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Parametrization and Effectiveness of Moving Target Defense Security Protections for Industrial Control Systems

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Parametrization and Effectiveness of Moving Target Defense Security Protections for Industrial Control Systems

By

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To Natasha Garcia, Penelope Chavez, Miles Chavez, and all of my family.

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Abstract

Parametrization and Effectiveness of Moving Target Defense Security Protections for Industrial Control Systems

Critical infrastructure systems continue to foster predictable communication patterns and static configurations over extended periods of time. The static nature of these systems eases the process of gathering reconnaissance information that can be used to design, develop, and launch attacks by adversaries. In this research effort, the early phases of an attack vector will be disrupted by randomizing application port numbers, IP addresses, and communication paths dynamically through the use of overlay networks within Industrial Control Systems (ICS). These protective measures convert static systems into "moving targets," adding an additional layer of defense. Moving Target Defense (MTD) is an active area of research that periodically changes the attack surface of a system to create uncertainty and increase the workload for an adversary. To assess the effectiveness of MTD strategies within an ICS environment, performance metrics have been captured to quantify the impacts introduced to the operational network and to the adversary. Our MTD strategies are implemented using Software Defined Networking (SDN) to provide a scalable and transparent solution to the end devices within the network. We show that our MTD techniques are feasible within an ICS environment and that they can improve the resiliency of ICS systems. Our MTD strategies meet the real-time constraints of ICS systems and incur latency impacts of less than 50 ms and in most cases, well under 20 ms. Resiliency is improved by introducing crash tolerant and Byzantine fault tolerant algorithms to detect and prevent attacks against the SDN controller. We also evaluate the success rates of individual adversaries, distributed adversaries, and those attempting side-channel attacks to learn the frequencies at which the MTD techniques reconfigure the system. We demonstrate the effectiveness of our approaches in simulated, virtualized, and representative ICS environments.

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- Adrian Chavez, Jason Hamlet, Erik Lee, Mitchell Martin, William Stout. "Network Randomization and Dynamic Defense for Critical Infrastructure Systems." Sandia National Laboratories ReportSAND2015-3324 (2015).

- Moses Schwartz, John Mulder, Adrian Chavez, and Benjamin Allan. "Emerging Techniques for Field Device Security." *IEEE Security & Privacy* 6 (2014): 24-31

Chapter 1

Introduction

Historically, control systems have primarily depended upon their isolation [2] from the Internet and from traditional Information Technology (IT) networks as a means of maintaining secure operation in the face of potential remote attacks over computer networks. However, these networks are incrementally being upgraded [3] and are becoming more interconnected with external networks so they can be effectively managed and configured remotely. Examples of control systems include the electric power grid, smart grid networks, micro grid networks, oil and natural gas refineries, water pipelines, and nuclear power plants. Given that these systems are becoming increasingly connected, computer security is an essential requirement as compromises can result in consequences that translate into physical actions [4] and significant economic impacts [5] that threaten public health and safety [6]. Moreover, because the potential consequences are so great and these systems are remotely accessible due to increased interconnectivity, they become attractive targets for adversaries to exploit via computer networks. Several examples of attacks on such systems that have received a significant amount of attention include the Stuxnet attack [7], the U.S.-Canadian blackout of 2003 [8], the Ukraine blackout in 2015 [9], and attacks that target the control system data [10] itself. Improving the computer security of electrical power grids is the focus of our research.

The power grid is responsible for providing electricity to society, including homes, businesses, and a variety of mission critical systems such as hospitals, power plants, oil and

gas refineries, water pipelines, financial systems and government institutions. The "smart grid" acts as an advanced power grid with upgrades that provide power distribution systems and consumers with improved reliability, efficiency, and resiliency [11]. Some of the upgrades include automated energy load balancing, real-time energy usage tracking and control, real-time monitoring of grid-wide power conditions, distributed energy resources, advanced end devices with two-way communications and improved processing capabilities. Advanced end devices, which are being integrated into smart grids, include Programmable Logic Controller (PLCs), Remote Telemetry Units (RTUs), Intelligent Electronic Devices (IEDs), and smart meters that are capable of controlling and performing physical actions such as opening and closing valves, monitoring remote real-time energy loads, monitoring local events such as voltage readings, and providing two-way communications for monitoring and billing, respectively. These new devices replace legacy devices that have been in place for decades that were not originally designed with security in mind since they were previously closed systems without external network connectivity. Although these new devices aid efficiency, they may create more avenues for attack from external sources.

Finally, control systems are often statically configured [12] over long periods of time and have predictable communication patterns [13]. After installation, control systems are often not replaced for decades. The static nature combined with remote accessibility of these systems creates an environment in which an adversary is well positioned to plan, craft, test and launch new attacks. Given that the power grid is actively being developed and advanced, the opportunity to incorporate novel security protections directly into the design phase of these systems is available and necessary. Of particular interest are defenses that can better avoid both damage and loss of availability, as previously documented in the power grid [6], to create a more resilient system during a remote attack over computer networks.

1.1 Challenges

One of the main challenges of our research is to ensure that the computer security protections themselves not only improve the security of the overall system, but also do not impede the operational system from functioning as expected. A security solution that is usable and practical within an IT environment may not necessarily be practical within an Industrial Control System (ICS) environment. ICS systems often have real-time requirements and any newly introduced software or security solution must also meet those same requirements.

Another challenge is to identify useful metrics that quantify the effectiveness of the *Moving Target Defense (MTD)* techniques from the perspective of both the adversary and the defender of the system. The goal of the adversary is to exploit the system before the MTD defense modifies the environment in time. The goal of the defender is to change the environment frequently enough to evade an adversary but not too frequently so that the system performance is negatively impacted. Finding the correct balance so that the adversary cannot exploit the system while throttling the MTD strategy so it does not prevent the system from maintaining a normal operating state.

Gaining access to a representative ICS environment is another challenge when developing new security protections for ICS systems. Modeling and simulation tools can be effective, but gaining a true understanding of the consequences and effects of deploying a new security protection in practice requires validation within a representative ICS environment. Several factors, such as network load, processor load, and memory load are difficult to accurately project within a simulated environment. The harsh working conditions of ICS systems (such as the wide temperature ranges) are one element to consider when deploying new technologies within these environments.

1.2 Contributions

The goals of our research are to develop and combine several MTD techniques that increase the adversarial workload while minimizing the operational network impacts. When new computer security defenses are introduced into a system, there is often a trade-off between usability and security of the operational network. It is expected that the operational network will maintain high availability and responsiveness while also protecting against a new set of adversaries after applying such defenses. Quantifying and measuring the associated costs to both the adversary and the defender of the system when deploying MTD techniques are contributions of our research. The domain of focus for our research resides within critical infrastructure systems; effective MTD strategies for these distinct environments will be identified. Additionally, the parameters of each MTD strategy when deployed within a simulated environment, virtualized environment, and a representative critical infrastructure environment are evaluated against a variety of adversaries.

Some of the goals of an adversary include gaining unauthorized access to the system, causing the system to operate outside of what was originally intended, introducing uncertainty to the operator, and exfiltrating information – all within a certain time bound. The time bound is an added complexity to the adversary so that they can complete their goal before detection by the defender of the network. Also of note is that the adversary may even attack the computer security protection itself directly or indirectly. To cover this case, the critical infrastructure environment itself is evaluated for security threats after the new MTD security protections are applied. The first set of metrics captured are those focused on the increased workload added to the adversary. Examples of these increased costs imposed on an adversary when applying new computer security defenses include reducing the value of an adversary's knowledge about the system, for example, by changing key parameters so that an adversary's insights are out of date; delayed (or eliminated) potential of exploitation, increased risk of detection, and increased uncertainty about system operations.

The goal of the defender is to maximize the effectiveness of each MTD strategy by protecting against an adversary while minimizing the operational impact to the system. The second set of metrics captured are the costs that are associated with the defender of the system when deploying new security protections. These costs include delayed system performance, delayed network performance, equipment costs, training costs, and labor costs to interoperate with the existing infrastructure. For MTD techniques specifically, the frequency at which the MTD technique changes elements of the system is evaluated and compared against scenarios where one or more adversaries are attempting to defeat those protections. Additionally, the resiliency of the MTD protection itself is also evaluated when an adversary targets the newly introduced security protection.

Another contribution of our research comes from the adversaries that are included as a part of the threat model under consideration. Several types of adversaries with different capabilities and strategies to defeat the defenses introduced are evaluated. Singleton adversaries as well as multiple, distributed adversaries are analyzed against each MTD technique deployed individually and in combination with one another. Additionally, it is also important that the introduced security solution does not become a target itself. The threat model is expanded so that the security protection itself is considered as part of the attack space. We have built in fault tolerant algorithms directly into the MTD techniques so that the security protection itself does not become a liability to the ICS system. As a result, the MTD techniques developed are more robust, resistant, and resilient to survive and detect several classes of adversaries who have an understanding of the ICS system as well as the security protections themselves.

