SDN-Controlled Isolation Orchestration

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Contents

Abstract

Numerous data breaches and ransomware attacks in recent history have highlighted the importance of data security. There is always a trade off between security and end-user autonomy. Organizations need methods of securing data without overly hindering productivity. Current systems either do not provide enough control over data usage or overly restrict users and hinder productivity.

This project designs and implements a system intended to provide fine-grained control over data while allowing end-users more freedom over their systems. Our system leverages the confidentiality benefits of virtualization to provide end-users with multiple environments to work. These environments are protected by security controls proportional to the data contained within. Users are allowed environments for high-risk activity and are confined to interact with sensitive data in low-risk environments. We build a data provenance tracking system to label, update, and transmit data provenance labels. Provenance labels determine how data is distributed among different risk environments. We build a distributed network control system to manage what network connections each environment can make. Network connections can be allowed or denied based off a centralized rule matrix.

We perform benchmark testing on the data provenance tracking system and network control system, and find that their overhead does not pose a threat to the usability of the systems it governs. We evaluate the mechanism that transmits provenance labels and likewise conclude that it does not impede the usability of the system or the network on which it transmits. We also monitor the latency, or responsiveness, of the network control system and found minor impact.

1 Introduction

With the rise of data breaches and ransomware attacks in recent years, the importance of data security in the 21st century is clear. Data breaches and ransomware attacks can cost organizations significant recovery time and money, likely interrupting or affecting their day-to-day operations. In 2020, ransomware payments increased by 311% from previous years to a total of $350 million [1].

The COVID-19 pandemic has also sparked a large movement of people to fully remote work preventing them from being connected directly to a corporate network and potentially leaving themselves and the data they are handling vulnerable on a home network. Current solutions for this problem involve difficult-to-use security controls that can impede day-to-day work [2]. Organizations also must maintain the confidentiality, integrity, and availability of their user data. This must be done with access controls to ensure the data is only accessed when it needs to be and by the processes and people that need to access it. Though proper access controls greatly reduces potential attack surface, they can increase difficulty of working with the data.

Current access control mechanisms do not offer the flexibility and security needed to keep up with these modern issues. In this paper, we leverage multiple isolated environments to separate various levels of sensitive information. We develop a centralized organizational access control system to integrate with and broker information access and migration between environments. We measure file and network access events in each environment and send these events to the centralized access control system. This system makes decisions on whether or not the actions are permitted, which is then forwarded to the environments to enforce the decisions.

In traditional systems, access controls decisions are made and enforced on endpoints. This system will enable security administrators to influence when information can cross boundaries by combining a network based, centralized access control system along with Mandatory Access Controls to ensure policy is enforced. Additionally, the isolation of data into separate environments along with data provenance tracking helps to ensure data does not become contaminated with more sensitive data without also changing the data's provenance level.

Despite these benefits in our system, there are operational and financial costs associated with implementing it. First, all endpoints must be capable of running multiple Virtual Machines. This requires a significant amount of processing power that may not be included with a typical workstation. Each endpoint must also maintain a constant network connection to communicate with the centralized access control system. Additionally, the centralized access control system must be capable of processing large amount of incoming data and the network that supports the system must be capable of transferring the data with little latency.

The remainder of the paper is structured as follows. In Section 2, we discuss background information on access control mechanisms, virtualisation, software-defined networking, as well as works related to this paper. In Section 3, we discuss the design of the centralized access control system as well as a high level overview of the data provenance system that is run on

each endpoint. Section 4 includes details about the proof of concept we built to implement our design. In Section 5, we discuss the tests we ran to measure behavior of our implemented system and analyzed the results. Finally, we discuss lessons learned, future work, and the implications of our work in Section 6.

2 Background and Related Work

This research focuses on methods to transmit and maintain data provenance while minimizing organization overhead and maintaining user autonomy. To provide the reader with a better understanding of the landscape, we introduce the concepts of access control mechanisms and data provenance. We also report on similar works in the fields of data loss prevention, intrusion detection systems, virtualization, and software-defined networks.

Private organizations have long lacked a mechanism to securely store and regulate access to data of multiple sensitivities when stored on an individual's machine. Popular access control schemes do not offer the fine-grained control in a modern work environment (Bell-LaPadula or Role-based Access Control), or require significant overhead to maintain the system (Attribute-based Access Control)[3][4][5].

2.1 Access Control Mechanisms

Access control mechanisms provide a way to ensure data confidentiality and integrity. There exists a large variety of different mechanisms, each with different configurations. With all of these schemes, different systems can use different configurations and mechanisms for their specific needs. This paper is based around Mandatory Access Control and a variation of Attribute-Based Access Control.

Currently, Discretionary Access Control (DAC) is one of the most common schemes for access control. DAC governs the access of information based on the user's identity, authorization, the information itself, and whether the user is requesting to read, write, or execute the information [6]. Any subject in a DAC system can pass its access, or a subset of its access, to any other subject [7]. For example, the user "user" in a Linux system could grant everyone access to a file it is the owner of. Because of this, DAC is much more flexible than other mechanisms and is therefore used widely in standard operating systems such as Microsoft Windows and Linux [8]. Unfortunately, it is simple to bypass DAC, as once a user has a piece of data, there is no restriction on its usage. As such, a user could simply re-distribute the data to users who were not authorized to read the data by the original owner [7].

In contrast, Mandatory Access Control (MAC) is a high security access control scheme that allows security administrators to define a policy that is guaranteed to be enforced for all users. These security policies are arbitrated by a "reference monitor" [4], or an authoritative system that enforces policy. With MAC, users do not have the ability to override security controls.

With DAC, a user could modify the controls on the SSH configuration file which could allow unauthorized users access to the user's SSH keys, creating a severe security vulnerability. MAC allows a security administrator to enforce controls, preventing users from creating insecure controls on files. With MAC, users without sufficient authorization cannot grant more access to an object, preventing a central issue with DAC.

One key implementation of MAC is the Bell-LaPadula Model (BLP). BLP was designed to be used by the US military to formalize the Department of Defense Multi-Level Security policy [9]. BLP focuses solely on data confidentiality and does not look at data integrity. There are three primary security properties that define BLP: The Simple Security Property prevents a user from reading an object at a higher security level, the Star Security Property prevents a user from writing to an object at a lower security level, and the Discretionary Security Policy allows further restriction of access using an access matrix [3]. These three rules are more simply stated as "read down, write up", which means that a person at a specific security level can read from any lower security level and write to any higher security level. There is also a Strong Star Property which allows a subject to only write to their security level, but not a higher or lower level [10]. This property allows for a higher level of integrity than typical BLP provides.

Though DAC and MAC are both valid access control schemes on their own, it is more common to implement them using a higher level scheme such as Role-Based Access Control (RBAC) or Attribute-Based Access Control (ABAC). RBAC is a method to implement MAC or DAC by assigning users to "roles" where each role has a specific set of permissions. RBAC is currently the gold standard for access control in many organizations as it is easy to implement and provides sufficient security [4]. A major drawback of RBAC is that it is not fine-grained. To provide small changes in access control, new roles must be created which can cause an unmanageable number of roles to exist. In contrast to the coarse-grained control of RBAC, ABAC provides much more fine-grained control. With ABAC, objects are controlled using an access control equation, allowing complex decisions to be made on whether a user is authorized to access the object [5]. For example, an object could be made to be accessible by all users in organization A, all users in organization B that also have a specific level of clearance, or a specific person in organization C. With RBAC, this would be very difficult to implement in an efficient manner, but ABAC allows for fine-grained control [4]. Though ABAC allows for very fine-grained control, implementing ABAC on an enterprise level can incur large development, implementation, and performance costs due to its high complexity [5].

2.2 SELinux

Security-Enhanced Linux (SELinux) allows security administrators to implement MAC policies on a Linux device. SELinux was originally developed by the NSA to implement the Department of Defense's Multi-Level Security (MLS) system into Linux [11][9]. SELinux is commonly configured via targeted policy or MLS mode. Targeted policy contains a large selections

of policies for common Linux applications. MLS allows for classification levels for users and files and implements the Bell-LaPadula model. MLS mode is typically only used my government organizations due to its complexity [11]. Everything in a system with SELinux has a label - including files, processes, and ports. Labels are comprised of an SELinux User, role, type, and level. The SELinux user is conceptually similar to a normal Linux user, SELinux maintains a mapping of SELinux user to regular Linux user. In targeted mode, type is the most important part [11]. SELinux's type enforcement applies policies that define whether a process running with a certain type can access a file labeled with a certain type [11].

2.3 Data Loss Prevention & Intrusion Detection Systems

Organizations that store important data have been increasingly targeted by cyber criminals in recent years. The Department of Health and Human Services (HHS) estimates that almost 30 million patient records were breached in 2020 [12]. In response to the increase of cyber crime, organizations have invested in Data Loss Prevention (DLP) tools. A DLP tool identifies data on a system, organizes that data into classifications, and enforces organizational policies on sensitive data [13]. Corporate data generally exists in the following locations: large centralized/distributes file at rest, moving throughout the network and with external devices, and on endpoints such as laptops and USB drives [14]. For our purposes we will mainly focus on securing data at endpoints, specifically end-user machines.

DLP products faces two main challenges: volume and accuracy. DLP tools are required to process terabytes of stored data, analyze the network traffic of the entire network, and track activity for thousands of endpoints [13]. It is essential that the identification process is efficient and scalable. These products generally use pattern matching and hashing to identify data types. The issue arises when data is reformatted or transformed in a way that avoids programmatic detection [13]. Allowing users to manually classify data is also problematic; human error poses threats to accuracy and consistency. Lastly, a DLP tool must be able to understand and enforce policy requirements as specified by the organization.

An example of such a tool is UC4Win. UC4Win is a data loss prevention solution for Microsoft Windows. Like our project, it uses system calls to provide fine-grained policy protection. UC4Win also shares goals with this project - "the enforcement of a defined policy concerning the usage of sensitive data" [15]. UC4Win accomplishes this by modifying Windows system calls to interpose itself between applications and the operating system [15]. However, our project monitors the system through Linux's logging module. One benefit of this approach is that it takes advantage of native Linux functionality and does not require modifications to the operating system. Due to the difference in mechanisms, UC4Win benefits from increased visibility into user actions and has the ability to block system calls before they happen. UC4Win utilizes Obligation Specification Language (OSL) - a mechanism to encode policy requirements into a machine readable format. One of the biggest limitations of DLP enforcement systems is

that they "might not be able to withstand sophisticated attacks, and thus may not be suitable to defend against data disclosure by malicious attackers such as hackers" [15]. For that reason, organizations often employ intrusion detection systems (IDS).

There are three main methodologies for detecting intrusions: signature detection, anomaly detection, and stateful protocol analysis [16]. Different implementations of an IDS will have unique mechanisms of event gathering, storage, and processing. Signature detection, also known as "knowledge-based detection", searches for patterns that have been recorded in previous attacks [16]. Anomaly detection creates a profile of expected behavior from monitoring normal day-to-day activity and flags abnormal behavior as potential attacks. Stateful protocol analysis, also known as "specification-based detection", is similar to anomaly detection – it relies on knowledge of specific protocols to create rules that determine if activity may be malicious [16].

Demand for IDS tooling has increased in response to the rise of cyber crime. Accenture's Cyber Investigations, Forensics and Response team found a 125% increase in cyber crime in the first half of 2021 [17]. CrowdStrike Falcon is a popular suite of enterprise cyber security tools. CrowdStrike installs hosts on all endpoints that monitor events, analyzes the endpoints for abnormal activity, and stores that activity in "Threat Graph"[18]. Threat Graph is a proprietary data structure that summarizes a device into a "state." That state is stored as the graph node and events are stored as the transitions between nodes [19]. Since Crowdstrike falcon is a commercial product, detailed information of how it works is limited beyond the filed patent.

There are two relevant subsets of intrusion detection systems: host-based intrusion detection systems (HIDS) and network-based intrusion detection systems (NIDS). HIDS is a variant of IDS that generally monitors activity on an end user's operating system. HIDS often relies on a kernel level event audit system to generate system logs, process logs, user commands, and file access logs [20]. Audit software can be resource intensive but it has high visibility into a system [20]. NIDS monitors network traffic flows on a device. NIDS consumes less resources than HIDS but only having visibility into network traffic reduces accuracy [20].

