlowChecker [43]	Binary decision graphs model checking	At application runtime	Verifies consistency of network configuration
NICE [44]	Finite-state model checking	At application runtime	Does not scale well for large applications
VeriFlow [45]	Equivalence classes and forwarding graphs	Real-time verification	Not suited to a multi-controller setup
FortNOX [35]	Alias reduced rules	Real-time verification	Resolves rule conflicts based on security privileges
FLOVER [46]	Non-bypass properties verified using SMT solver	Real-time verification	Includes resolution of *set* and *goto* actions
FatTire [48]	Intersection operations over all possible paths	At network configuration	Computes fast failover rules from policies

then computes all possible paths for these specifications, and performs the intersection operation, to identify those which fulfil all criteria. These policies are then translated into OpenFlow rules using a modified version of the NetCore compiler [49]. The authors have prototyped their solution which takes as input a FatTire application and a network topology, and outputs policies for individual elements in the network.

Table I presents a brief overview and comparison of these different solutions.

III. SDN SECURITY AS A SERVICE

In this section we examine how the SDN paradigm facilitates additional network security measures which go beyond network protection, enabling services such as anonymization, enhanced trust, and remote management.

A. Anonymization

In [50], Mendonca et. al present an SDN-based anonymization service to counter IP-based profiling on the Internet. Sophisticated data mining systems today are able to piece together significant detail about Web users from their IP addresses, attributes such as location, Internet usage patterns and possibly even their identity. Static IP address assignment also renders a user vulnerable to online censorship, active attacks, and breach of data. Existing approaches to reclaim anonymity, such as Onion routing overlays (e.g. ToR and Tarzan) are inefficient and have significant latency issues.

The authors propose **AnonyFlow**, a solution where Internet users offload trust to their primary ISPs which assign temporary IP addresses and disposable flow-based identifiers to user traffic exiting their domains. This is similar to the concept of NAT: third parties on the Internet no longer have visibility in the ISP network and are therefore unable to correlate user traffic to specific IP addresses with which they build composite user profiles. The authors present this as an additional service an ISP may choose to provide, similar to the caller-ID blocking service which withholds customers' phone numbers and call information from call recipients.

Previous attempts at such anonymization solutions required specialized gateways to track user state and traffic flows. The SDN paradigm dramatically simplifies this deployment: the controller can coordinate the implementation of custom routing policies across multiple switches in the network on an on-the-fly basis. The anonymization function is performed by the switches at line speed. Testbed results using commercial OpenFlow-enabled switches reveal that AnonyFlow causes near-negligible impact on throughput.

A similar approach is taken by Jafarian et al. [51] to anonymize network hosts to protect from online adversaries. Adversaries typically use stealth scanning tools to remotely probe IP addresses at random in networks to identify targets. When a host responds, attackers can probe it further to identify vulnerabilities and launch specific attacks. A typical solution is to dynamically modify host IP addresses using NAT or DHCP but the address assignment may be infrequent and traceable, and inconvenient in that active connections are disrupted during an address change. The authors therefore propose **OpenFlow Random Host Mutation (OF-RHM)**, a mechanism to *mutate* IP addresses of network hosts randomly and frequently in a fully transparent manner. In this case, the controller assigns each host a random and temporary *virtual* IP that is translated to/from the host's *real* unchanging IP address. External parties can access the hosts using their virtual IPs which are circulated via DNS. Access to the host using the real IP is restricted solely to authorized parties.

OpenFlow-enabled network switches perform the translation between real and virtual IPs and the controller coordinates the mutation process across the entire network. Virtual IP addresses are picked randomly from a pool of unused addresses in the network. Host IP mutation is set to be rapid and unpredictable for maximum efficacy, and even in a limited, fragmented address space, each host should mutate at required rate such that no IP address is reused for a long period. The authors treat these requirements as a constraint satisfaction problem, solved using Satisfiability Modulo Theories (SMT) solvers. They propose two mutation strategies, Blind Mutation, where virtual IPs are chosen from the address space with uniform probabilty, and Weighted Mutation, where the selection is weighted based on previous usage of the particular IP address. The authors implement OF-RHM in Mininet with multiple NOX controllers and theoretical results indicate that OF-RHM invalidates up to 99% of the information gathered by remote scanners, saving up to 90% of hosts from sophisticated zero-day worms.