1.2.1 MTD within Critical Infrastructure

Critical infrastructure systems bring in a distinctive set of constraints and requirements when compared against traditional IT based systems. Critical infrastructure systems are often time sensitive with stringent real-time constraints in the case of cyber-physical systems [14]. It is therefore important for any new computer security protections introduced to also meet these same time requirements so they do not negatively affect the

operational network. Additionally, the most important requirements for these systems are often to maintain high availability and integrity due to the nature of the systems that they control (the electrical power grid, water pipelines, oil and natural gas refineries, hospitals, residential and commercial buildings, etc.). Any loss of availability can result in significant consequences not only in terms of economics, but also in terms of public health and safety. Similarly, compromising the integrity of these systems, such as sending maliciously modified commands, can result in similar consequences. Also of note, is that critical infrastructure systems are composed of both legacy and modern systems that must interoperate with one another without affecting availability and security. New security solutions must take this into account so that they can scale without the requirement of upgrading every device within the system.

Another goal of our research is to determine if MTD based approaches can successfully be deployed within critical infrastructure environments in practice while satisfying the distinct time constraints and requirements of these environments. Since the time constraints vary from one system to another, the stricter time requirement used for teleprotection systems are used here (12-20ms) [15]. For Supervisory Control And Data Acquisition (SCADA) communications, those requirements can, in some cases, be relaxed to 2-15 seconds or more. The computer security solutions presented here have the goal of falling under 10 ms of additional latency. Additionally, the MTD techniques that we developed were tested and evaluated within a simulated environment, a virtualized environment, and also within a representative environment containing industrial grade equipment. We have designed each environment to harness and measure the effectiveness of each of the new security protections developed.

1.2.2 Operational System Impacts

Given the strict time constraints of critical infrastructure systems, it is imperative to ensure that the security solution itself does not negatively impact the ICS network. Some of the metrics we measured include latency, bandwidth, throughput, dropped packets and number of retransmitted packets. Because ICS systems can be time sensitive, it is impor-

tant to ensure there are no dropped packets, minimal (if any) latency is introduced, and a minimal (if any) number of retransmits are required to maintain connectivity in order to satisfy the real-time constraints that these systems require. Each of these metrics support the high availability requirements.

Additionally, the ability of security solutions to interoperate with the existing infrastructure is critical. Intrusion Detection Systems (IDS), Intrusion Prevention Systems (IPS), firewalls and even security operations personnel are examples of components that need to interact with and be trained on the new security solution introduced. The interface to the security protection must interoperate with each of these systems to aid an operator who may potentially be actively defending their ICS network or basing their decisions on the feedback received from the security protection. These requirements placed on the security protections support the high availability and high integrity needs of ICS systems.

The goal of our research is to quantitatively measure the MTD techniques developed within the context of an ICS environment. Determining the measurable limits of overhead that an ICS system can support (if any) to harness such security protections is a necessary first step to understand the feasibility of introducing these MTD techniques. These limits serve as parameters that can be used as part of the MTD technique to ensure that the specified limit is not exceeded. One example of a parameter bounded by the environment that our research investigates, is the balance of how frequently a MTD approach should reconfigures the system so that the ICS environment maintains the required response time needed to operate correctly. The faster the MTD technique reconfigures the system, the higher the overhead that is required from the underlying environment.

1.2.3 Adversary Workload Impacts

An additional goal of our research is to quantitatively determine the effectiveness of the MTD techniques deployed. MTD is an active area of research that seeks to thwart attacks by invalidating knowledge that an adversary must possess to mount an effective attack against a vulnerable target [16]. MTD approaches are designed to continuously modify

and reconfigure system parameters with the goals of evading, confusing, and detecting an adversary. We evaluated the amount of work required by an adversary to defeat the applied MTD protections. A number of adversary strategies in attacking the defense were analyzed. The time it takes for an adversary to accomplish their goal is then passed as an input parameter into the MTD technique to ensure that it is moving faster than the adversary. We considered both individual adversaries as well as multiple distributed adversaries when evaluating each of the MTD techniques.

We also investigate side-channel information that can be gathered from an adversary to understand the frequency at which the MTD technique reconfigures the system. This information can aid an adversary in understanding how fast they must craft and execute their attack. We have identified solutions that can mitigate these side-channel threats. One such mitigation would be to re-randomize the network configurations at random intervals. This solution would help prevent adversaries from inferring how frequently the MTD technique re-randomize configurations by passively observing network traffic.

Finally, adversaries who have the goal of launching an attack against the security protections themselves are also considered. There are documented cases [17, 18] where a security protection itself becomes the point of entry for an adversary. Software that is designed to protect a system should be similarly scrutinized for security flaws in the same way that any application being integrated into a system would be. We have demonstrated that the MTD techniques developed can be combined with crash tolerant and Byzantine fault tolerant algorithms to become more resilient against adversaries attacking the system as well as the data of the system.

1.3 Organization

The remainder of the dissertation is organized as follows: Chapter 2 summarizes background material and related MTD work; Chapter 3 covers the applications where MTD techniques can be effective within ICS environments; Chapter 4 covers the threat model

of what, specifically, our MTD defenses do and do *not* protect against; Chapter 5 describes the MTD techniques developed for our research; Chapter 6 describes the theory related to the crash tolerant and Byzantine fault tolerant algorithms implemented within our research; Chapter 7 describes the experimentation testbeds, network topologies and configurations used for our research; Chapter 8 discusses our simulated results based on a variety of adversaries probing the network that are applying different attack strategies; Chapter 9 outlines our results from the virtualized environment developed; Chapter 10 describes the results obtained from the representative ICS environment that was used when applying each of the MTD techniques developed; and finally Chapter 11 describes the limitations of each of the MTD techniques deployed, the lessons learned along the way that can be used to build upon our research, the future directions and the potential future environments that the research results presented here can be applied towards, and a summary along with concluding remarks of our research.

Chapter 2

Background

Artificial diversity is an active area of research with the goal of defending computer systems from remote attacks over computer networks. Artificial diversity within computer systems was initially inspired by the the ability of the human bodies natural immune system to defend against viruses through diversity [19]. Introducing artificial diversity into the Internet Protocol (IP) layer has been demonstrated to work within a software-defined network (SDN) environment [20]. Flows, based on incoming port, outgoing port, incoming media access control (MAC) and outgoing MAC, are introduced into software-defined switches from a controller system. The flows contain matching rules for each packet and are specified within the flow parameters. If a match is made within a packet, then the flow action is to rewrite source and destination IP addresses to random values. The packets are rewritten dynamically while they are in flight traversing each of the software-defined switches. Although applying artificial diversity towards SDN has been demonstrated, the effectiveness of such approaches has not been quantitatively measured. Furthermore, to our knowledge, the approach has not been deployed within an ICS setting, which differs substantially from traditional IT based systems.

It has also been demonstrated that IP randomization can be implemented through the Dynamic Host Configuration Protocol (DHCP) service that is responsible for automatically assigning IP addresses to hosts within the network [21]. Minor configuration modifications to the DHCP service can be made to specify the duration of each host's IP lease

expiration time to effectively change IP addresses at user defined randomization intervals. However, this approach only considers long-lived Transmission Control Protocol (TCP) connections, otherwise disruptions in service will occur as the TCP connection will need to be re-established. Service interruptions within an ICS setting is not an option due to their high availability requirements. Quantifying the effectiveness of such approaches has also not been performed within an ICS setting outside of surveys [22] that evaluate MTD techniques within an IT setting, where IP randomization by itself was qualitatively ranked to have low-effectiveness with low operational costs. Also of note is that IP randomization approaches by themselves have been demonstrated to be defeated through traffic analysis where endpoints of the communication stream can be learned by a passive adversary observing and correlating traffic to individual endpoints [23]. An additional concern when leveraging SDN as a solution, is that the SDN controller of the network can be viewed as a single point of failure [24]. The same can be said, at a smaller scale, for each of the SDN switches that are providing access to a subset of the users on the network. Increasing the resiliency of the SDN network by eliminating the single points of failure and combining MTD techniques together is one of the focus areas of our research.

Anonymization of network traffic is an active area of research with several implementations available in both the commercial and open source communities. MTD and anonymization are related in that they both have the goal of protecting attributes of a system from being discovered or understood. One of the early pioneering groups of anonymous communications describes the idea of onion routing [25] which is widely used today. This approach depends on the use of an overlay network made up of onion routers. The onion routers are responsible for cryptographically removing each layer of a packet, one at a time, to determine the next hop routing information to eventually forward each packet to their final destinations. The weaknesses of this solution are that side channel attacks exist and have been demonstrated to be susceptible to timing attacks [26], packet counting attacks [27], and intersection attacks [28] that can reveal the source and destination nodes of a communication stream.