AlarmNet is a combined host-based IDS and network-based IDS that utilizes a neural network to process event data. AlarmNet is not unique in this. Machine learning is an extremely common tool to process data for an IDS [21] . AlarmNet uses "word embedding methods and convolution neural network" to transform data into an intermediate state to be consumed by the decision making neural network [22]. Once the decision making neural network is sufficiently trained, it is put into a decision making module that detects malicious activity on a system. Our system processes the same data as AlarmNet, however, we employ an algorithm to parse event data. We use that data to detect when data crosses a boundary based on a set of predetermined rules. Host event data is collected by AuditD for our system and AlarmNet [22].

AuditD is a component of the Linux auditing system that can be configured to produce logs of specific events on the system [23]. Specifically AuditD refers to the audit daemon that communicates messages from the Linux kernel to the user. The specifics of delivery can be configured from `/etc/sysconfig/auditd` and `/etc/auditd.conf` [24]. Audit rules are contained

in `/etc/audit.rules`. These rules configure which messages should be delivered from the kernel. AuditD can be configured to transmit a variety of messages. We will focus on two types of rules: actions and watches.

Actions log system calls (syscall), which is how an application interacts with the operating system. Common use cases include requesting disk IO and network resources AuditD can be configured to log syscalls made by the operating system and can be filtered by: the specific syscall, the arguments of the system call, and the file system (if relevant) among other things. The alternate approach to using AuditD is to implement "watches", which logs whenever a "watched" file is accessed. Watches and actions generally accomplish the same goal. Figure 1 shows an example of how AuditD logs an application opening a file.

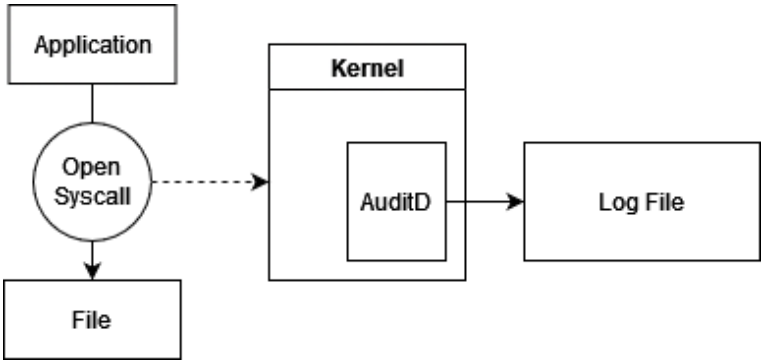

Figure 1: How AuditD Logs File Interactions

Similar to AlarmNet, our proposed system utilizes AuditD, but for a different purpose. We propose the use of AuditD to log file access syscalls, linking them to the application and targeted file. This allows us to determine when files are accessed by multiple applications and use that information to define access controls.

2.4 Data Provenance

Our project shares similar goals, complications, and mechanisms with both DLP and IDS systems: the intent to minimize data loss and the need to efficiently and accurately classify information. However our system does not process information at a data element level. Instead, we focus on the origination and purpose of the data, also known as data provenance. "In its strongest form, data provenance supports information and process integrity by documenting the entities, systems, and processes that operate on and contribute to data of interest. This serves as an unalterable historical record of the data's lifetime and its sources" [25]. Recent research has included applications in operating systems and security [26] [25].

Some of the limitations of data provenance include integrity and storage. Relying on provenance metadata can be risky if the authenticity of the metadata cannot be verified [25]. Additionally, a data set will accumulate metadata throughout its life cycle. It is risky to trim the associated metadata since it is impossible to determine what part of the history will be relevant

in the future, [25]. We propose a solution to mitigate this limitation in specific situations by adopting a practice commonly used in data taint analysis and employing a variation of RBAC.

When using data provenance for access controls for data loss protection - it is essential to know what types sensitive data may be at risk within a given data set. We claim that in that situation, knowing the order in which the data set was manipulated is irrelevant - the important information is the potential sum of the data within. For example, there are three data sets: the first containing first names, the second containing last names, and the third containing social security numbers. Separately, these data sets are important but not critical. However, if these data sets were combined it would be considered personable identifiable information (PII)[27]. The order in which these data sets are combined does not matter in this context, only the fact that the data set now contains PII and must be subject to organizational security controls accordingly.

In data taint analysis: when a suspicious data element comes into contact with other elements in the system, those elements are deemed equally suspicious[28]. In a system that cannot determine with certainty whether the suspicious data element compromised another, any interactions must be assumed to be malicious. In that same vein, we propose the use of that doctrine with the interactions of data provenance.

RBAC commonly chosen over ABAC because the functional use of ABAC requires prohibitive overhead [5]. Therefore we propose a system akin to RBAC that employs the data provenance doctrine ascribed previously to dictate access controls throughout an organization. The "roles" represent the security requirements associated with that data set.For example: Payment Card Information (PCI) requires specific security controls and by definition must contain certain data elements [29]. Therefore a data set containing PCI would also carry metadata declaring as such. For the remainder of this paper, we will refer to a data set's role as its classification. Depending on the setting, users may be required to interact with data sets that have varying classifications. It could be useful to have a system minimizes contamination between classifications but allows a user to access their entire workflow without interruption.

2.5 Virtual Machines and Containers

Virtualization refers to to the technique of creating isolated environments within a physical computer. These isolated environments are usually virtual machines or containers. The virtual machine, also known as a guest, behaves as if it is a physical machine but all the physical components are simulated by the real physical machine (also known as the host) [30]. The program that manages virtual machines is known as a "Virtual Machine monitor" or more commonly, as a "hypervisor." There are two types of hypervisors: Type 1 hypervisors are "bare-metal" and host the virtual machine directly on physical hardware, Type 2 hypervisors run on top of an operating system. Generally Type 1 hypervisors are faster since there is no host operating system.

Containers function differently from virtual machines. Containers are isolated instances of

an operating system that share a kernel [30]. This difference makes containers faster. Often containers are used in situations that require instantiating numerous virtual environments simultaneously. However, containers require a host operating system and the containers must be the same operating system, since kernels are not cross-compatible with other operating systems. Since containers share code, there is always a risk that malicious code within a container will spread to other containers or escalate privileges into the host OS [31].

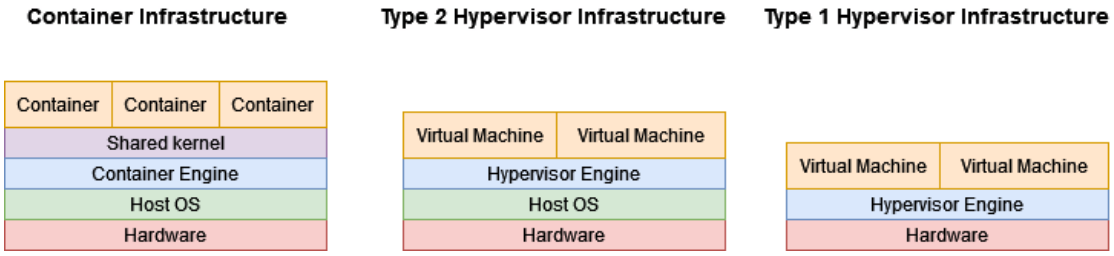

Figure 2: Virtualization Infrastructures

Virtual machines were created to partition IBM mainframes into logical segments and quickly caught on as an efficient mechanism for running multiple applications at the simultaneously [32]. In addition to performance benefits, virtualization offers isolation. In a traditional system, applications on a system can see each other and interact with shared resources. In a virtual system, every virtual instance is cut off from the other, only the virtualization engine can see and interact with the virtual systems. Security researchers leverage this feature constantly. Malware is often examined within virtual machines so that any damage is contained to the virtual machine. Additionally, relying on isolation can improve existing security policy [33].

Because virtualization relies on isolation, if an attacker can break isolation they can leverage their access and infect other virtual machines or the host operating system [32]. Often systems are configured to intentionally break isolation. For example VirtualBox provides the capability of sharing clipboards between machines, this makes it easier to work with, however an attacker could leverage that to spread malicious code or exfiltrate data [34].

Qubes OS is an operating system that leverages the isolation capabilities of a type-1 hypervisor to provide unique security capabilities to the end-user. The goal of Qubes OS is to minimize the impact of insecure applications by isolating insecure activities from critical data. Each isolated container is known as a "qube." Qubes instantiates one qube known as dom 0 that serves as the buffer between other qubes and the hypervisor and acts as a qube manager. Each qube has access to a suite of virtualized devices, each abstracted into a qube itself [35].

Qubes OS has been used as the basis for a variety of systems that can utilize isolation or improve user experience. SAFE-OS is a patented system that builds on Qubes by creating the Dom U, a variant of Dom0, designated for untrusted materials. SAFE-OS also abstracts away the isolation components from the user interface, presenting a unified view to the user [36]. However, Qubes OS is not stable enough for enterprise and only works on specific sets of hardware. The difficulties of installing and configuring Qubes OS may be prohibitive. Our proposal seeks to

demonstrate security controls designed around virtualization without the use of Qubes-OS.

Bitvisor is a system developed by a multitude of universities and companies at the behest of the National Information Security Center (NISC) of Japan [37]. This system introduces a hypervisor that provides encryption/decryption for storage devices and network connections. Bitvisor aims to minimize data loss from end-user devices for government and corporate organizations [38]. Specifically, data loss that originates from unauthorized use of USB drives or physical theft of the laptop [39]. Bitvisor is similar to our project in that it leverages virtualization to minimize data ex-filtration.However, we propose a virtualization scheme that focuses on minimizing software and network level data ex-filtration and Bitvisor aims to minimize data ex-filtration through hardware.

Hysolate is a commercial product that isolates end-user machines into a non-persistent "risky zone" and a "secure zone." The "risky zone" enables employees of an organization to browse the internet, handles device IO, and exercises minimal security controls in the name of end-user autonomy. The "secure zone" stores all the organization's critical applications and data. Networking and on-device controls configured by a cloud hosted control panel. Hysolate's features are extremely limited in scope. The virtualized machine can only be a non-persistent version of Windows 10. Therefore, any data saved only the hard drive is lost on reboot and a new Windows 10 image must be requisitioned at start time. Organizations cannot configure an OS image ahead of time. Any changes to the image must occur every time an end-user installs the image. Additionally, the system only creates one boundary on the end-user system. This limits organizational policy to essentially a boolean operation of "is this secure" or "is this untrustworthy", there is no mechanism to enforce unique security controls based on the classification of data [40]. Our project explores the security benefits of using virtualization as an access control boundary, but with persistent hosts and multiple boundaries.

Shamon is a system that utilizes a Type 1 hypervisor, SELinux, and IPsec tunnels to enforce MAC policies on a group of computers on an untrusted network. The goal of this system is to extend the fine-grained control of SELinux and RBAC to a distributed system. Generally, RBAC schemes do not lend themselves well to large networks as they quickly require too many roles to be feasible. This system presents the concept of using virtual machines as a mechanism to simplify RBAC implementations [41]. Shamon allows for the assurance that MAC policies are enforced across systems and that distributed computations can be protected. Shamon assumes that the network between physical machines is untrusted but offers a trustworthy mechanism for communication between virtual machines sharing a host. We share this concept of using isolation to simplify access control models and apply it to a different use case: a system of virtual machines across a trusted network but with the added responsibility of maintaining data provenance throughout the system. Virtual machines in our system interact in the same fashion, regardless the underlying physical machine.

For this paper, we chose to use VirtualBox, a Type 2 hypervisor. We considered both Docker containers as well as Xen and QubesOS, but decided to use VirtualBox. Docker containers

provide ease of use as they are small and lightweight, but do not provide the same security benefits and extensibility as a Type 1 or Type 2 hypervisor. We decided against Docker as we wanted to avoid container kernel security vulnerabilities [31]. Also, since OpenVSwitch requires kernel modules, it must be installed on the host and the Docker container must run in privileged mode [42]. Docker privileged mode allows processes inside the docker container to access all devices on the host as if it were root. This can result in security problems if the container were to become compromised [43]. Type 1 hypervisors provide the security benefits of a hypervisor without the performance costs of a Type 2 hypervisor, but they can be more difficult to work with. Since the hypervisor engine is not run on top of an operating system, it can be more difficult to configure. When investigating Type 1 hypervisors, we were working of off QubesOS. Though QubesOS provide immense security benefits over other options, it does not function on all hardware and is difficult to configure and use.