B. Out-tasking Network Security Management

Small business and home networks are particular targets for online attack. The reasons are primarily lack of specialized security protection (e.g. dedicated firewalls, IPS systems, security expertise) due to the cost factor, a homogenous and predictable network architecture, and an erroneous belief in security through insignificance [52]. Kindsight Security Labs report that 10% of home networks are infected with malware in the second quarter of 2013 [53]. Small businesses are particular targets, they are the most victimized in the category of businesses; 31% of recorded cyberattacks in 2012 targeted businesses with fewer than 250 employees [54]. The Federation of Small Businesses, the UK's leading business organization, comprising some 200,000 small UK businesses, states that cybercrime currently costs its members up to 800 million pounds per year [55].

Feamster [56] points out that the SDN paradigm enables users to outsource their network security to professional third parties who possess operational expertise as well as a broader view of the network. There are already preliminary moves towards such an arrangement: basic ADSL modems can be easily configured to to use third party DNS services such as Google DNS and OpenDNS which provide protection from a range of malware, typo protection, phishing and optional content filtering. Software defined networking enables a complete transition and gives full control to a third party service. Research trials are already underway [57] where ISPs are installing Lithium OpenFlow controllers to remotely manage home networks on behalf of residential customers.

The basic model for residential users is as follows: programmable network access points in the home periodically dispatch traffic statistics to the (remotely based) controller which runs specialized algorithms to detect spam filtering and botnet detection, and implements the relevant protection policies (filtering rules, blacklists, etc.). The author identifies open research challenges in this scenario: devising a methodology for collecting statistics that strikes the appropriate balance between the scale of the data collected, efficacy of threat detection and maintaining user privacy. Suggested solutions include intelligently sampling the data depending on specific deployment scenarios and making the process dynamic (i.e. the controller could have the ability to demand finer-grained statistics if the need arises). The issue of collecting appropriate statistics on flows for security monitoring is explored in greater detail in [58], and specifically in the context of home networks in [59] and for large networks in [42].

To protect user privacy, the author proposes that ISPs or home users obfuscate IP addresses in flow statistics and anomaly detection algorithms work (on aggregate data) at the level of IP prefixes rather than specific IP addresses. Furthermore, the user may locally deploy privacy preserving algorithms to screen sensitive data before the results are uploaded to a central server.

C. BYOD and Secure Data Offloading

Software defined networking can also be leveraged to secure data offloading from mobile and handheld devices. Smartphones and tablets greatly enhance productivity, but sensitive data may need to be offloaded from the device on to the network for further processing, sharing, or archival. Dictaphone audio recordings may be offloaded to remote servers for software-based transcription, and patient data may be collected from bodyworn medical sensing devices for cloud-based data mining. There is also a trend among business and corporate employees to use their personally owned handheld devices to access corporate networks, creating a wealth of security problems. In such situations, SDN can dynamically slice and allocate network resources in a secure and elastic way as per the specific requirements of offload applications.

Gember et al. [60] identify in more detail the hurdles facing secure data offloading: offloading may require energy-intensive processing on the mobile device to capture execution state and the data transfer may incur problematic latency issues. Additionally, offloading must permit differentiated security settings, according varied access privileges and protections to different classes of data. Offloading, furthermore, must not rely on dedicated resources (which may cause bottlenecks in the system or single points of failure), and it must be scalable (multiple applications may vie to offload data with different objectives and policies).