The Onion Router (Tor) is one of the most popular and widely used implementations of onion routing with over 2.25 million users [29]. Tor is able to hide servers, hide services, operate over the TCP, anonymize web-browsing sessions, and is compatible with Socket Secure (SOCKS) based applications for secure communications between onion routers. However, it has been shown empirically with the aid of NetFlow data that Tor traffic can be de-anonymized with accuracy rates of 81.4% [30]. The results are achieved by correlating traffic between entry and exit points within the Tor network to determine the endpoints in communication with one another. Furthermore, Tor has an overhead associated with the requirement to encrypt traffic at each of the onion routers; this overhead would need to be limited within an ICS environment to meet the real-time constraints required of these systems. Similarly, garlic routing [31] combines and anonymizes multiple messages in a single packet but is also susceptible to the same attacks

Overlay networks have similar goals as Tor with the goal of reducing the overhead associated with a Tor network. It has been shown that overlay networks can be used to mitigate Distributed Denial of Service (DDoS) attacks [32]. The overlay networks reroute traffic through a series of hops that change over time to prevent traffic analysis. In order for users to connect to the secure overlay network, they must first know and communicate with the secure overlay access points within the network. The required knowledge of the overlay systems prevents external adversaries from attacking end hosts on the network directly. This design can be improved by relaxing the requirement of hiding the secure overlay access points within the network from the adversary. If an adversary is able to obtain the locations of the overlay access points, then the security of this implementation breaks down and is no longer effective.

Steganography is typically used to hide and covertly communicate information between multiple parties within a network. The methods described in current literature [33] include the use of IP version 4 (IPv4) header fields and reordering IPsec packets to transmit infor-

mation covertly. Although the focus of the steganography research is not on anonymizing endpoints, it can be used to pass control information to aid in anonymizing network traffic. The described approach would have to be refined to increase the amount of information ($log_2(n)$ bits can be communicated through n packets) that can be covertly communicated if significant information is desired to be exchanged. Steganography techniques have the potential to facilitate covert communication channels for MTD techniques to operate correctly but have not been applied in this fashion.

Transparently anonymizing IP based network traffic is a promising solution that leverages Virtual Private Networks (VPNs) and the Tor [34] service. The Tor service hides the user's true IP address by making use of a Virtual Anonymous Network (VAN) while the VPN provides the anonymous IP addresses. The challenge of this solution is the requirement that every host must possess client-side software and have a VPN cryptographic key installed. In practice, it would be infeasible for this approach to scale widely, especially within ICS environments where systems cannot afford any downtime to install and maintain the VPN client-side software and the cryptographic keys that would be necessary at each of the end devices. To reduce the burden on larger scale networks, it may be more effective to integrate this approach into the network level, as opposed to at every end device, using an SDN based approach. The goal of the research presented here is to provide a similar service within an ICS system with the ability to scale to a large number of devices without significant interruptions in communications.

2.1 Moving Target Defense Techniques

MTD is an active area of research that seeks to thwart attacks by invalidating knowledge that an adversary must possess to mount an effective attack against a vulnerable target [16]. For each MTD defense deployed, there is an associated delay imposed on both the adversary and on the defender of the operational system. A goal of our research is to quantitatively analyze the delays introduced by each additional MTD technique applied individually and in combination of one another within an ICS environment. Our analysis

will aid in optimally assigning the appropriate MTD techniques to enhance the overall security of a system by minimizing the operational impacts while maximizing the adversarial workload to a system. We have quantitatively captured the delays associated with IP, port and path randomization from the perspectives of both a defender and an adversary. Our results have focused on both network based and host based MTD strategies. Our research evaluates each of the MTD defenses placed at various levels of a system and aggregates the total delays placed on an adversary. Analysis of such MTD defenses across an entire system is used to determine the effectiveness of such approaches holistically.

2.1.1 Adversarial Distributions

We model several adversaries with different strategies to reverse engineer the MTD techniques developed. In our analysis, the success rates of the adversarial strategies fit either the binomial distribution or the hypergeometric distributions depending on the adversarial strategy applied. Since we are interested in both the probabilities of success and the expected number of attempts needed for an adversary to reverse engineer our MTD strategies, the probability and expectation functions of these distributions are utilized in our analysis. These functions inform the MTD techniques of how frequently they should reconfigure the system.

The binomial distribution consists of a population of size N that contains k success cases in the population, $N - k$ failure cases, and n independent attempts permitted to find a success case using a random variable X that selects from the population *with* replacement. The probability of finding k success cases in the binomial distribution is defined as:

$P(X = k) = \binom{n}{k} p^k (1-p)^{n-k}$ [35]

The expectation formula for the number of attempts before the first expected success in the binomial distribution is defined as follows:

$E(X) = \frac{1}{p}$

The hypergeometric distribution consists of a population of size N that contains k success cases in the population, $N-k$ failure cases, and n independent attempts to find a success case using a random variable X that selects from the population *without* replacement. The probability of k successes in the hypergeometric distribution is defined as:
$P(X = k) = k/N$
Thus, the probability of failing to find a success case given k probes is $\hat{p} = 1-p = 1-k/N$. Since the hypergeometric distribution does not replace failed attempts, the probability of finding a success case improves with each subsequent attempt. The general expectation formula for the hypergeometric distribution is defined as:
$E(X) = \frac{N+1}{2}$

The general expectation formula does not limit the number of attempts until the first success is encountered. However, in our research we do place an upper limit on the number of attempts an adversary can make to reverse engineer the MTD strategy. Because we place an upper limit on the number of attempts allowed by an adversary, the expectation formula must be modified to both model the MTD strategies that periodically redefine the success cases as well as the continuous stream of attempts that are coming from the adversary. To find the expectation of several independent experiments repeated where an adversary is limited to k attempts to find the first success case, the expectation function becomes: the original expectation of the hypergeometric distribution plus the original expectation of the hypergeometric distribution multiplied by the number of failed attempts before the first success. The second part of the formula accounts for the number of failed attempts before the first success is found when limited to k attempts since the MTD strategy would redefine the success cases after k attempts are made. More simply put, the formula can be written as follows:
$E(X) = \frac{N+1}{2} + \frac{N+1}{2} \times (\hat{p}) = \frac{N+1}{2} + \frac{N+1}{2} \times (1 - k/N) = \frac{N+1}{2} \times (1 + \hat{p})$

The adversaries we model closely follow these two distributions. Since we are interested in the effectiveness of each MTD technique, our goal is to maximize the expectation value

for an adversary to successfully reverse engineer our MTD strategies. As the number of attempts required by an adversary increases, the level of noise produced by the adversary and the amount of resources they must spend to defeat the MTD approaches also increases. Additionally, as the expected number of attempts increases for the adversary their probability of finding a success case decreases within either of the two distributions. The best strategy for a defender to maximize the expectation value on the number of attempts until the first success case and minimize the probability of finding a success case is to expand the size of the population as much as possible. The population size in our research is the amount of entropy available to the defender of the system. In general, we show that the more entropy that the defender has available, the more uncertainty that is placed on the adversary to defeat each of the MTD techniques.

2.2 MTD Categories

The MTD strategies evaluated as part of our research include IP randomization, port randomization, communicate path randomization, and application library randomization. Because power systems are statically configured and often do not change over long periods of time, those environments are ideal for introducing and evaluating MTD based protections. The goal of our research is to increase the adversarial workload and level of uncertainty during the reconnaissance phases of an attack. Since it remains an open problem to completely stop a determined, well-funded, patient, and sophisticated adversary, increasing the delay and likelihood of detection can be an effective means of computer security. There are a variety of MTD approaches that can be categorizing according to where the defense is meant to be applied including at the application level, the physical level, or the data level of a system. Five high level MTD categories have been described as part of a MTD survey [36], which include dynamic platforms, dynamic runtime environments, dynamic networks, dynamic data, and dynamic software. These categories are described in the sections that follow within the context of a critical infrastructure environment.

2.2.1 Dynamic Platforms

PLCs, RTUs, and IEDs vary widely from one site to another within an ICS environment. There are a number of vendors that produce these end devices with different processor, memory and communications capabilities. These devices are responsible for measuring readings from the field (such as power usage within a power grid context) and taking physical actions on a system (such as opening or closing breakers in a power grid). Many of these end devices are several decades old and they must all be configured to work together. If an adversary has the ability to exploit and control these types of end devices, they would have the ability to control physical actions remotely through an attack over computer networks. At the physical layer, several MTD strategies exist to increase the difficulty of an adversary's workload to successfully exploit a system. One strategy rotates the physical devices that are activated within a system [37, 38, 39]. For this strategy to work, the physical devices and software may vary widely, but the only requirement is that they must be capable of taking in the same input and successfully producing the same output as the other devices. If there are variations in the output, then alerts can be generated to take an appropriate action. These approaches increase the difficulty from an adversary's perspective because the adversary would be required to simultaneously exploit many devices based on the same input instead of exploiting just a single device. The difficulty for the defender comes in the form of having additional devices that must be administered and managed while also ensuring the security of the monitoring agents is maintained and that they do not become additional targets themselves. Strategies such as n-variant [40] MTD techniques run several implementations of a particular algorithm with the same input where variations of outputs would be detected by a monitoring agent. Others [41] have shown firmware diversity in smart meters can limit the effectiveness of single attacks that are able to exploit a large number of devices with a single exploit. Customized exploits would have to be designed specifically for each individual device. We have captured quantitative measurements of the delays introduced to an adversary and a defender to measure the effectiveness of these approaches.