2.6 Software-Defined Networking

Software-Defined Networking (SDN) is a networking paradigm that increases flexibility in network management by abstracting the control system away from vendor-specific technology [44]. SDN provides a centralized programmable platform that can control an unlimited number of networking devices. Each networking device communicates with the SDN controller to receive configuration changes and packet flow control information. The SDN controller also receives analytical traffic data from the networking devices, enabling visibility into the traffic flowing in the network.

Software-Defined Networking is the culmination of three decades worth of research into making computer networks more programmable [45]. Motivated by the desire for fine-grained control, dynamic operation, rapid development of network services, and research experimentation at scale, so called "Active Networks" became the foundation of what we now know as SDN. Much of the promises of Active Networking still apply to SDN; primarily, unified control over networking devices across vendors and models [46].

The most common protocol used for SDN is OpenFlow [45]. The OpenFlow protocol defines a standardized mechanism by which networking devices can be controlled dynamically and programmatically. The rapid growth in popularity of OpenFlow can be attributed to the OpenFlow community's focus on backwards-compatibility with existing protocols and technologies. OpenFlow-enabled switches store one or more tables of packet-handling rules that define how the switch should handle a packet that matches the rule. When there are no rules defined the switch requests a flow decision from the controller [47]. Upon receiving such a decision, the switch stores the rule in its table and handles the packet accordingly.

Standard SDN implementations with OpenFlow focus on controlling the networking hardware, primarily switches, that handle network traffic [48]. These implementations are simple to deploy, but only allow a coarse level of control over the network traffic. Host-based SDN

extends the traditional SDN to include control over each host that is connected to the network [49]. A host-based SDN implementation allows much finer control over what network traffic is allowed or denied based on what application process is operating on the network traffic, which user executed the application, as well as which device the traffic is originating from [48]. Host-based SDN is implemented by deploying an agent to each endpoint device that will connect to the network. The endpoint-host routes all communications through the agent, enabling the agent to report on the traffic being sent and the applications or process that are sending it. Since our design relies on OpenFlow to regulate network connectivity between clients, we must be able to assume that OpenFlow is trustworthy.

One tool that assists in deploying SDN is FRESCO. FRESCO is "an OpenFlow security application development framework designed to facilitate the rapid design, and modular composition of OF-enabled detection and mitigation modules" [50]. FRESCO provides a set of simple software libraries that enable network and security administrators to build custom network protection applications. With FRESCO, administrators can build firewalls, filters, detection systems, and other network protection applications. FRESCO integrates with the popular NOX OpenFlow controller to provide a Development Environment and a Resource Controller. Since we rely on OpenFlow, we need it to be trustworthy. The existence of FRESCO as a means to create security tools helps demonstrate OpenFlow as trustworthy and reliable.

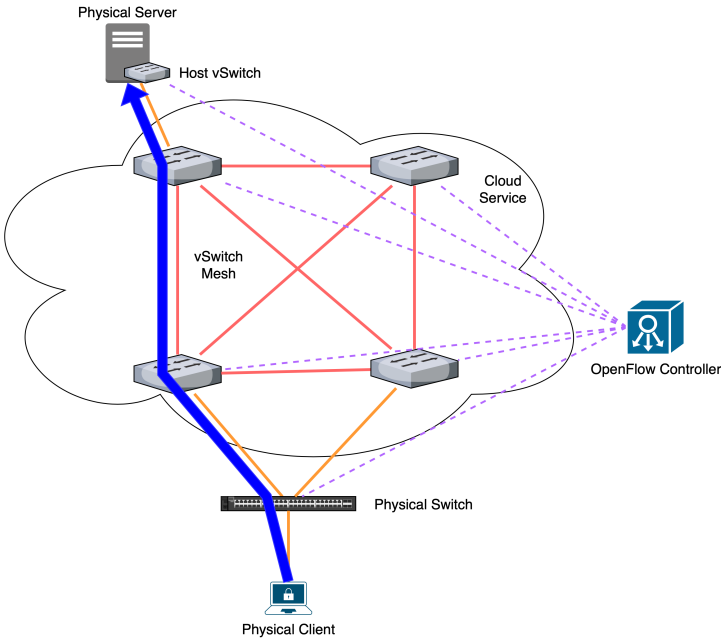

Figure 3: Architecture of Scotch overlay network. The vSwitch Mesh acts as an overflow buffer for when the physical switch's connection to the OpenFlow Controller gets saturated. Each vSwitch is also configured to overflow to one of its neighbors. vSwitches can dynamically be added and removed by the cloud service

A similar research project on SDNs is Scotch. The Scotch research team endeavored to develop a solution to dynamically scale the capacity of the control plane's path throughput [51].

They accomplish this by forwarding packets from the overloaded phyical switches to virtual switches which have non-congested control-plane paths to the SDN controller. The mesh of virtual switches acts as backup for the physical switches, allowing them to offload to the vSwitch mesh and still ensure the packets will be routed correctly.

This solution helps prevent DOS attacks which could exploit the limited bandwidth capacity of the physical switch's control plane, which typically has a smaller bandwidth than the data plane. The solution also supports more specific OpenFlow flows, which can be leveraged to provide a finer-grain access control scheme, that require more bandwidth to direct traffic. At scale, our project would likely benefit from an implementation of the Scotch project, as our control plane will likely become saturated with requests for each process.

Another research team worked to improve the Scotch project, and in the process created SDNShield. The SDNShield project provides a solution to defend against the potential DDOS vulnerabilities of the OpenFlow control plane [52]. SDNShield works by filtering traffic, to reduce congestion and remove malicious packets. By filtering packets on the control plane, SDNShield is able to prevent edge switches and the SDN controller(s) from being overwhelmed by control traffic. SDNShield utilizes a similar architecture to Scotch (shown in Figure 3), but adds a set of virtual machines running filtering algorithms connected to each virtual switch. These filtering algorithms are used to reduce the amount of malicious traffic flowing on the network. For any network that is planning to scale, SDNShield is a necessary component to safeguard the core networking infrastructure from malicious actors as well as inevitable device failure. A real life implementation of our design would require an SDNShield-like architecture to overcome vanilla OpenFlow's traditional availability concerns.

2.6.1 IPTables & NFTables

Options for controlling the flow of traffic exist for the local machine as well. IPTables (now succeeded by NFTables) provides kernel-level control over how network packets flow in and out of a computer [53]. This low level control can prevent packets from reaching the rest of the operating system, keeping potentially malicious packets away from the user space. NFTables allows users to define rules without needing root or administrator permissions. Using IPTables, the user can define basic allow/deny policies, as well as load balancing and routing [54]. IPTables can control at the packet level and the flow level, as well act as firewall, NAT, and load balancer. In contrast, SDN allows us to control these policies on a flow level, only, from a logically centralized point. For that reason, we chose to implement SDN over on-device IPTables/NFTables.

2.6.2 Caching Flow Rules

The OpenFlow protocol defines configuration options which control how long an OpenFlow-capable device caches the flow rules before requesting an update from the SDN controller [55]. This cache length thus determines how quickly changes to flow rules propagate to the enforcing

devices. Having cache length which is too short requires the devices to request the flow rule each time a flow occurs, increasing latency. Having a cache length that is too long means that changes to flow rules don't propagate to the devices fast enough. Determining the optimum cache length, which allows reasonable latency while being able to be updated quickly, is central to running an effective SDN system.

3 Design

In this Section we describe the design of our infrastructure explaining our intentions, decisions, and assumptions. We complement the information with diagrams to elucidate our infrastructure design. We created a proof of concept for our design, details for which can be found in Section 4.

3.1 File Provenance

Since security goals often motivate organizations to limit user autonomy on corporate devices, this paper blueprints a system that leverages data provenance to maximise user autonomy without sacrificing confidentiality, integrity, or availability. Users within an organization would have machines capable of virtualization, a suite of virtual machines specified to a purpose, and a interactive experience that abstracts away the complexities of working with multiple virtual machines simultaneously (inspired by Qubes). For the remainder of this paper, virtual machines will be referred to as clients. Each client should have a specific use case, can only store data required to fulfill that goal, and has security controls proportional to the criticality of the data within. For our purposes, it is irrelevant whether the clients share a physical system or not.

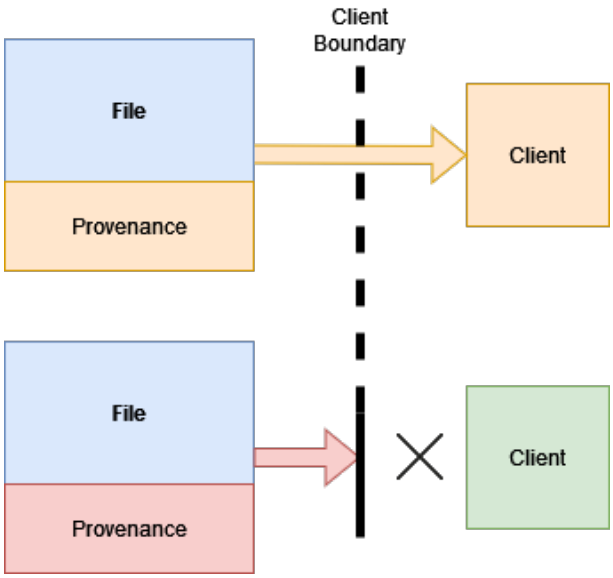

Figure 4: File crosses client boundary and is allowed or blocked dependent on provenance.

This system enforces two sets of boundaries: between applications and between clients. Each client will have a administrative service known as the Provenance Updater monitoring file access events. When data crosses the application boundary, we store data related to its data provenance. The Provenance Communicator is a similar administrative service monitors network activity and supplies relevant provenance metadata to a centralized decision-making entity when that data crosses the client boundary. The decision making entity decides if the data is allowed to cross the boundary or not as shown in Figure 4. When data is allowed to transition between clients, the appropriate provenance metadata is communicated from the decision making entity to the receiving client's Provenance Communicator to ensure consistency across clients. The client boundary is enforced by network switches completely invisible to the client as shown in Figure 14.

When data attempts to cross a boundary, its permission to do so is verified by access control policies configured by the organization. The contributing factors to the decision to pass through a client boundary is the destination client and the provenance of the data itself as demonstrated in Figure 4.

When data passes through the application boundary, its provenance may be updated to reflect the change in sensitivity for the data within the file. As shown in Figure 5, the new provenance is dependent on the which application's boundary is being crossed. We assume that any given interaction transmits all potential data available to that application during its lifetime to the file that it is interacting with.

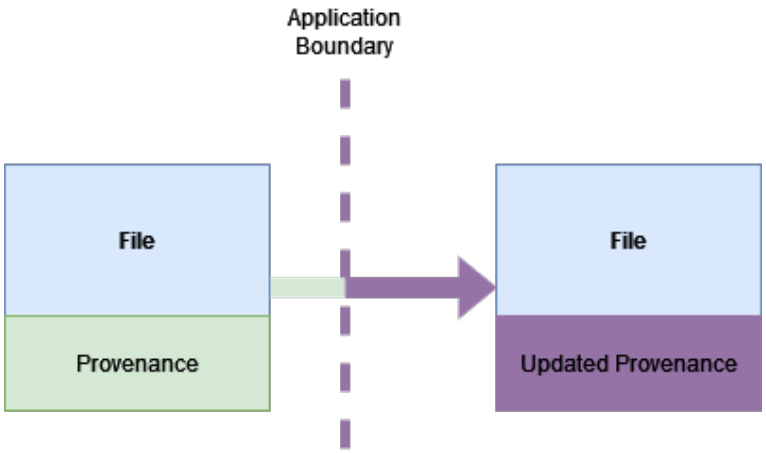

Figure 5: File crosses application boundary and its provenance is updated.