To meet these needs, Gember et al. propose **Enterprise-centric Offloading System (ECOS)**, an enterprise-wide solution enabling mobile applications to offload data in a tightly controlled environment as per the privacy, performance, and energy constraints of users, and process the data by opportunistically leveraging diverse compute resources. The network controller negotiates the requirements of the mobile application, e.g. is encryption feasible with current energy resources, are trustworthy compute resources currently available, what level of security is required, etc. Applications can choose if they want energy savings or latency improvements and the controller leverages idle resources from the enterprise pool. Data is also graded into distinct categories, user-private, enterprise-private, and no-private, enabling the controller to implement differentiated service policies for each type. Since SDN manages flows in real-time, the mobile device can also move within the network during the offloading process.

ECOS is prototyped using OpenFlow and Android. Experimental results indicate that latency improves by as much as 94%, energy savings up to 47%, and as much as 98% reduction in execution state that applications need to communicate.

IV. Challenges and Future Directions

In this section we discuss potential challenges and future security-oriented applications for software defined networking.

A. Securing SDN

Whereas, so far we have summarized research where SDN enables greater security for networks, we discuss here the major challenge of securing SDN *itself*. In a position paper [61], Kreutz et al. make a persuasive case for the need to incorporate security and dependability into SDN design from the group up. They note that threats in SDN are not only of a different nature as compared to traditional networks, but,

by virtue of SDN being highly programmable, the potential impact is also far more serious. They outline certain categories of threats which may be used to attack SDN, including the following:

Forged traffic flows may be used to attack network entities, including DoS attacks on switches and controllers. Switches in the network may be exploited or hijacked to launch attacks on other entities. Control plane communications may be targeted with DoS attacks or exploiting weaknesses in TLS/SSL implementations. Faulty or hijacked controllers could wreak havoc in the whole network. Furthermore, the interface between the controller and high level applications is a potential point of attack.

The authors also briefly indicate potential solutions for these threats. Stringent authentication mechanisms and trust models could counter common identity-based attacks. DoS attacks may be addressed by enforcing rate bounds for control plane requests. Controllers should be replicated for resiliency. There should be a diversity of protocols, controllers and tools employed to reduce the set of common implementation vulnerabilities. Mechanisms could be implemented to ensure secure and timely collection of data forensics and administration of software updates. Sandboxing techniques could isolate security domains in SDNs and communication between these domains could be tightly controlled by well-defined protocols. The network could also be strengthened by employing tamper-proof devices to securely store credentials and sensitive data.

Research efforts have already started to address some of these challenges. For instance, the issue of DoS attacks and forensics collection is examined in more detail by Shin et al. in [62]. The authors describe the *control plane saturation* attack in which botnets may be used to overwhelm the control plane with a series of uniquely crafted forged flow requests and also saturate the limited buffer capacity on the switches. They also note that current SDN mechanisms for polling network traffic statistics are not ideally suited for monitoring applications since they do not provide the desired level of detail and granularity that may be required to deal with threats. In response to these needs, the authors present **AVANT-GUARD**, a set of extensions to the data plane. DoS attacks may be mitigated by enabling switches to proxy the TCP handshake with the packet source before allowing flow requests to traverse up to the control plane. Essentially, the switch does not forward flow requests to the controller until the source successfully completes the handshake and the switch receives some guarantees that the source is genuine. These may even involve receiving a few data packets from the source after the handshake before the switch contacts the controller with the flow request. Furthermore, AVANT-GUARD also allows the control plane to define traffic statistics or conditions for which switches transmit asynchronous notifications and payload information to the control plane. Switches may even be instructed to insert pre-defined flow rules into flow tables when a condition is met. This mechanisms allows security monitoring applications to define customised alarms, perform forensics on network traffic, and specify threat reaction strategies for the data plane.

Wen et al. [63] present a first-line defence against potential network attacks mounted via the controller API interface. Even if the network itself is fully trusted, malicious or poorly designed applications can misconfigure the network. To alleviate this threat, the authors propose **PermOF**, a solution which isolates the controller kernel modules at runtime such that applications cannot call on them directly, and defines a set of fine-grained permission categories which allow the network operator to sharply define access privileges allowed to applications.