2.2.2 Dynamic Runtime Environments

Instruction Set Randomization [42] and Address Space Layout Randomization [43] are MTD techniques that modify the execution environment of an application over time. The effectiveness of such techniques has been measured in traditional enterprise networks but has not yet been measured on devices found within ICS based environments where real-time responses are a major requirement. The impact upon the real-time response requirement has been measured along with the adversaries increased workload when ISR [44] and ASLR [43, 45] are enabled.

We provide a quantitative evaluation of an open source implementation of the Modbus protocol, libmodbus, when a cluster of SDN controllers are running. We also evaluate the impacts imposed on both the defender and adversary while taking into account the maximum amount of delay these systems can tolerate. We then performed the same analysis within a representative environment using an embedded Linux based PLC, a "SoftPLC," that executes ladder logic code. Finally, we analyzed the tradeoff between security and availability within a representative ICS environment. While evaluating these tradeoffs, we also must satisfy the requirement that the cluster of SDN controllers that are communicating with one another do not negatively affect the operational network by saturating the network links.

2.2.3 Dynamic Networks

The opening paragraphs of this chapter describe many of the network randomization research efforts that have been performed. This subsection focuses on our research related to dynamic networks since the prior work has already been described. Our research builds upon these results and is focused on introducing diversity into network parameters such as IP addresses, application port numbers, and the paths that packets traverse in a network. Our research analyzes the resilience of network MTD techniques against several adversaries with different capabilities. We have evaluated distributed adversaries to better understand the adversarial workloads when several adversaries are working together to defeat each MTD approach. We have also evaluated the resiliency of each MTD approach

when distributing the SDN controller within the network as part of the defense. The SDN controller is distributed so that there is no longer a single point of failure within the SDN network. We then analyze and assess the feasibility of the MTD approaches given the adversarial and defensive capabilities. To evaluate each MTD technique in a representative environment, we interoperated our MTD solution with a Hewlett-Packard Enterprise (HP) SDN-capable switch as well as with a Schweitzer Engineering Laboratory (SEL)-2740 SDN capable switch to gain an understanding of the tradeoffs observed within a representative ICS environment.

Our research also has the goal of finding the exact point at which the benefit of each MTD strategy to the defender is maximized and the adversarial workload is maximized. While we were performing our analysis, we also take into account that we are targeting ICS systems which have strict real-time and high availability constraints. Finally, we have evaluated the MTD parameters used, such as rates of randomization and the location of the MTD techniques themselves (at the network level or the end device level), to find the balance between security and usability to ensure that the solution does not hinder the operational network. The contribution of our research is to generalize and apply various MTD techniques to a wide variety of environments to assess their effectiveness.

2.2.4 Dynamic Data

Randomizing the data within a program is another technique used to protect data stored within memory from being tampered with or exfiltrated [46]. Compiler techniques to xor memory contents with unique keys per data structure [47], randomizing APIs for an application, and SQL string randomization [48] help protect against code injection type attacks. These techniques have been demonstrated on web servers and have shown varying levels of impacts to the operational systems. The benefits are that adversaries can be detected if the data being randomized is accessed improperly when the system is being probed or an attack is being launched in the case of SQL string randomization.

The same techniques can be applied and measured within a control system environment to assess the feasibility of applying such techniques and meeting the real-time constraints. For example, a historian server typically maintains a database of logs within an ICS environment. This server is a prime location to apply SQL string randomization towards database accesses. Data randomization can be performed on the data stored within the registers of a SoftPLC. To measure the effectiveness of this technique, metrics of the response times to find the delays introduced can be captured. After gathering these measurements, an evaluation of the delays introduced can be performed to ensure that they are within the acceptable limits of an ICS environment. These are a few examples of where data randomization can be applied within an ICS setting.

2.2.5 Dynamic Software

Introducing diversity into software implementations helps eliminate targeted attacks on specific versions of software that may be widely distributed and deployed. In the case of a widely deployed software package, compromising a single instance would then compromise the larger population of deployed instances. To introduce diversity and help prevent code injection attacks in networks, the network can be mapped to a graph coloring problem [49] where no two adjacent nodes share the same color or software implementations. This type of deployment helps prevent worms from spreading and rapidly infecting other systems in a network using a single payload. These techniques should also be considered as a defensive mechanism within an ICS environment. However, metrics and measurements need to be gathered and evaluated using software that is deployed and found within operational ICS environments.

At the instruction level, metamorphic code is another strategy that has primarily been utilized by adversaries to evade anti-virus detection [50]. The code is structured so that it can modify itself continuously in time and maintain the same semantic behavior while mutating the underlying instructions of the code. The idea is similar to a quine [51] where a program is capable of reproducing itself as output. Metamorphic code reproduced semantically equivalent functionality but with an entirely new and different implementation

with each replication. There are many techniques to develop metamorphic code generating engines which are outlined in the ensuing sections, but they are typically not used as a defensive strategy.

When software remains static, it becomes a dependable target that can be analyzed, tested and targeted over long periods of time by an adversary. Introducing diversity at the instruction level helps eliminate code injection attacks, buffer overflows, and limits the effectiveness of malware to a specific version of software in time. Once the code self-modifies itself, the malware may no longer be effective, depending on the self-modification being performed. Several techniques [52] exist to use self-modifying code as a defensive mechanism such as inserting dead code, switching stack directions, substituting in equivalent but different instructions, inlining code fragments, randomizing register allocation schemes, performing function factoring, introducing conditional jump chaining, enabling anti-debugging and implementing function parameter reordering.

2.2.5.1 Dead Code

Dead code refers to function calls to code fragments that do not contribute to the overall goal of an algorithm and is a useful strategy to deter an adversary. Dead code fragments have the goal of causing frustration, confusion, and generally wasting the time of an adversary in analyzing complex code fragments that are not of importance to the overall algorithm. However, techniques do exist to dynamically detect dead code [53] fragments, so this strategy should be deployed with care. Also of note is that if the size of a program cannot exceed a certain threshold, it may be necessary to take into account the available space on the system so that the code does not overly cause an excess amount of bloat and exceed space limitations.

Dead code can help protect against an adversary who is statically analyzing and reverse engineering a software implementation. In this case of a MTD protection, when the dead code is included, the goal is to cause the adversary to spend a significant amount of time analyzing code that is not useful to the overall software suite. This technique

serves as a deterrence and a decoy to protect the important software. Dead code is often used as an obfuscation technique of software to make it more difficult for an adversary to understand [54].

Although this technique may be effective against certain types of adversaries performing static code analysis, the security is based on the assumed limited analytical and intelligence capabilities placed on an adversary. This assumption is not valid when considering nation state adversaries who have a wide array of resources in terms of finances, staff and intelligence available. The technique also breaks down and fails when dynamic code analysis is performed to recognize that the dead code does not actually provide any contributions to the overall functionality of the software under consideration.

2.2.5.2 Stack Directions

The direction that the stack grows can be chosen to grow either at increasing memory addresses or decreasing memory addresses [55]. Buffer overflow attacks must take into account this direction to effectively overflow the return address so that the adversary can execute their own arbitrary code. One strategy to eliminate such an attack is to either run a program that dynamically selects the direction of the stack at runtime or to run two instances of a program in parallel with each instance having their stacks growing in opposite directions. The two programs would then be overseen by a monitoring agent to ensure that there are no deviations in results between the two programs. It is possible that an attack can still succeed in both cases at the same time, but only in very specialized cases where the original code is written in such a way that the overflow works on different variables simultaneously in both directions that the stack grows; This is, however, unlikely to occur on the majority of code that is of practical interest to an adversary.

This technique must consider possible space limitations of the system and the overhead to detect deviations between the two versions of software. If both versions are running on the same system, then the processor utilization may also be a concern for other applications running on the system. If the implementations are on separate systems, then the

network overhead to communicate the results of each run must also not negatively impact the system in question. An additional area of importance is the security of the monitoring agent to validate that a possible attack is in progress. Many security protections often become a target [17] for adversaries and also need to be taken into consideration.