This system requires visibility into clients' in order to track provenance transitions at the application barrier. For this purpose we suggest adopting techniques common in host based intrusion detection systems and data loss prevention tools to detect when the contents of a file require an update to its provenance. We suggest the use of AuditD systems to detect boundary crossings. AuditD can provide file access events, giving us the ability to know every time a file is accessed and by which application - which is enough information to determine if and how the application boundary has been crossed. We also propose the use of Linux's Extended

File Attribute system to maintain persistence of provenance metadata. It is possible that other mechanisms are better suited to the task, in Section 6.2 we discuss the benefits and limitations of our chosen tools.

To meet our confidentiality expectations we rely on the trustworthiness of the Provenance Updater and the Provenance Communicator. The principle of least privilege [56] requires that an application only access the resources that are required for its function. Following that principle: all applications with administrative access, have it because it is required for that application to function. The Provenance Updater and communicator are set administrative services on every client because they require administrative access to modify file provenance data. But they do no not have the unnecessary power of a driver or kernel module. Relying on the principle of least privilege allows us to assume that these services are trustworthy. The untrusted zone is the user space on an end user machine, which we have segmented into smaller parts using virtualization. This segmentation reduces the impact if one of the untrusted zones is compromised.

To create a centrally-managed boundary between every client on any number of physical hosts required to implement this provenance tracking system, we suggest taking advantage of the benefits of programmable networks such as SDN. With SDN we have centrally managed and dynamically modifiable control over client agents (acting as firewalls) to reflect the organization's access control policy. All client agents rely on a centrally located SDN controller to configure rules that dictate how to manage communications with other clients. This system ensures that all communications are subject to organization access controls as shown in Figure 14.

The integrity and availability of the system rely upon trusted network communication between the Provenance Communicator and the SDN controller as facilitated by SDN endpoints and OpenFlow. OpenFlow is known to be susceptible to DDOS [52], but technologies such as Scotch and SDNShield that OpenFlow can be trustworthy if modified. Further, the ability to easily create security tooling through FRESCO demonstrates that the OpenFlow environment is robust enough to be trusted in a system with high confidentiality and integrity requirements.

In the next Section we will describe the technical details of our design and walk through how we built a proof of concept.

4 Implementation

In this section, we describe the design of our system by explaining each component in detail and expanding on how the components interact. We provide flow charts and diagrams to accompany each component.

Our goal is to design a system that enables centralized, fine-grained access control based on data provenance. In service of that goal, we build a proof-of-concept from open source components and leveraging features of the Linux operating system.

To demonstrate how each of these components interacts, we describe the journey of a single file in one of our client environments. Figure 6 provides a visual representation of this journey.

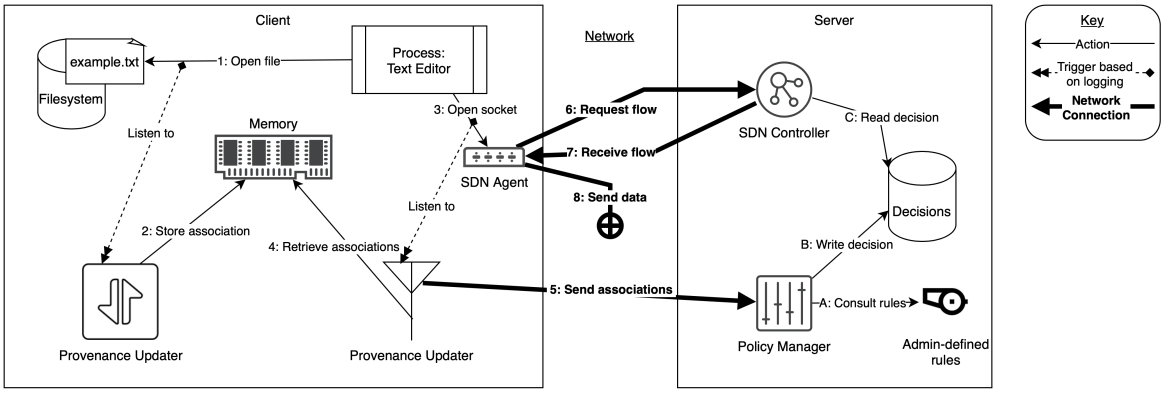

Figure 6: Overview Of A File Traversing The System

For example, we assume a file exists on the filesystem of the client, that we call `example.txt`. When this file is opened by an application, for example a text editor, the provenance updater keeps track of the file that was opened along with its sensitivity level. This remains in memory until the application is closed. When this application connects to a socket, the provenance communicator sends all file provenance information to the server. The server receives the request with source and destination IP addresses as well as any file provenance information to be sent. The Policy Manager checks a set of rule defined by the admins of the system. It then writes a decision, allow or deny, to a central store. If the request has file information to another environment within the system, the Policy Manager sends the provenance information to that environment. The client's open socket is routed through the SDN agent. The SDN agent requests a set of actions from the SDN controller for each new connection for which it has not seen recently. The SDN controller checks the decision store, constructs the list of actions (in this case, actions are as simple as dropping the packet, or allowing it through to the destination IP address) and returns a flow with the list of actions and the conditions on which to match (IP source and destination). The SDN agent then uses that flow to allow or deny a connection until the flow expires, or a different connection is established, and the agent requests a new one.

In the following sections, we describe each component in more detail.

4.1 Virtualization Scheme

This proof of concept leverages VirtualBox, a Type 2 hypervisor that supports the creation of multiple concurrent virtual machines. We configure a Debian Linux virtual machine with the appropriate settings and install/develop the software required to maintain our system. Modifications are described in the next subsection. We use VirtualBox's import/export functionality to create copies of our virtual machine. Throughout this Section, all references to "virtual machines", "containers", and "client" refer to a virtual machine that use this image.

This system relies on the ability for each user to support a suite of clients, each configured for a specific use case. The virtualization design assumes that the clients cannot communicate except through monitored network channels, that network communication is managed by SDN flows via a configured vSwitch, and each client is running security software. Additionally, we create two systems to be installed on all clients: the Provenance Updater and the Provenance Communicator. Both of these rely on AuditD logs and we create a program to interpret those logs, turn them into event classes, and call the relevant provenance tool as shown in Figure 7.

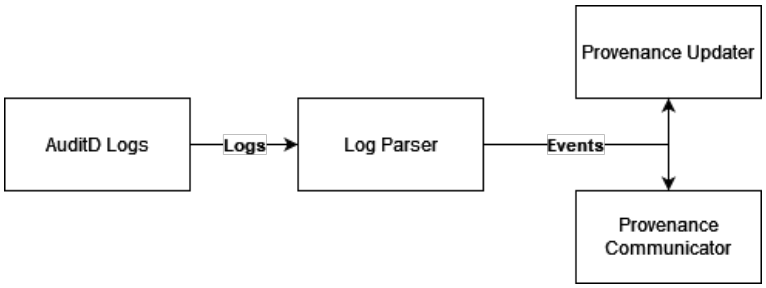

Figure 7: Provenance Updater and Provenance Communicator Flow Chart

4.2 Client-side Components

Each client environment in the system runs a small set of software to keep track of what files have been opened by what applications, whether certain network connections are allowed, and control what the user can do on the client environment. The following sections describe each piece of software in more detail.

4.2.1 Provenance Updater

We create the Provenance Updater to track when an file crosses the application boundary. We do this by processing AuditD logs to track when an application accesses a file. As shown in Figure 8, When an application accesses a file, we update its provenance to reflect the potential changes in content. Since applications will interact with many files throughout their life cycles, application boundaries are stored in memory and are also updated on file access. When a file crosses the network boundary and, because it is being sent by a program, it will trigger the Provenance Updater. In those situations, the Provenance Updater communicates with the program handling the inter-client boundary called the Provenance Updater to ensure that any incoming data is correctly tagged.

File provenance is stored using the Linux Extended File System, which allows users and applications to attach arbitrary data to files in the same manner that the operating system assigns tags such as “Date Created” and “Date Last Modified.” Once set, a file is linked to its provenance as long as it stays on that client, when a file is transmitted to another client the

Provenance Communicator interacts with the recipient client's Provenance Communicator to maintain integrity.

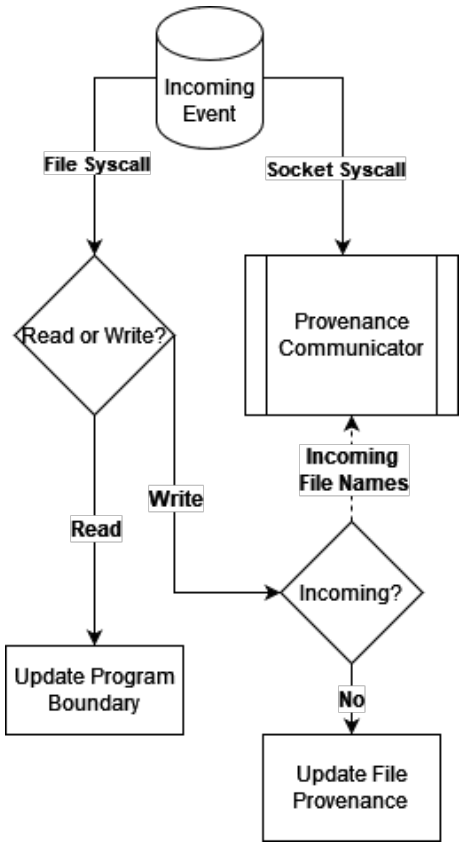

Figure 8: How the Provenance Updater Handles Events

As shown in Figure 8, the Provenance Updater acts on incoming events. These events are instantiated from AuditD's logs via Python script. The functionality of the Python script is visualized in Figure 9. With a fully configured AuditD, an event will generate multiple logs that are can be tied together by a unique identifier (UID). Regardless of the event, AuditD will issue a log messaged "PROCTITLE" when an event is done being logged. The log processor parses log messages, storing relevant data by UID, until it reaches the "PROCTITLE" message. When a "PROCTITLE" occurs, the event associated with that UID is sent to the appropriate next party.

It is essential to properly configure the AuditD logs to properly log events of interest without overwhelming the system. We used auditctl, a command line tool, to configure AuditD. Action rules generate "SYSCALL" logs detailing which syscall was used and which process called it. To create a rule use: `auditctl -a always, exit`. This tells AuditD to always log syscalls on their exit. There are other options for -a but they are not important to understand this paper. To prevent the volume of log entries from overwhelming the system, each rule has a filter that only tracks events that occur in the home directory or subdirectories. The -F parameter allows for filtering action logs by the argument. For example: `-F dir=/home/user` would limit logging to syscalls that impacted a file within the home directory or a subdirectory of home. -S allows filtering based on specific syscalls; `-S connect` only logs the 'connect' syscall. This system

relies on the following action rule:
`auditctl -a always,exit -F dir=/home/user -F perm=wa` which logs all syscalls within the user home directory.

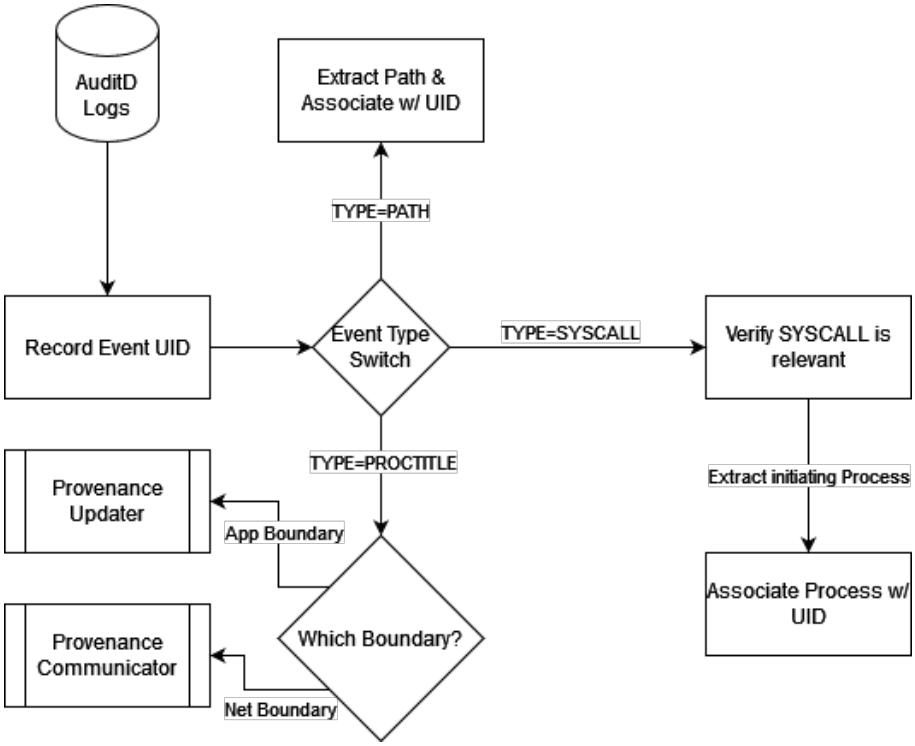

Figure 9: Processing AuditD Logs into Events

Watch rules generate "PATH" logs that communicate when and which file has been accessed with a matching Linux permission (read, write, executable, etc). Watch rules are created with auditctl's -w option, with the directory as an argument. For example: `auditctl -w /home/user` will create a watch in the home directory. Watch rules only take two optional arguments: -p and -k. -k functionality is the same as in action rules. -p specifies which permissions to watch for. `-p w` sets a watch for any writes to a file. This project uses two watches:
`sudo auditctl -w /home/user -p w -k process_monitor` and
`sudo auditctl -w /home/user -p r -k process_monitor`. They are identical except one watch is for writes and the other uses `-w r` to watch for reads.