These research efforts are steps in the right direction but there is an immense amount of work to be done before SDN can be confidently deployed in the real world. Cyberthreats are multiplying, evolving very rapidly, and growing increasingly sophisticated, and the potential impact of successfully attacking a highly configurable network may be catastrophic. We can no longer afford a reactive security strategy that the industry took with traditional networks. It is critically important that the security threats to SDN be realised at this early juncture in its evolution, and we consider it a promising sign that the research community is taking note of it.

We discuss next how the SDN paradigm of decoupling control and data planes may help secure other types of networks.

B. Federating Heterogenous Networks

The SDN programmable networks vision is already being applied to unify network management in WiFi networks [64] [65], to provide programmable interfaces across the wireless stack [66], for accessing services in IEEE 802.15.4 networks [67], and in coordinating services across heterogenous networks [68]. It is anticipated that SDN will also be a key driver in the emerging Internet of Things paradigm [69], where the centralized control element and standardized protocols facilitate the process of federating disparate devices such as mobile phones, smart TVs, computers, household appliances, sensor devices, healthcare monitors, etc. and enable implementation of federated policies on top. How to manage privacy and trust in a seamless and efficient manner across heterogenous networks and multiple devices is a critical question.

There is already a marked trend in this direction in home networks research: networking appliances and devices in homes and buildings is now practical [70] [71] [72], and there is a critical need to assure the privacy and security of residents [73]. The model for deployment of home networks is similar to SDN in that there is a centralized intelligence: certain research and industry efforts [74] [75] recommend enhancing the capabilities of the residential Internet home gateway device to serve as the controller entity and orchestrate operations between high-level user-defined applications and networked devices.

There is considerable potential for new research in the design and implementation of security policies for such scenarios. Smaller devices, such as actuators and sensors, generally possess limited compute and battery resources, and cannot run resource-intensive cryptographic protocols. There is therefore an urgent need for mechanisms which translate security privileges across domain boundaries and contribute to enforcing a

uniform federated security policy in a seamless and efficient manner. We expect the controller will play a key role in this regard. Existing research in wireless sensor networks may prove useful: an illuminating example is that of Sizzle [76] which implements a minimal footprint HTTPS stack between two endpoints, a Web browser and a miniaturized wireless device. With Sizzle, a user can control resource-constrained wireless devices (such as sensors, thermostats, etc.) from a browser window with end-to-end SSL protection. As we noted earlier, standard SSL operations are not practical for small devices. In this case, a basestation acts as a gateway device between the Internet and the wireless sensor network, and amortizes the high cost of an SSL handshake across multiple data transfers.

C. Coupling Overlays and Underlays

With advancement in virtualization technologies, overlay networks have become a popular choice for managing data centers and enterprise networks, and successful recent examples include Midokura MidoNet [77], Nicira NVP [78], IBM's Distributed Overlay Virtual Ethernet (DOVE) [79] and PLUMgrid [80]. Overlay networks enable finer customization, differentiation in services, and remote management, but may suffer from operational issues in larger and more complex deployments such as wide-area networks due to the loose coupling between the virtual overlay and the underlying physical hardware.

We believe SDN provides strong impetus for deploying overlays in wide-area networks to provide benefits for the average Internet user. Common overlay networks used today, including peer-to-peer networks (e.g. BitTorrent), VOIP services (e.g. Skype), and content delivery (e.g. Netflix) have little or no visibility into the underlying network, ISPs are unable to provide users with performance guarantees, and the user experience tends to suffer. For this reason the research community has advocated augmenting overlays to enhance end-to-end performance and security of Internet applications. These include mechanisms to proactively detect and reroute around failed links [81], reduce network latency by strategically employing network processor subsystems [82], countering DoS attacks [83], and restricting traffic flow to trusted regions in the network [84]. Nakao et al. even suggest creating a separate routing *middle layer* which extracts topology information from the Internet and passes it up to the overlay, enabling it to make path-aware routing decisions [85].