2.2.5.3 Equivalent Instruction Substitution

Many techniques exist to introduce diversity into a program by substituting equivalent instructions [56]. The goal of substituting equivalent instructions for multiple instances of a program is to maintain equivalent functionality while diversifying the implementation of the underlying software. The benefit is that the difficulty of identifying functionally equivalent software implementations from one another is increased from the adversaries' perspective. This increases the difficulty placed on an adversary who is attempting to develop a scalable malware solution designed to compromise a large number of systems using a single exploit. The tradeoff is typically in the increased performance of the variants of equivalent instructions. In many cases, compiler optimizers will automatically reduce high level programming modifications to the same optimized assembly instructions using dependency graphs [57]. To disable compiler optimizations, compiler flags must be enabled to maintain the intended diversity within the binary executable. The impact on the defender and operational network of applying this approach needs to be measured within an ICS environment so that the feasibility of applying this approach to other environments can be quantitatively measured and evaluated.

2.3 Research Goals

The goals of our research address several of the research gaps identified in the above literature review. Specifically, our research will develop MTD based techniques, measure MTD techniques for their effectiveness, capture operational metrics of MTD based techniques, develop a scalable SDN based solution tailored towards ICS, and combine several MTD techniques into a single solution. We will also provide quantitative evaluations of the effectiveness of each MTD approach based on the parameters that are specific to each MTD technique.

We have performed a quantitative evaluation of several MTD techniques effectiveness within an operational setting, coexisting with the same protocols and devices typically found within a smart grid environment. The same MTD techniques are also evaluated in other environments beyond the smart grid. Initially the impacts to both the adversary and defender are measured within a virtualized environment, then in a laboratory testbed, and finally within an operational microgrid environment. The microgrid environment results are performed to verify and validate the results obtained from the virtual and laboratory environments. We then perform an evaluation on the tradeoffs between the operational network impacts introduced by the MTD techniques and the increased adversarial workload incurred from the MTD technique applied. Finally, the optimal combination of the parameters applied towards each MTD technique is evaluated, individually and in combination, by minimizing the operational impacts and maximizing the adversarial workloads required to defeat each defense.

Another area of research we investigate is the rate at which each MTD technique must reconfigure itself in order to successfully evade an adversary. Simulation based studies on the effectiveness of MTD strategies have been performed [58], but operational experimentation is needed to determine the frequencies of movement needed by each MTD approach. If the adversary is able to attack the system more quickly than the defender reconfigures the systems, the adversary can continue to make progress towards exploiting the system until they eventually succeed. In this scenario, the effectiveness of the MTD technique would strictly be the delay introduced to the adversary. A certain amount of delay may be the primary goal of the defender, which would make this approach feasible. On the other hand, if the goal of the defender is to prevent the adversary from successfully attacking a system, independent of time delays, then the MTD technique would be considered ineffective. We evaluate and measure the frequencies of randomization for each MTD based approach to be effective in protecting against a variety of adversaries.

For each of the MTD technologies developed as part of our research, we evaluate their effectiveness within a virtualized environment and within a representative environment of a control system in order to verify and validate the MTD techniques in theory and in practice. Although every environment is different and will yield a distinct set of results, without a representative ICS test environment and associated results, it is difficult to anticipate all variables that could materialize within an operational network.

Another goal of our research is to generalize the measurements that quantitatively determine the effectiveness of each MTD technique so that they can be applied more broadly towards a variety of environments outside of ICS. The effectiveness of each MTD defense will change and be dependent upon the environments that they operate within. "Internet of Things (IoT)" describes environments where a large number of physical items communicate with one another, machine-to-machine communications and person-to-computer communications, that will continue to be extended to other physical "things" [59, 60, 61]. For example, path randomization may be more limited in an ICS environment versus an IoT environment as the real-time constraints may not necessarily be a primary driver in an IoT environment. We parameterize the adversaries' capabilities, the delays introduced to both adversary and defender, and the environment of operation as part of the contributions of our research. Many MTD strategies lack quantitative measurements [62] that capture the effectiveness of such techniques outside of specific ad-hoc scenarios. Furthermore, the precise period in time at which to diversify is also an important unexplored area of research that needs to be taken into consideration. For example, it may not be beneficial to continuously load the operational system by constantly re-randomizing different parameters when the system is idle and not under attack or any sort of threat. Our results for port randomization show that randomization periods should be based on a combination of the number of probes and the time units since the previous randomization period occurred instead of solely based on time units alone. Our research also combines and measures several MTD techniques categorized by type [36] to find the adversary-defender tradeoffs that elevate the overall system security.

Combining the techniques mentioned above to create an MTD solution that provides full anonymity is needed for time critical systems. ICS environments fit this need and currently have no single solution existing to counter the reconnaissance phase of an attack. Some of the areas that need to be addressed from the prior work identified in this chapter are reducing the overhead costs of multiple layers of encryption, evaluating MTD techniques within an ICS environment, developing metrics on the effectiveness of MTD strategies, scaling up the MTD techniques to a large number of nodes, reducing the number of single points of failure, and relaxing the requirement to hide nodes participating in the anonymous service. Addressing these areas of research will provide insights into when and where MTD techniques can be effectively deployed. Additionally, taking into consideration that ICS environments are composed of both legacy and modern devices is an area of research that is needed. Many of the legacy (and some modern) devices may not be capable of implementing IP randomization, port randomization, and overlay networks on the end devices directly. A few of the reasons for this are that many of the end devices found within an ICS environment contain proprietary software, proprietary firmware, or are legacy devices without the computational resources available to implement new security features. To resolve these issues, we have researched and developed a transparent solution to the end devices that merges the above capabilities in an ICS environment, external to the end devices.

Chapter 3

MTD Applications and Scenarios

MTD strategies can benefit a broad range of environments that span enterprise IT systems that are widely connected and ICS networks which are completely isolated from the Internet. Each environment has different requirements and constraints for which the MTD approaches and parameters must be specifically configured in order for the strategy to be feasible in a practical setting. Some of the MTD parameters that can be adjusted include the frequency of reconfigurations, the amount of entropy supplied to the MTD technique when performing IP randomization, the maximum number of hops between endpoints tolerable when performing path randomization, the size of a binary when performing application randomization, and the number of SDN controllers available as part of a cluster to support crash tolerant and Byzantine fault tolerant algorithms. The requirements and constraints of these systems include meeting strict performance measurements (latency, bandwidth, and throughput constraints), satisfying the North American Electric Reliability Corporation (NERC) Critical Infrastructure Protection (CIP) Standards [63], the International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) 27000 series of Information Security Management Systems standards [64], and conformance to the National Institute of Standards and Technology (NIST) Cybersecurity Framework [65].

Each environment has their own unique set of requirements and constraints that must be met in an operational setting. Because MTD approaches can be applied broadly

across a number of environments, a few examples of use cases will be discussed in this chapter. Each of these environments will serve as motivating examples for the types of scenarios where MTD strategies are effective techniques for providing additional layers of defense. The examples will also document the parameters of the MTD strategies that can be adjusted to meet the requirements and constraints of the target environment. The focus of our research is on ICS environments, but the approaches can be applied similarly to the other environments described. In this chapter we discuss what some of those applications and environments might look like before narrowing our focus on ICS environments in Chapter 4 and beyond.

3.1 Industrial Control Systems

Examples of systems that are categorized as ICS include the electrical power grid, oil and natural gas refineries, and nuclear power plants. The primary requirement for many of these systems is to maintain high availability and integrity [2]. In the electrical power grid, the high availability requirement comes from the criticality of the types of systems that depend on the power grid to operate (hospitals, governments, educational institutions, commercial & residential buildings, etc.). Figure 3.1 shows an example power grid and the components found at various layers of the network. These systems involve a number of utilities communicating with one another and the distribution of power across a geographically disperse area of customers. A study was performed with the goal of quantifying the economic costs associated with service interruptions to the U.S. power grid and are estimated to be approximately $79 million annually [66]. From the 2003 blackout in New York [67], the estimated direct costs were between $4 billion and $20 billion [68] while there were also in excess of 90 deaths [69]. Though these interruptions were not due to remote attacks over computer networks, such attacks are capable of causing similar disruptions. The need for computer security within an ICS setting is clear as the impacts and consequences of downtime can be dire.