Employing watches and action rules provides enough data to the Provenance Updater to detect when a file crosses the application boundary. A drawback to using logging as the mechanisms for enforcing a boundary is that we only know about events after they happen and therefore cannot take preventative action. Further discussion on the limitations of retroactive enforcement can be seen in Section 6.2.

4.2.2 Provenance Communicator

We created the Provenance Communicator to transmit file provenance to other clients and the Policy Manager.

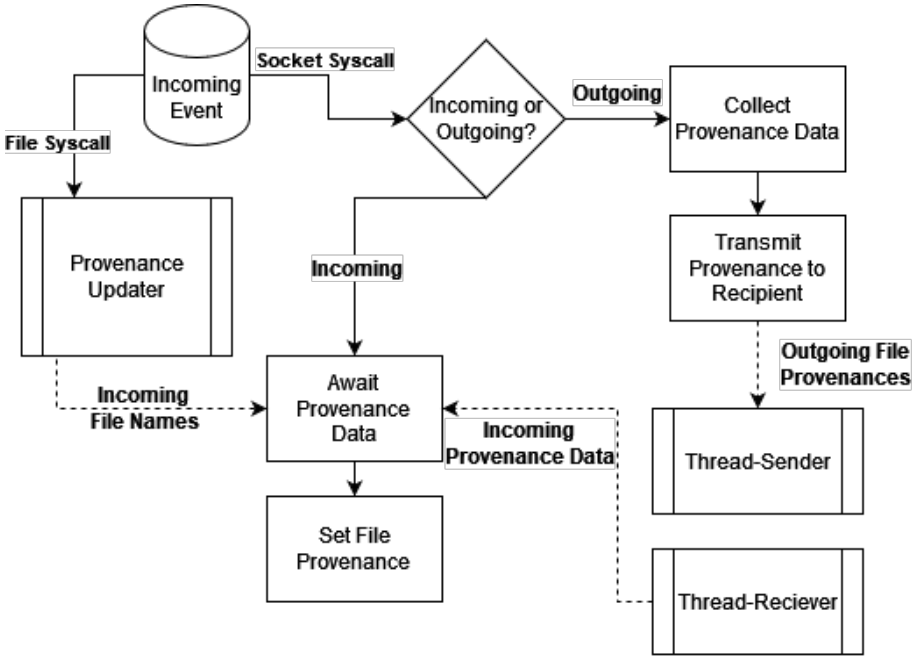

Figure 10: How the Provenance Communicator Handles Events

As shown in Figure 10 The Provenance Communicator uses AuditD to detect when a process opens a socket. AuditD is configured with the following rule: `auditctl -a always,exit -F arch=b64 -S connect -S bind -S socket -S accept -k socket_monitor`

When the socket is opened, the Provenance Communicator transmits the file provenance of all the potential files that may be sent through that connection. The SDN controller then communicates that information to the receiving party, which has their own Provenance Communicator installed. The Provenance Communicator also listens for incoming provenance metadata from the controller, and assigns the appropriate provenance to files as they are transmitted through the socket.

When the client and server are initialized, the client first forms a connection with the server on port 1338 (by default). This connection will later be used to send data to the client. The socket_monitor script parses logs from AuditD to capture when a socket is opened. The socket_monitor script also keeps track of files opened by processes. When a socket is opened by a process, the socket_monitor script sends all files the process opened, along with their provenance levels and the source and destination IP addresses and ports, to the client script. The client script uses two background threads to manipulate, parse, and send and receive data to and from the server in the background without disrupting AuditD log parsing. After data is sent to the client script, the sender thread will parse and send data to the server over port 1337 (by default).

The server contains three threads. One thread for sending data to clients, one thread from

receiving data from clients, and one thread for initializing the connections on port 1338. This model allows for the fewest amount of bottlenecks while processing data. After the receiving thread receives data from the client, it will store the data into a location that the Policy Manager can access. The Policy Manager can then poll the server script and make decisions on whether or not it will accept the traffic. If it accepts the traffic, the server script will tell the sender thread to forward the data to the receiving client. If it rejects the client, the server script will simply discard the data.

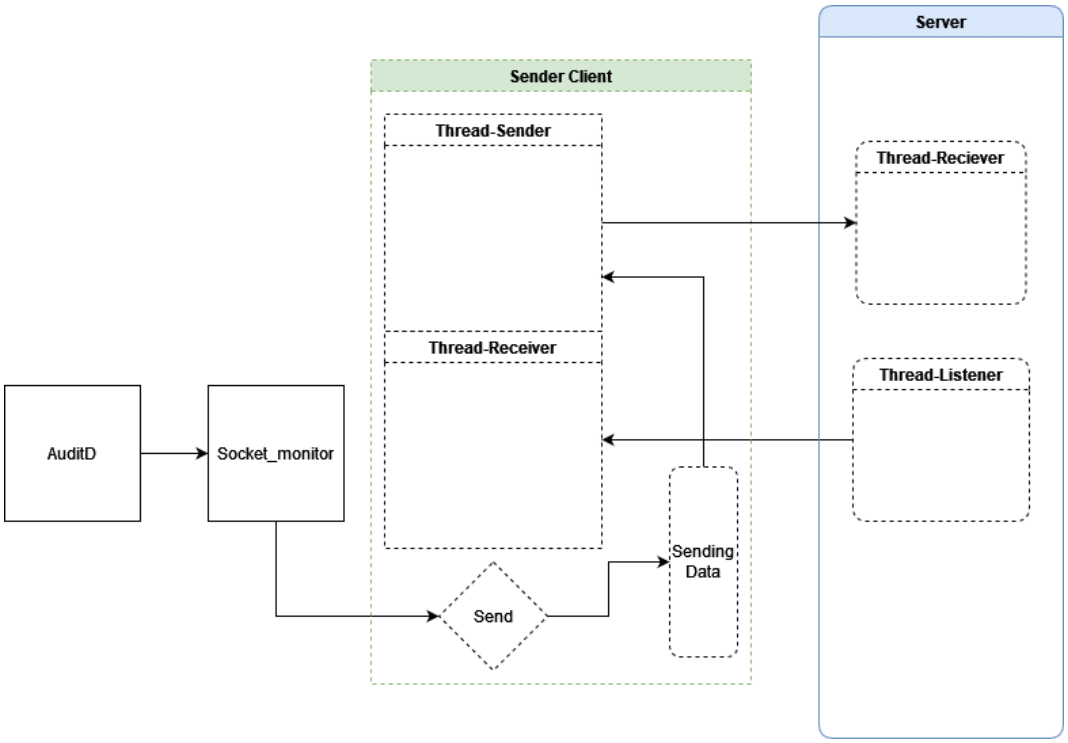

Figure 11: Sender Provenance Communicator Flow Diagram

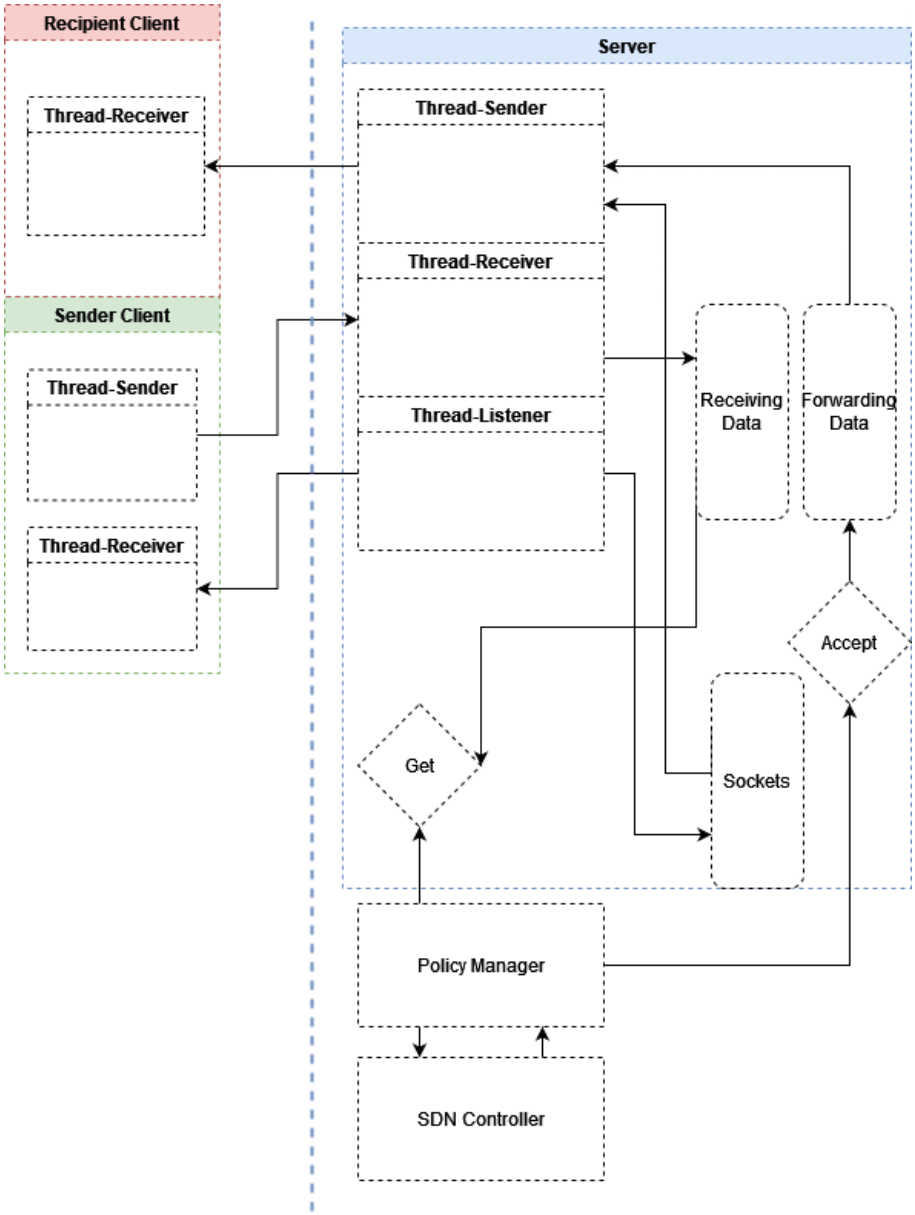

Figure 12: Server Provenance Communicator Flow Diagram

When the receiving client receives the data, it will parse it and send it to the socket_manager script. This script will find the received files and edit their labels according to the sensitivity labels that were provided by the server.