Overlay networks deployed on OpenFlow networks can use native SDN protocols and open APIs to directly query and configure the underlying physical network for significantly improved performance and reliability and concrete service guarantees. Highly efficient overlay networks can be easily set up over SDN underlays and configured with desired properties. We are already witnessing a rapidly growing interest in unregulated and decentralized peer-to-peer overlays to manage cryptocurrencies and secure anonymized communications (such as Bitmessage [86]). In the future, we anticipate overlays with verifiable security properties may be designed to enable routine everyday tasks such as secure banking and online shopping. More esoteric possibilities include bypassing censorship (such as the Infranet project [87]), or constructing specialized overlays for sensitive functions such as anonymization [88] and decentralized electronic voting. SDN could directly contribute to the health of the network by improving lower-level path selection, enabling load-balancing solutions, and tightly controlling access into the network.

D. Beyond OpenFlow and Network Functions Virtualization

Currently we are also witnessing a move towards instantiating sophisticated compute capabilities in the network itself. This trend goes a step beyond the OpenFlow SDN vision (exemplified in the work we have covered thus far) in which switches and routers are considered minimal data forwarding devices. In contrast, **Switchblade** [89] uses programmable FPGA hardware to deploy extra features 'on-the-fly' in forwarding elements, providing functions such as customized protocol processing, path splicing, etc. Similarly, the **Cisco onePK** [90] platform seeks to build greater functionality into the forwarding path, delivering a range of functions such as encryption, transcoding, and deep packet inspection, and release APIs which give developers fine-grained control over these processes.

Narayanan et al. [91] suggest an application extensibility framework for deploying middlebox functionality (such as encryption) on programmable switches which is compatible with the OpenFlow protocol. Their solution abstracts the packet processing modules on the switch and creates a virtual port on the switch. Network operators desiring to use the processing functionality can use OpenFlow rules to route traffic to the new port.

A complementary trend is that of **Network Functions Virtualization (NFV)**: specialized network middleboxes (such as firewalls, encoders/decoders, DMZs, deep packet inspection units) also suffer from lack of innovation in that they are typically closed black box devices running proprietary software. Researchers have proposed that specialized middleboxes be defined entirely as virtualized software modules and managed via standardized and open APIs [92] [93]. This brings in the benefits of reducing expenditures in purchasing and maintaining customized hardware, and time-to-market for new services is accelerated. However, the real value of NFV lies in meeting economics of scaling demand. With the traditional model, growing demand for services requires purchase and installation of new hardware which takes time and effort. With NFV, network services are elastic, and new resources can be allocated to meet demand in minutes.

SDN is essential to interconnect these virtualized network functions in a dynamic and transparent manner. Developers can write powerful applications by stitching virtualized function modules in desired service chain configurations, and use SDN protocols to optimize traffic flows along the chain and maintain end-to-end QoS and policy control. Carriers can use NFV/SDN in this manner to service flows more accurately and efficiently.

Open research questions in this context include how to architect and manage these middleboxes satisfactorily, to address the inevitable increase in latency when hardware functionality

is coded in software, and how to best distribute functions across the network, i.e. increase 'in-network' capabilities for security functionality such as firewalls, network caching, and DRM-management in an efficient and scalable manner.

V. Conclusion

Research in software defined networking is still in its early stages, and we consider it a healthy sign that there is already significant work being done to develop innovative new security solutions and applications for these networks.

In this paper, we have undertaken a comprehensive review of security-oriented research in software defined networks. We have classified current work in two main streams: *threat detection, remediation and network correctness* which simplify and enhance security of programmable networks, and *security as a service*, which offers new innovative security functionality to users, such as anonymity and specialized network management.

Furthermore, we discuss possible challenges and future directions for security in SDN: these include the critical question of securing SDN itself, of orchestrating security policies across heterogenous networks, customizing overlay networks to provide secure environments, and extending the OpenFlow paradigm with customized hardware and network functions virtualization and building a richer set of features in the forwarding path.

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