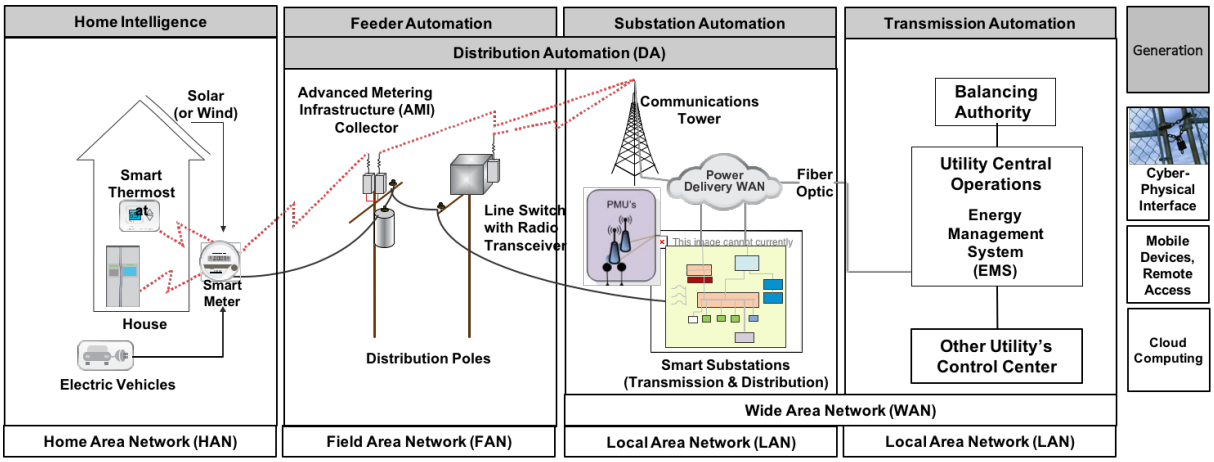


Figure 3.1: An example power grid that shows the high level components from generation of power to transmission to distribution and finally to delivery at a residential home.

3.1.1 Use Case

Because ICS systems operate with both legacy and modern devices, there is a mixture of serial and IP communications. Typical protocols deployed within ICS networks include Modbus [70], Distributed Network Protocol (DNP3) [71]. and Process Field Net (PROFINET) [72]. These protocols are widely used within ICS environments and many, such as Modbus, were not designed with security in mind since these protocols were originally intended for serial communications, and only later expanded, with Modbus TCP, to function over IP networks. Still the expectation was that such IP networks would be controlled and isolated. Modbus is a protocol that can be used to read and write memory values to ICS end devices, such as PLCs or industrial computers that can either sense readings from equipment or perform physical actions based on digital inputs received. Some of the physical actions include opening or closing a valve within a water pipeline, opening or closing breakers within a power system, or shutting down a power plant.

Given that ICS systems are becoming more interconnected to business networks for ease of maintenance and management, remote attacks over computer networks become a real possibility since the business networks are connected to the Internet. However, as demonstrated by Stuxnet [7], a network connection to the Internet is not a requirement to exploit a system, and the attack against Home Depot [73] shows how vulnerable operational tech-

nology can be exploited to penetrate additional systems. In a scenario where the Modbus protocol is configured to read and write memory values from and to, respectively, a PLC that controls a physical process, an adversary could launch a man-in-the-middle (MITM) attack [74] to spoof values read/written to the PLC's memory. Since legacy PLCs are fundamentally different from the systems we are accustomed to working with (in terms of the memory and processing resources available) and because they were designed with the understanding that they would be used only within closed system environments, integrity and authentication checks were typically not built-into these systems. As ICS environments have evolved, PLCs and other end devices are becoming more connected externally. As a result, end devices that do not have integrity and authentication checks built-in are susceptible to adversaries eavesdropping on communications and/or maliciously modifying those communications via MITM attacks. To mitigate such an attack, a defender could deploy a number of strategies to protect against this threat.

If the adversary has direct access to the network and has the ability to observe or modify traffic, spoofed packets can be injected or replayed into the network. The goal of the adversary in this scenario would be to maliciously write incorrect values into a PLC's memory space to cause an unintended physical action to take place within the system. One defense that could protect against an attack where the adversary crafts and injects packets into the network could be to deploy a MTD strategy that randomizes application port numbers in the communication channel (the Modbus standard port number is 502). Continuously changing this value in time would require the adversary to constantly track and learn the new random mappings that are active. Another defense that can be deployed would be to configure a secure communication channel between the endpoints to prevent the adversary from maliciously observing and spoofing traffic. This solution would require the adversary to compromise the underlying encryption algorithm or a cryptographic key.

The optimal solution that a defender should select depends on the capabilities of the end devices as well as the amount of delay that can be tolerated by the network. If the

end devices are capable of supporting some of the more well-established modern encryption algorithms, such as the Advanced Encryption Standard with at least a 128 bit key length (AES-128) [75], then that is the ideal solution. However, the end devices may either not be capable of supporting AES or they may not be able to afford the computationally expensive tasks, in terms of central processing unit (CPU) utilization [76], to support an encrypted channel. The amount of CPU available depends on the current load of the system. The other option is to deploy a gateway system that is capable of serving as a proxy to harness the necessary security protections [77, 78, 79, 80]. The MTD approach described above follows the gateway solution and is capable of minimally delaying the network communications while adding on an additional layer of defense into the network. The parameters of the MTD techniques can then be adjusted to meet the criteria required by the ICS system to maintain a high availability system while avoiding the computationally expensive price of encrypting all communication channels.

3.1.2 Constraints

One of the major challenges for new technologies to be deployed within ICS environments is the fact that legacy and embedded devices occupy a large portion of these systems. Some of the devices found are decades old and do not have the processing or memory resources available to harness modern security technologies. This can be attributed to the fact that many of these systems were developed starting from the 1880's to the 1930's [81] and many legacy devices are still in place today. Another constraint is that, even if the devices are modern and capable of harnessing new security technologies, the software and specialized hardware are often both closed and proprietary [2]. The proprietary nature creates a challenge for security researchers to understand, integrate, and test new security protections directly into the end devices themselves. In this scenario, an additional gateway system is typically introduced to proxy the end devices with the new security technologies enabled. This proxy creates an additional hop that packets must traverse which affects latency.

Another challenge is the diverse set of equipment that can be found within ICS environments. These devices, from multiple vendors, must interoperate with one another which is a challenge of its own. Adding computer security protections into each of these devices directly in a vendor neutral way requires agreement and collaboration between a number of competing parties. This is a challenge that is outside of the technical scope of work and can often times be the most difficult piece of the puzzle. These constraints cannot be ignored as new security technologies must be retrofitted into the existing environment with competing vendors working together, as completely replacing all of the equipment is not a valid option.

3.1.3 Requirements

ICS systems have several requirements, regulations, and standards that must be met. Perhaps the most important requirements for ICS environments are to minimize the amount of delay introduced into a system and to ensure the integrity of the commands communicated within these environments. Latency is one of the primary metrics used and is typically constrained to 50 milliseconds and in some cases can be in the nanosecond [82] scale. Any delays on the operational network can result in instability of the power system [83]; therefore new security protections must meet the strict time requirements to be relevant and feasible within these systems. Integrity is also a key requirement as data integrity attacks could manipulate sensors, control signals, or mislead an operator into making a wrong decision [10]. Also, interoperability requirements, as mentioned in the preceding subsection, must be met. The International Electrotechnical Commission 61850 (IEC-61850) [84] standard has outlined a general guide to achieve interoperability. To maximize the benefit of new security features introduced into an ICS system, these requirements and standards need to be met.

3.2 Information Technology Systems

Enterprise networks and business networks are often categorized as IT systems. IT systems, like ICS systems, also have a mixture of legacy and modern devices. However, in comparison to ICS systems, most computing systems in enterprise environments are com-

paratively modern. Even with potentially 5 or 10 year-old versions of Windows or Linux running, these systems generally outperform their counterparts in ICS environments and communicate over IP based networks through Ethernet, fiber, or wireless connections [85]. IT systems are also not necessarily isolated from the Internet and may be more widely accessible in comparison to an ICS environment. An example enterprise network can be a network with two departments that each have access to a variety of network services. Each department would also have external access to the Internet through a demilitarized zone as shown in Figure 3.2. Modern security protections are also available in these networks since they generally have enough CPU and memory resources to implement and execute security features. Given that these networks are widely accessible, there are benefits to both the defenders and the adversaries of these systems.