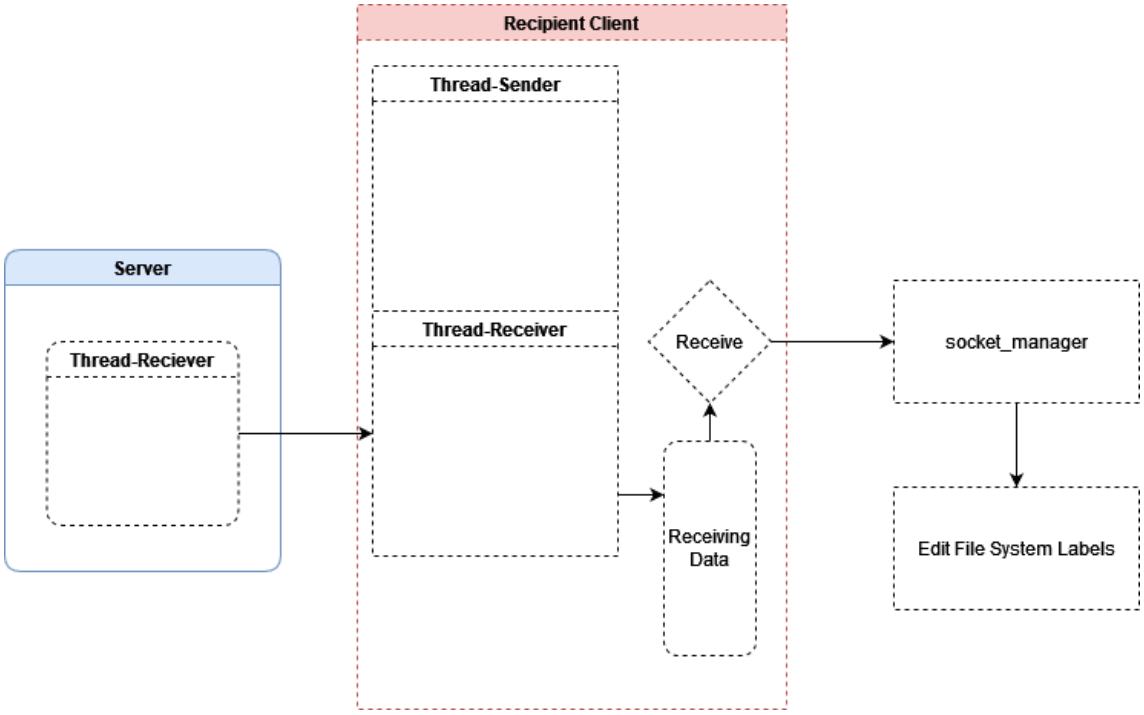

Figure 13: Recipient Provenance Communicator Flow Diagram

4.2.3 SDN Agent

Every client has a virtual switch associated with it, also known as an SDN agent. This agent handles all network traffic from its corresponding machine, and enforces network controls communicated from the SDN controller. The SDN agent abstracts the network policy away from the client (see Figure 14). Our SDN agent of choice for this project was Open vSwitch, as it is the most popular OpenFlow virtual switch [57]. We configured the switch to communicate with our controller (see Section 4.3.2) to receive flow rules. Configuration is minimal, but followed these steps:

1. Install Open vSwitch (OVS):
   `sudo apt-get install openvswitch-switch openvswitch-common`
2. Ensure OVS is running:
   `sudo /usr/share/openvswitch/scripts/ovs-ctl start`
3. Add a bridge to the switch:
   `sudo ovs-vsctl add-br main2`
4. Add the primary NIC to the switch as a port:
   `sudo ovs-vsctl add-port main2 enp0s3`
5. Set the controller for the switch:
   `sudo ovs-vsctl set-controller main2 tcp:{ip address}:{port, typically 6653}`

6. Remove the ip address assigned to the NIC:
   `sudo ip a flush dev enp0s3`
   Note: This command will likely make Debian believe that it does not have access to the Internet. Even though an alert may pop up, the client has connection to the Internet after running the rest of the commands

7. Set the bridge as the active NIC:
   `sudo ip link set main2 up`

8. Set the DHCP client to use the bridge NIC to obtain a new IP:
   `sudo dhclient main2`

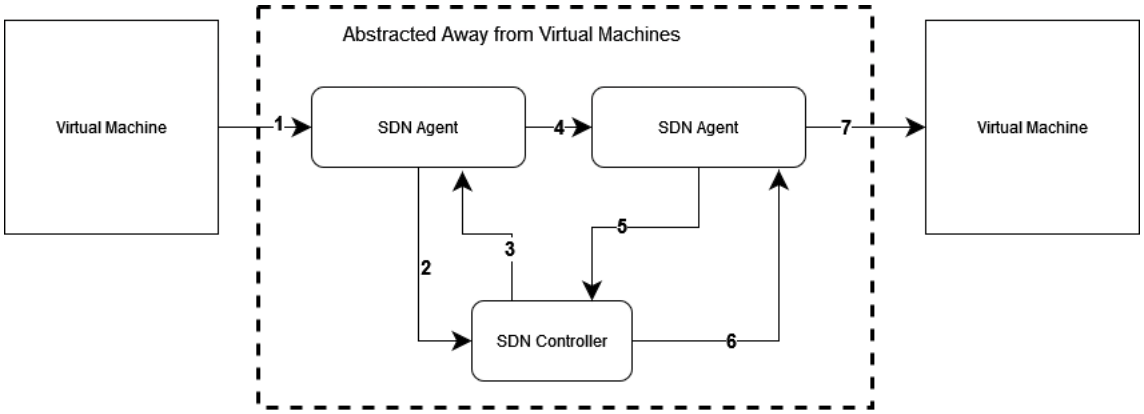

Figure 14: SDN Agent Flow

4.2.4 MAC Policies: SELinux

As part of this project, we investigate both SELinux and AppArmor to implement MAC enforcement on our virtual machines. SELinux and AppArmor both have strengths and weaknesses that enable each to work well in specific scenarios. SELinux is exceptionally powerful as it enables MAC enforcement for labeled files. These file classifications are associated with the file itself. If the file is moved, the classification, and therefore the policies associated with it, retain on the file. SELinux also allows for extremely fine grained access control including differentiating between ports that sockets can connect to.

Though SELinux has multiple benefits, there are many drawbacks that make it difficult to use. SELinux is not supported on most Linux distributions. SELinux is only fully supported on Red Hat Enterprise Linux (RHEL) and CentOS, but has partial support on Debian and Fedora. It is possible to enable SELinux on other distributions, such as Ubuntu, but the features are incomplete and it does not function well. SELinux development tools (`se-troubleshoot` and `se-troubleshoot-server`) are also not available for Debian, requiring the use of a RHEL based distribution for developing SELinux policies effectively, as these tools provide human-readable explanations of SELinux errors, which is essential in troubleshooting.

SELinux's policy system allows the creation of fine grained policies, but manual creation of policies is difficult. This creates a roadblock in developing policies for specific access control scenarios, such as a Privileged Access Workstation (PAW) model. Typically, SELinux policies are configured using booleans (policies built into the SELinux reference policy than can be turned on and off), file labeling, and local policies. Allowing a specific user to access only a small set of files would require significant relabeling of the file system as well as a custom policy. It is important to ensure all system critical executables and files are still accessible by the restricted user.

4.2.5 MAC Policies: AppArmor

As a replacement for SELinux, we also investigated AppArmor, a MAC security control module developed by Canonical [58]. AppArmor is installed and implemented by default in many Linux distributions such as Ubuntu and openSUSE. This native integration leads to a much simpler setup and wide range of working distributions, unlike SELinux which only has full support on RHEL.

Though SELinux and AppArmor are both ways to implement MAC on Linux, there are fundamental differences in the way they function. The largest difference is that SELinux uses file labeling to apply policies to files while AppArmor provides controls based on the path of the file. Each of these methods has advantages and disadvantages. SELinux's file labeling allows for policies applied to files to move with the file. In other words, if a file is moved, the policy will continue to apply to the file. With AppArmor, this is not the case as policies are based on path and file name. On the other hand, the path based system involves much less overhead and is less intrusive than SELinux's file labeling, which requires a full file system labelling process on start along with file re-labeling when certain operations occur. The other major difference between SELinux and AppArmor is the method to create policies. SELinux policies are designed to be created using automatic generation commands. The policy language is extremely complicated and has limited documentation, encouraging use of the tools provided. This makes it difficult to create custom, more unconventional policies. With AppArmor, the policy language is designed for administrators to write policies manually and has extensive documentation. For the purposes required by this project, manual policy generation provides significantly more fine-grained and easy control when compared to SELinux's automatic generation tools.

To test AppArmor's policy capabilities, we implemented a simple policy file in Ubuntu that would allow programs executing with the policy to read, write, and execute to specific directories along with the directories needed for general Linux system functioning (including `/lib`, and `/bin`). The policy can be found in Section 7. In this instance, the confined user (such as a PAW user or one following PCI compliance) would be able to execute all programs located in typical Linux binary locations (`/lib`, `/bin`, `/usr/lib`, and `/usr/bin`), read and write to typical configuration locations (`/usr/share` and `/etc`), read and write to the user's

home directory, and read, write, and execute in specially defined directories in the directory `/test`. This will allow system administrators to restrict the programs that are able to be run by the confined user. Though AppArmor does not support fine grained socket policy like SELinux does, this could be implemented with simple firewall rules.

4.3 Server-side Components

The server, or servers at scale, run two services to orchestrate the entire system. The Policy Manager handles interpreting rules and communicating file provenance from source clients to destination clients. The SDN controller enforces the rule decisions for network communications.

4.3.1 Policy Manager

In this section, we propose the use of an access control matrix to determine which boundary crossings to allow and which to prevent. The component that contains this matrix is called the Policy Manager. The Policy Manager gives us the ability to dynamically control the network activity of all clients from a single controller.

The Policy Manager accepts connections from the client file provenance communicators, receives requests for file or network connections, consults the access control matrix, makes a determination and records it, and either communicates the file provenance information to the intended recipient, or drops it. The SDN controller can then read the decision and provide a flow to the SDN agent that either allows the packet through or drops all packets to the specified IP. This integration allows for fine-grained access control and ensured confidentiality.

4.3.2 SDN Controller

The SDN controller manages all communications between clients and contains network policy elements that define how source and destination environments can communicate. The SDN controller can manage communication between two containers of the same compliance, different but compatible compliance, or between a clients and an unmanaged environment, i.e., the Internet. Policy is abstracted out to a separate entity known as the Policy Manager (See Section 4.3.1). The SDN controller we chose was RYU, due to its friendliness for researchers as it is simple to use and modify, and it is written in Python [59]. Configuration of the RYU controller was as follows:

1. Install RYU into the user's home directory on a dedicated server
   ```
   git clone git://github.com/osrg/ryu.git
   cd ryu; Python3 ./setup.py install
   ```

2. Configure the controller. A template to modify can be found at:
   `ryu/ryu/app/`
   We recommend simple_switch_13.py as it supports OpenFlow v1.3

3. Navigate back to the main folder and run install again:
   `cd ~/ryu; pip3 install .`

4. Run the SDN controller with the now-modified configuration:
   `ryu-manager ryu.app.simple_switch_13`

For the purposes of this paper, the SDN controller was left to the default configuration of simple_switch_13.py; that is, a simple L2 switch. In future works, we plan to integrate the SDN controller with the Policy Manager (see Section 4.3.1) to provide dynamic control over which connections are allowed or denied.

5 Results

To test the feasibility of the system, we run several stress tests, latency tests, and modify the system to record relevant statistics. Our stress testing executes a Python script that causes files to rapidly cross the application barrier and the client barrier. During that stress test, we record statistics and observe the behavior of the Provenance Updater, Provenance Communicator, and the Policy Manager.

5.1 System Capabilities

The system currently tracks file movement across different in-system machines, enforcing whether a file is allowed to move from one environment to another. Processes withing each environment are also tracked as they interact with files, and the system updates the file's metadata if needed (for example, if the process has two files open, which when combined, changes the categorization of the files). Each environment also has AppArmor controls which assist in ensuing the environment meets its respective compliance requirements (e.g. PII, PCI, and HIPPA). The SDN controller, and its associated flow rules, enables logically centralized control over what websites environments can access, acting as a centralized firewall for all connected environments.

5.1.1 SDN Performance

To gauge the impact the system would have on a network of clients, we ran some baseline tests with a single client connected to the system. While the system performed better than expected, there are still issues that would make scaling the system difficult. We first tested how long it took to apply a policy and what affect that had on the overall latency of a connection.

As shown in Figure 15, the initial ping echo request takes significantly longer than the rest of the pings. This is because each time a new server is pinged, the SDN agent must request a flow rule. On average, this request adds about 119ms to the response time. Subsequent pings use the cached flow rule and thus do not suffer from this added latency.

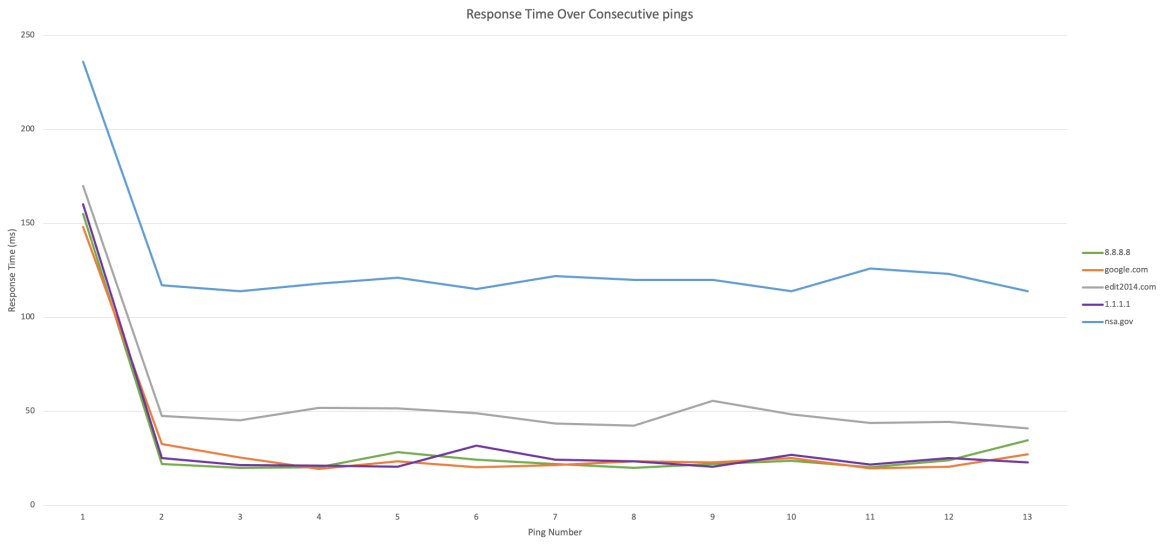

Figure 15: Response Time For Consecutive Pings To A New Server

We also tested throughput to check if the additional latency affects how quickly data can be transferred. This test was conducted on a 10 mbps upload, 100 mbps download connection for the Ubuntu VM running both with and without our project configured. Both configurations used a speedtest commandline tool maintained by Ookla [60]. We ran the speedtest three times for each configuration and averaged the results. Figure 16 shows there was no effect on the throughput of the system by the project.

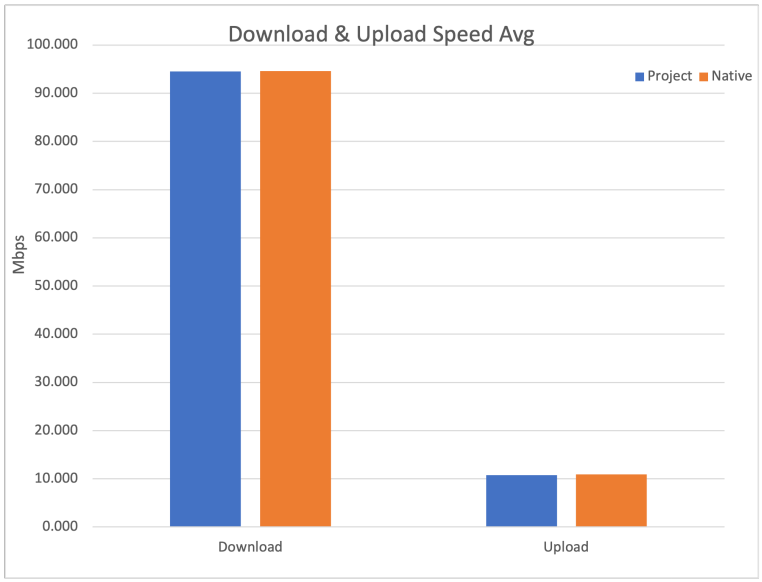

Figure 16: Average Throughput With The Project Installed, And With Native Ubuntu

5.2 Stress Test

We performed the stress test by using a Python script that created and modified a preset number of files in a given amount of time in order to generate many events in short periods of time. The script generated up to hundreds of events a second forcing the Provenance Updater to handle dramatic changes in the amount of events to process at once. The script also caused files to cross the client boundary interacting with the central server and other clients. We did not detect any server bottleneck. The server and SDN controller could handle transmitting provenance metadata between multiple clients.

5.3 AuditD Processing Overhead

We analyze the latency of how long it took our system to respond to an event. We record the exact time of the event as reported by AuditD and record the exact time that we finished processing the event. We compile that latency by how many events were occurring at the time. The goal of this analysis is to determine if there is a relationship between the frequency of events and latency. Essentially, we determine if our system lags behind when many events happen simultaneously.

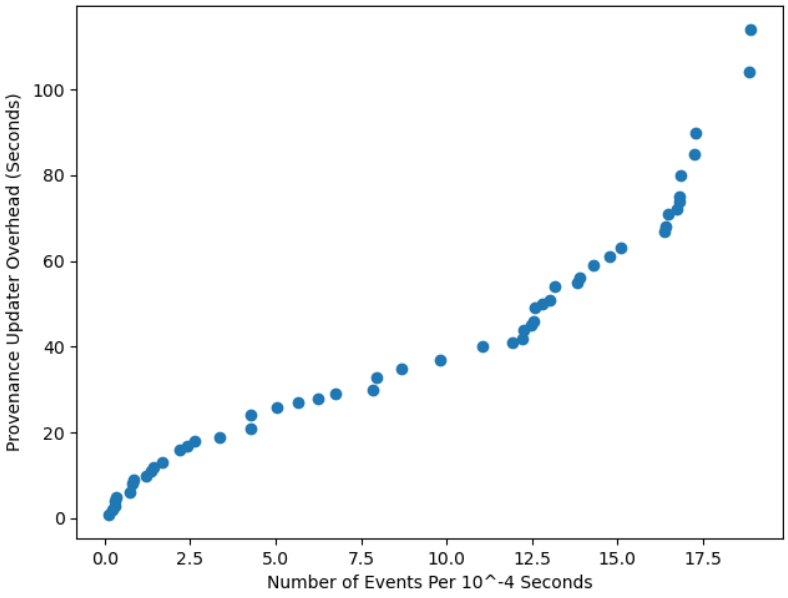

Figure 17: Overhead of Processing AuditD Logs

Figure 17 shows that the Provenance Updater can take up to 20 seconds to process events. There is a distinct trend line between the frequency of events and the processing time. It appears that processing AuditD logs introduces latency, but there is not enough data to prove that the relationship is causal. We hypothesized that additional latency is introduced when many files cross the network boundary at the same time.

To investigate that hypothesis, we record latency in the same fashion as the last trial. The

latency is measured against the number of files crossing the network boundary as a result of the event.

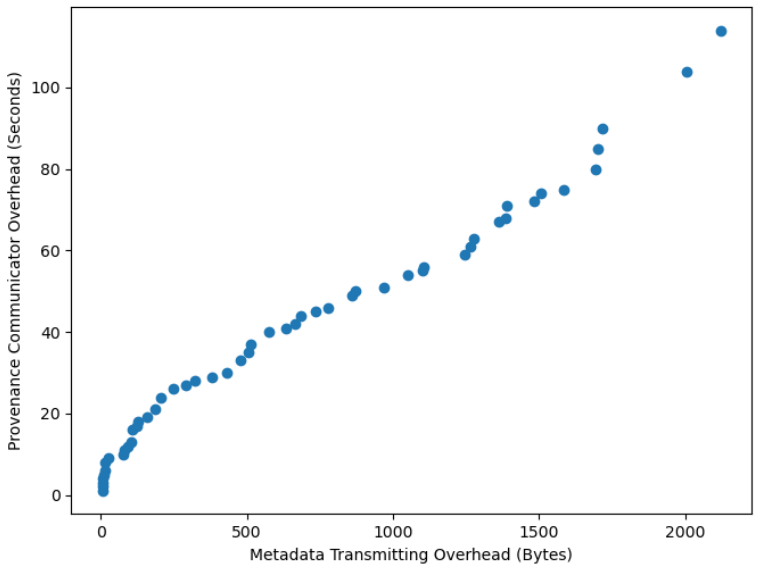

Figure 18: Internal Latency of Transmitting File Metadata

As seen in Figure 18, the overhead quickly increases as the number of files crossing the boundary increases, but not consistently. There appears to be a trend, but the data set is unevenly skewed. There are relatively few instances of the Provenance Communicator transmitting many bytes at once. In the future, additional trials with balanced samples could allow for stronger conclusions.

5.4 Provenance Communicator Overhead

A system that adds overhead to every network connection must be relatively lightweight since the overhead will be applied many times and may exacerbate network congestion or overload servers. We modify the system to report the amount of bytes sent to communicate file provenance data to other clients. We record that data in conjunction with the amount of files with provenance metadata transmitted.

As seen in Figure 19, there is a consistent relationship between the amount of bytes transmitted and the number of files sent, with the largest transmissions approaching 2,000 bytes. As a result of our reliance on the AuditD system, the size of the transmission is directly proportional to the application sending data and how many files have crossed that application's boundary during its lifetime. As shown in Figure 20, the majority of transmissions were smaller than 750 bytes.

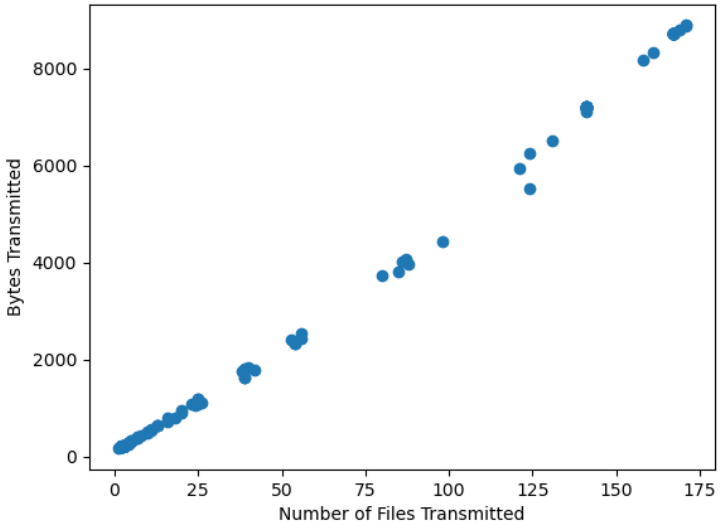

Figure 19: Network Overhead of Transmitting File Metadata

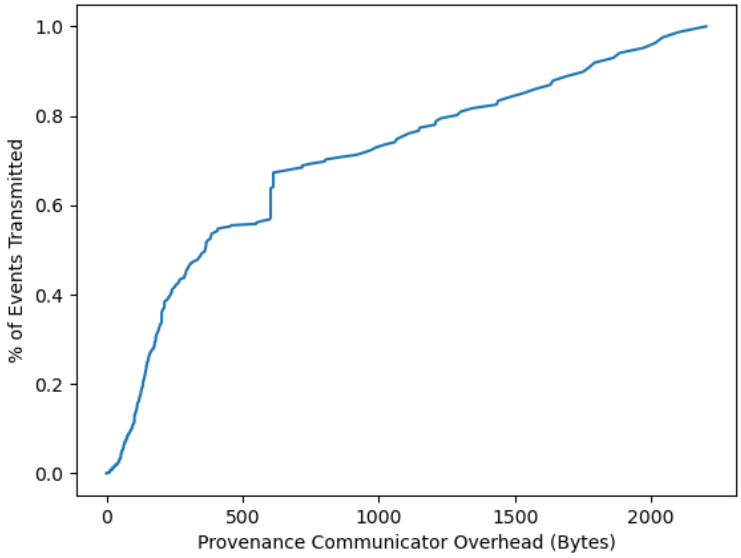

Figure 20: Cumulative Distribution of File Metadata Size

We notice that web browsers generate the most traffic. Our system ran Firefox and we notice that Firefox frequently makes outgoing connections and constantly interacts with operating system. Since web browsing is one of the most common use cases for a computer, we can expect that any implementation of this system would need to, at the minimum, handle the amount of events generated by a program like Firefox. Even at its worst, Firefox only required the transmission of 175 file provenances with a negligible overhead of around 2,000 bytes. Modern devices and networks can trivially handle that level of overhead, and we detect no significant performance penalties related to the transmission of file provenance.