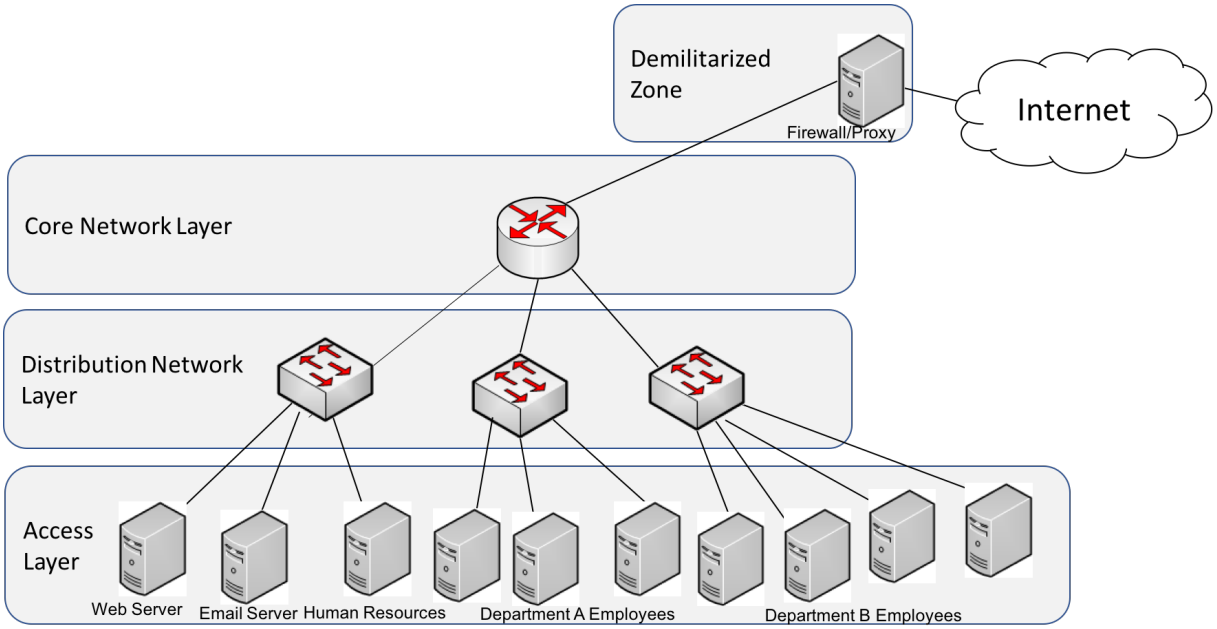


Figure 3.2: An example enterprise network with the core layer supporting the backbone of the network, the distribution layer supporting communications within the enterprise, and the access layer connecting end users and servers. The diagram here shows two departments (A and B) with access to web, email, and human resources servers. These networks also typically have an Internet connection through a demilitarized zone to protect the network with firewall, proxy and security services from external threats.

The defenders of these systems can receive alerts, perform analysis on suspicious activity, and actively defend against ongoing threats while inside or outside of the office. The defenders also have access to a wide range of tools that can assist in automating the detection and response of threats within networks. IT systems also have a larger community of IT system administrators who are similarly tasked with defending their systems. This community is quite a bit larger than that of ICS security specialists because IT systems are more widespread and accessible to the general public. IT security administrators can also communicate and federate their tools to correlate events, share observed threats and mitigations, while also having access to the latest security tools [86]. Although the IT system administrators can be perceived to have a strong advantage in securing their networks over that of ICS system administrators, they also have the challenge of facing well-resourced adversaries..

The adversaries also have a large community of capable, determined, and motivated individuals to accomplish their goals in exploiting IT based systems. Botnets [87], or compromised systems that are under the control of an adversary, can be purchased in large amounts (in the tens of thousands) to assist an adversary in launching a distributed denial of service (DDoS) attack [88]. Prices per bot are reported to be as low as \$0.03-\$0.04 per bot according to a Symantec report [89]. Newly discovered zero-day exploits [90] can even be purchased on the black market for more immediate use. Another advantage that favors the adversary is the ability to acquire the software and equipment deployed within IT systems so that they can perform offline analysis and exploitation. Once the adversary is confident in their testing, they can then launch the actual attack against the operational system with a high level of confidence for success.

3.2.1 Use Case

Since IT systems are widely connected, potential adversaries may already have access to the IT system that they are attempting to exploit. In an enterprise setting, one scenario could be focused on an adversary who has the goal of gaining knowledge about the underlying network to plan and launch an attack. The reconnaissance phase of an

attack is the first step in the so-called "cyber kill chain" [91]. Disrupting this process and adding MTD techniques to randomize IPv4 addresses is one possible mitigation strategy that can be deployed by a defender of the IT system. In this scenario, the goal of the defender would be to re-randomize IP addresses every instance in which an adversary has discovered an IP address on the network in order to invalidate that adversary's knowledge.

Another use case is in a similar but upgraded environment where IPv6 addresses are configured. The MTD strategy of randomizing IPv6 addresses buys the defender 96 additional bits of potential entropy since IPv4 addresses are limited to 32 bits and IPv6 addresses contain 128 bits. In an IPv4 setting, an adversary can brute force the entire IP space and find the random mappings, depending on how frequently the defender re-randomizes IP addresses and the specifications of the adversary systems. Additionally, distributing the adversary can defeat an IPv4 randomization scheme by brute force more quickly, however the distributed attack can also be noticeably observed and potentially detected by a defender. The goal of MTD applied towards IPv6 addresses is to increase the difficulty for an adversary to reverse engineer the random IP address mappings since these addresses contain 128 bits. Even in a distributed case, a brute force attack would be unlikely to succeed as the adversary would be extremely noisy.

3.2.2 Constraints

The operational constraints a defender faces within an IT enterprise system includes maintaining high Quality of Service (QoS) standards [92], protecting sensitive/proprietary hardware and/or software within the network, and enforcing the properties of confidentiality, integrity and availability within the active network services along with their associated communications. The defender can accomplish each of these goals by deploying a number of off-the-shelf or open source security tools. Economics is another constraint for enterprise IT defenders who must purchase and maintain an additional set of tools to protect their network. It is often a difficult task to quantify the return on investment [93] for computer security protections which makes for a challenge when attempting to convince decision makers to include any new security protection.

From the perspective of the adversary, one of the main goals is to limit the amount of noise introduced into the IT system so that they can go by undetected. The goal of the adversary is to launch an attack with the highest probability of success which may require extended periods of persistence within the network. If the adversary is detected, then they may be forced to completely change their approach all together. Once the adversary achieves success, they may or may not desire persistence within the environment depending on their goals. The adversary is well positioned since they have continuous access to many IT systems and they also have a wealth of resources available to plan, launch, and execute an attack within an enterprise environment.

3.2.3 Requirements

One of the requirements of the defender is to install, support, and maintain any new security tools introduced into the network. The tools installed should elevate the level of security and not hinder the job of the security operation center staff. The defender must also understand how the tools work individually and the implications, if any, of using the tools in combination with other possibly already deployed tools. The security tools themselves should not introduce any new vulnerabilities when integrated. It is important for the security tool to be effective and not become a target. One last requirement is that the defender must ensure that the new security tools do not violate any of the QoS parameters configured. Any negative impacts on the network itself can create losses of revenue and productivity within an enterprise IT environment.

3.3 Cloud Computing Systems

Cloud computing environments provide several cost-effective services that are available on-demand from a pool of configurable computing resources, typically managed by a third party, for consumers to reserve and access at any time [94]. Examples of the services provided include Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS). An example network topology of several users accessing cloud computing resources is shown in Figure 3.3. There are a number of cloud providers

available including public providers, private providers, community providers, and several hybrid combinations of providers.

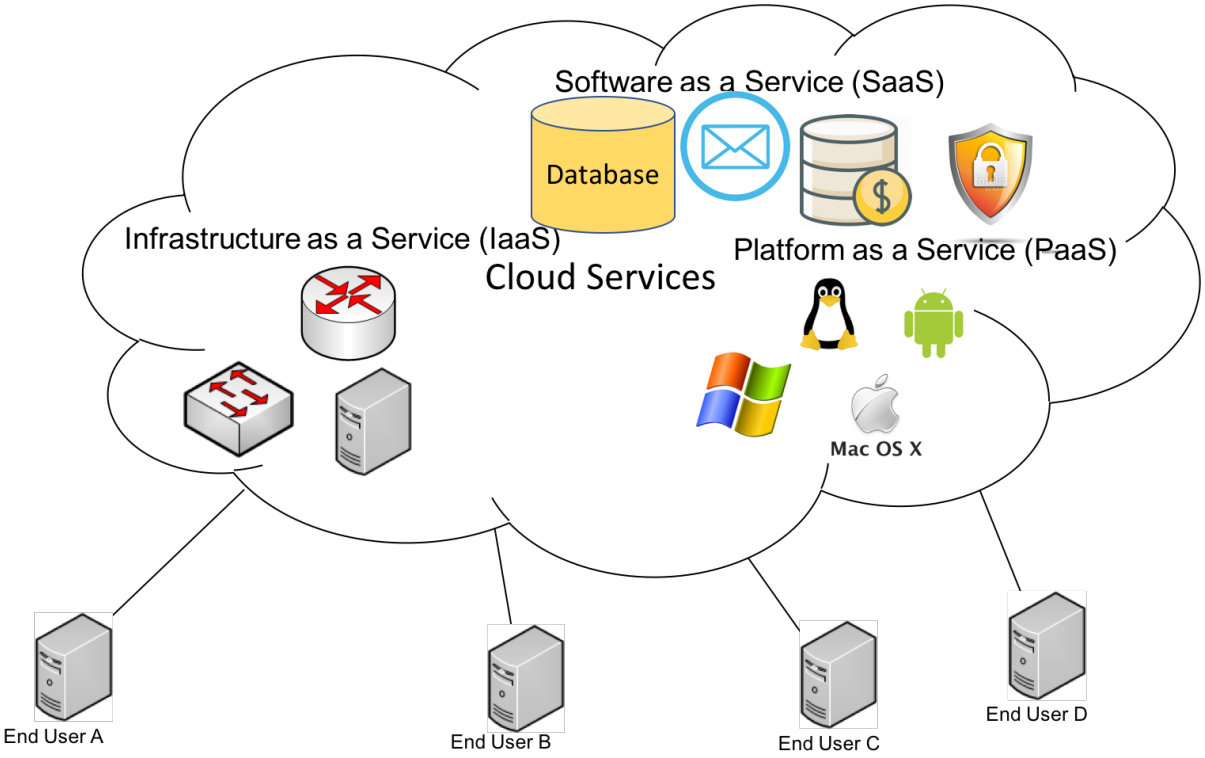


Figure 3.3: An example of several users accessing cloud computing resources such as IaaS, SaaS, and PaaS services.