6 Discussion

This section is dedicated to elements of our project that are not evaluated in experiments, but nonetheless may be insightful for individuals interested in continuing this research. We discuss limitations of our work, what we learned during the development of this project that may be useful to others, and ideas on how to extend this research.

6.1 Machine Learning for SDN Flows

The SDN controller and Policy Manager currently require rules specific to certain sites and environments. To define generic rules would require a group of specific rules to be created. This process can be improved in many ways (including building a rule generator that allows generic rules to define all the necessary specific rules), but one of interest to this group is the implementation of machine learning. Such an implementation would require the creation of three modes: Training Mode, Shadow Enforcement Mode, and Enforcement Mode.

Training Mode would allow the system to learn from current activity on the network, building up its model of allowed flows. This mode assumes there is no malicious traffic on the network, though tools could be made to mark traffic as malicious in the training mode.

Shadow Enforcement Mode acts as a debugging mode, allowing the system administrators to see what traffic would be blocked if the system was turned on, without that traffic actually being blocked. In this mode, administrators can review what traffic is blocked, and not blocked, and provide feedback to the machine learning model.

Enforcement Mode actually enforces the blocked/allowed flows, and presents blocked flows to administrators for review and feedback. When flows are blocked, users should receive some sort of notification (a redirect to a website, or a built in system notification) alerting them to the fact that the flow was blocked and their actions are monitored.

6.2 AuditD

Throughout the creation of our proof of concept, we wanted to determine the usefulness of AuditD in creating access control boundaries. As documented in Section 4, AuditD can be configured to provide suitable insight into a system to create application boundaries and transmit data required for client boundary transitions. However, since AuditD logged events after they happened, our implementation could only enforce access controls retroactively which allows for any manner of race condition and inconsistent behavior. Especially since, as shown in Section 5.3, relying on AuditD cannot guarantee the speed desired to reliably maintain accurate data provenance. Future implementations of this system should investigate alternate methods, we suggest modifying system calls as described in the UC4Win paper [15] to ensure timely detection and the ability to proactively enforce access controls.

6.3 Develop Specific MAC Policy on Clients

To improve the on-device security controls, developing and implementing specific MAC security policies for different types of clients (such as a PAW, Payment Card Industry (PCI) compliance, and Personally Identifiable Information (PII) compliance) is required. The proof-of-concept created in this paper can be adapted for different use cases.

One such use case is a PAW. PAWs are heavily restricted devices that minimize attack surface by blocking software by default and only allowing a small set of software that is critical to performing the workstation's sensitive tasks [61]. Microsoft developed this model as part of their enterprise-grade Windows security, but the model can be abstracted away for general systems. Microsoft's model includes enforcement of multiple anti-malware tools (such as Windows Defender and Secure Boot), Microsoft account restrictions (including strict password requirements), URL limiting for web browsers, restricted program execution to specific directories, prevent writing to disk, Full Disk Encryption, and provide restrictive firewall rules that block all inbound connections and only allow a small set of outbound connections [62]. Most of these enforcement methods can be implemented in the system developed for this paper. Web traffic limiting can be handled by either disallowing access to web browsers (along with tools such as `wget` or `curl`) or by implementing policy on the SDN Controller. Restricted program execution can be achieved with AppArmor. As described in Section 4.2.5, an AppArmor policy can be created to restrict execution to specific directories as well as disallowing writing to disk. Firewall rules can either be implemented directly on device using tools such as `iptables` or `ufw` or they can be implemented directly on the SDN Controller. Combining all of these features together, along with manually enabling Full Disk Encryption and Secure Boot, a PAW-like system can be implemented with the tools provided.

This can also be expanded to other, more specific policies such as PCI or PII. Network level controls can be implemented on device using firewall tools or at the network level using the SDN Controller. Application or file system restrictions can be implemented using AppArmor. To ensure that sensitivity levels of data are not tainted, the data provenance system can update sensitivity labels or prevent potential data interaction. These enforcement methods can be used to produce a wide range of specific policies for different use cases.

To further investigate the use cases of this system, a case study can be explored on vulnerable software running in a restricted environment on the same physical system as sensitive data. For this case, we will look at the recent vulnerabilities found in the Java library Log4j. These vulnerabilities (primarily CVE-2021-44228), enabled full Remote Code Execution (RCE) on the server using Log4j if the attackers had access to any logging function, which is very common. In our scenario, we will say that a Java based web server that uses Log4j is running on a machine [63]. This machine also processes credit card information and therefore must be PCI compliant. Without proper system segmentation and security considerations, a breach could occur if the vulnerabilities in the web server were exploited as attackers would have full access to credit

card information. By segmenting the system into individual virtual machines, applying MAC policies to restrict allowed applications, and monitoring and controlling network traffic with the SDN controller, we can first attempt to block the attack before it even reaches the server. If that fails the application restrictions would prevent an attacker from carrying out significant further damage. The attacker would only have access to the software required to run the web server and would not have write access to most directories on the system. Even if the attacker were able to attempt further connections, the SDN controller and provenance manager could detect traffic originating from an unknown application and block it. This shows that the system developed in this paper can be used to protect sensitive against major vulnerabilities.

6.4 Distributed MAC Policy

Another area of future work is developing a system to distribute AppArmor or SELinux policies from a centralized location. This further enhances the idea of logically-centralized policy and distributed enforcement. There are multiple potential paths to achieve this goal. First, policies could be directly built into virtual machine images. When a client needs to create a new container for a specific set of policies, it can retrieve the container image from a centralized server which contains the MAC policies needed. Another way to distribute policies is to expand the client and server communication software to also share policy updates. This could be directly connected to the policy manager as well to ensure a single set of rules applies to all aspects of the system. When the policy manager detects an updated policy, the server can send this new policy to all clients that need to know it and they can update their MAC enforcement. This method allows for more frequent policy updates and does not require re-building a virtualized container.

6.5 Integrate SDN as Access Control Enforcement

Currently, the SDN controller automatically approves all flows to the requested destination. In order to use the SDN controller as an access control enforcement mechanism, the SDN controller will have to integrate with a Policy Manager (see Section 4.3.1). As an initial goal, the Policy Manager will combine the request from the SDN controller with a matching request from the Policy Communicator (see Section 4.2.2), and determine if the communication is allowed based on the access control matrix. If the flow is allowed, the SDN will send the appropriate flow to the requesting switch, and the Policy Manager will send the file provenance information to the destination client (if that client is registered with the system). If the flow is not allowed, the SDN will send a flow to the switch denying the communication, and the Policy Manager will not send any information.

Another area in which to improve this work would be to modify the SDN agent running on each client to send the file provenance information along with the flow request to the SDN controller (by modifying the OpenFlow packet, as described in [47]). Sending the file provenance

information in the OpenFlow packet removes potential blocking behavior in the Policy Manager as it awaits a second packet containing the provenance information for the flow request (see Figure 21). We expect that this modification would greatly improve the reliability, integrity, and performance of the Provenance Communicator.

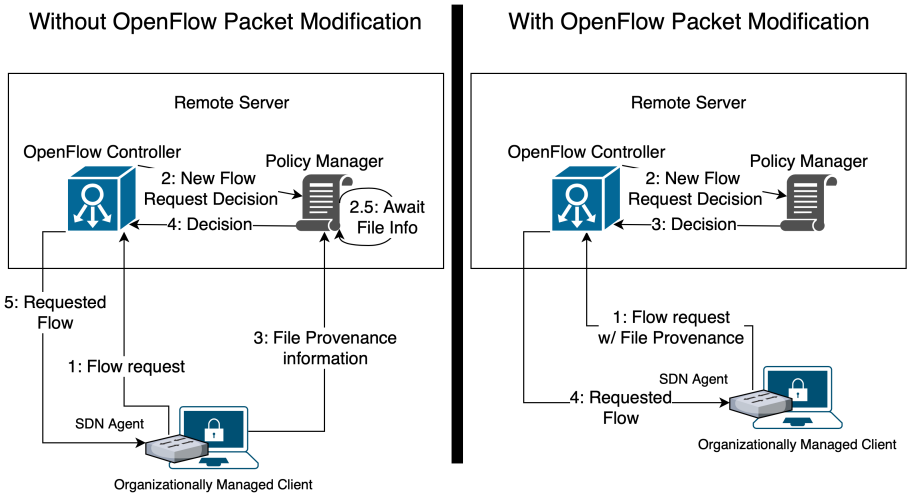

Figure 21: Modifying the SDN agent to send a modified OpenFlow packet removes a blocking step, a second packet, and likely will improve integrity, reliability, and performance

6.6 Develop Data Environment Transition Manager

To improve usability on devices, software should be developed that can automatically move data between isolated environments. If a file, such as a PDF document, is opened in an environment that is not suitable for handling potentially malicious data, such as an environment for work related emails, this software should be able to seamlessly move the PDF to a safe environment before it is opened to ensure proper data isolation. This safe environment could either be a separate VM running on the same client, or a containerized environment running within the work environment. Once a file was evaluated for integrity, the file could be moved back to the work environment for storage and transmission.

6.7 Improve Communication Scalability and Security

Currently, this system utilizes a single server to support the SDN controller and the Policy Manager. The performance of the system is thus limited by the capabilities of that server and its network uplink. This will become a much larger problem as more clients are added to the network. Adding more threads, increasing capability of the network card, and improving uplink speed to the server may partially alleviate this problem, but overall processing speed must be considered as well, especially in parts where threads are awaiting to acquire locks. In addition to the scalability of this system, communications must be secured to ensure data confidentiality

and integrity. All traffic generated by the SDN, Open vSwitch, and policy enforcement system is currently unencrypted. To ensure the security of these systems, the SDN and Open vSwitch should be configured to use TLS as defined in the OpenFlow specification. The policy enforcement system should also use TLS or an equivalent encryption standard to ensure confidentiality and integrity when transmitting file interactions and decisions.

6.8 Conclusion

In this paper, we create a fine-grained access control system based on data provenance and outline how to implement such a system. We build a proof-of-concept and benchmark the data provenance tracking systems. The provenance tracking system is accompanied by a virtualization scheme designed to isolate trusted zones connected through a software-defined network.

Our network configuration provides increased insight into each software process that sends data across the network. Our system correlates file transfers across containers to the originating processes in order to accurately mark and classify files on recipient containers for appropriate data provenance tracking. We collect and analyze test data and conclude that the addition of basic metadata into the flow protocol did not significantly impact the performance of the network.

In doing this research, we observe several areas in which future work can be conducted, including process monitoring improvements, on-device policy management, policy as a means for access control, policy enforcement with the SDN controller, boundary precision, and network stack complexity. More information about these potential future research areas are outlined above.

7 Appendix A

```
/test/ {
        # Read, execute lib directories
        /var/lib/** rixmk,
        /usr/lib/** rixmk,
        /usr/lib/ r,
        /usr/local/lib/** rixmk,

        # Read, execute bin directories
        /bin/** rixmk,
        /usr/bin/** rixmk,

        # Read, write configurations and share
        /usr/share/** rwk,
        /etc/** rwk,

        # Read, write home
        /home/** rwk,

        # Write /dev/null
        /dev/null wk,

        # Read from /test and /test/read,
        # write to /test/write,
        # read and execute from /test/execute
        /test/read/** r,
        /test/write/** rw,
        /test/execute rix,
        /test/ r,

        # Allow both types of sockets
        network inet dgram,
        network inet stream,

        # Explicitly deny setuid and setgid
        deny capability setuid,
        deny capability setgid,
}
```

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