Cloud providers currently available to consumers include Google Cloud Platform (GCP), Amazon EC2, Microsoft Azure, and The IBM Cloud to name a few. Each provider offers different services and can vary in functionality, price and usability. Some of the services cloud providers offer include storage, backup, computation, and software services. Each of the cloud environments are flexible and scalable so that users can dynamically expand and/or discontinue service as needed.

There are also several open source cloud implementations that users can deploy to stand up and evaluate their own private cloud. When a private cloud is configured, certain guarantees can be provided, such as the location of the servers, the verification of the users who have access to the cloud environment, and full control of the operations of the

cloud environment. These guarantees are not necessarily true within a public cloud environment. OpenStack is one example of such an implementation. These open source cloud services provide the user with more control and the flexibility to inspect and modify the implementation details as needed. However, this may come at a higher cost if the entire source code must be evaluated and assessed for security vulnerabilities before deployment. Although control is obtained with the physical devices, the source code used to deploy the private cloud may have embedded vulnerabilities making the system accessible externally. Furthermore, a security assessment is highly dependent on the team and scope of the assessment being performed so all vulnerabilities are not guaranteed to be identified. Consumers have many options when it comes to selecting a cloud provider, each with their own advantages and disadvantages.

3.3.1 Use Case

Cloud computing services can be a cost-effective solution for consumers to establish a robust infrastructure of resources that includes backup services, large amounts of storage, and the latest computing resources found on the market today. It is important to note that there are several security concerns that consumers must consider before making use of cloud services. One potential issue is that the resources made available within a cloud environment may be shared between many users. Several researchers or competing companies may be coexisting on the same physical system. If these resources are not clearly separated and protected, there is the possibility that proprietary information can be exfiltrated or compromised. Multi-tenant systems will also suffer from having high system loads in terms of processing, memory, and network metrics.

An adversary with the ability to bypass security protections that are designed to prevent lateral movements on a system [95] can potentially compromise applications on the target system. For example, an adversary aware of the applications running on each physical system that is managed by a separate customer on a cloud provider's environment can target and attempt to make a lateral movement. Additionally, an adversary can perform offline analysis of the target applications over extended periods of time with the goal of

finding an exploitable vulnerability that can be launched on the operational system at the time of the adversaries choosing.

A defender can protect against this scenario by introducing automated, artificial diversity into the application binaries. There are many opportunities to introduce diversity into the compilation process of an application such as randomizing the instruction set [96], randomizing register allocation schemes, or substituting different but equivalent sequences of instructions when possible [97]. Another approach is to randomize the layout of function locations in memory. In the scenario where an adversary is targeting a specific application binary, the adversary will need to target each unique binary separately. The approach would also reduce the success rates even when offline analysis is performed since each binary will be unique. In the event of a return-oriented program (ROP) [98] based attack, an adversary depends on function locations to be successful. Randomizing the function locations within memory would provide a layer of defense against ROP based attacks that the adversary would have to first bypass in order to initiate an attack.

3.3.2 Constraints

Cloud environments have the ability to support a wide range of scenarios that each have their own unique sets of constraints. Cloud providers may limit the QoS available to a consumer based on the consumer's needs and budget. The consumer would then have their selected constraints to satisfy, such as storage or memory constraints for example. The services desired by the consumer may also require specialized hardware or software that may or may not be possible to integrate into the cloud provider's environment. Another constraint to the defender would be the lack of control over the other users sharing or competing for the same resources; this may be an automated process or determined by the cloud provider but is largely outside the control of the consumer.

An adversary would similarly have the same set of constraints as the defender in a cloud environment. When evaluating a computer and network security defense strategies, however, the adversary is typically given more power to evaluate the effectiveness of the

defense under several worst case scenarios. The adversary is typically believed to have a larger budget and a larger number of resources available to accomplish their goal of exploiting a system. As previously mentioned in the IT and ICS environments, the adversary may have the constraint of needing to be stealthy, particularly in cases where they would like to remain persistent for an extended period of time.

3.3.3 Requirements

The requirements of the cloud environment often depend upon the needs of the consumer. For example, it may be desired that the computational resources provided by the cloud provider reside in a certain geographic location or region. This is an example of a request that could come from government entities that would like to make use of a cloud environment. The cloud provider has the ability to support such requests in many cases. The U.S. standard used to support cloud environments suitable for government entities is the Federal Risk and Authorization Management Program (FedRAMP) [99]. It is ultimately up to the consumer to decide what the requirements of the provider must be. It may also be required that the cloud services be offered privately to a consumer, with no other parties sharing those resources. These types of requirements must be enforced by the cloud provider and the consumer must, in some cases, trust that the cloud provider is appropriately implementing these requirements.

The requirements of the adversary are first to gain a presence on the cloud provider's environment. Depending on the adversary's goal, the next step for the adversary is to pivot and exploit another system within the environment. The adversary would ideally be stealthy in their attack so that the user and/or the provider would not detect their presence. In general, the adversary must operate within the bounds of the cloud provider, as may be defined by the defender, during their attempts to launch an attack.

Chapter 4

Threat Model

When evaluating the new computer security protections for their effectiveness, a threat model must first be established to define the adversaries' capabilities and the assumptions placed on the computer security protection. Additionally, the threat model describes the types of adversary capabilities that the security protections do not protect against. The focus of our research is on ICS based systems, including the network devices and the end devices in those environments. The threat model as a whole makes it clear when a particular protection is and is not an appropriate solution for a given environment or use case.

The network devices we examine in the work presented in this dissertation are comprised of SDN capable switches and non-SDN capable switches. SDN capable switches provide administrators with an interface to dynamically program switching decisions and develop custom switching algorithms directly into the switch. The programmer can interact with a switch directly or through a controller system that also communicates with all of the SDN-based switches configured in the network. Traditional switches do not have the capability to be reprogrammed and are often times proprietary without a user Application Programming Interface (API) available. Traditional switches are also distributed in nature whereas SDN devices are managed through a centralized controller system that has a complete understanding of the network topology.

The MTD strategies we examine for our research are those that introduce randomization into IP addresses, port numbers, inter-communicating network paths between systems, and the combination of the three techniques joined together. When IP addresses, port numbers and communication paths are randomized and deployed as defensive strategies, the threat model includes adversaries with the following capabilities:

- network access to the traditional network switches (non-SDN capable switches)
- access to the Switched Port Analyzer (SPAN) ports of all network switches outside of the edge switches
- ability to observe network traffic traversing traditional network switches (non-SDN capable switches)
- ability to collect network traffic traversing traditional network switches (non-SDN capable switches)
- ability to correlate end points within a network when in possession of packet captures
- ability to tap into network communication links outside of the edge switches connected to the end hosts
- ability to launch Denial of Service (DoS) attacks
- ability to launch Distributed DoS (DDoS) attacks
- access to the SDN controller(s)

In summary, the threat model defined for our research considers adversaries with access to network traffic, either just captured or also removed, injected, or modified in real-time from the interior switches of the network. Additionally, we assumed that the adversary will attempt to correlate all endpoints given the packet traces captured. Another assumption is that there may be several adversaries collaborating and attacking the system together at the same time or separately. For the DoS and DDoS attacks mentioned above, we have captured metrics to provide the thresholds on how to detect those types of attacks

given the number of probes observed within the network. Since the controllers aggregate all randomized information, we have developed Byzantine fault tolerant algorithms to protect these systems flows from being tampered with since all of the data is available for replication and consensus agreement. However, although adversaries with access to the controller would not be able to modify any one controller individually, the adversary would have the ability to understand the random mappings since the controller(s) aggregate all of the network flows installed within the network.

Also of importance are the adversaries that this threat model, as applied towards IP, port and path randomization, does *not* protect against. This threat model does not consider adversaries that are in possession of any of the following capabilities:

- access to the end devices behind the network switches
- access to the edge switches that are directly connected to the end hosts
- administrative access to the SDN capable switches

Adversaries with any of the above listed capabilities would have access beyond the point at which the MTD techniques protect against. Adversaries with access to the end devices would have access to the underlying information being randomized as well as the systems that are in direct communication with one another. Adversaries with access to the edge switches would be able to observe and identify the end hosts whose information is being randomized. An adversary with administrative access to the SDN switches would be able to learn all flows installed on those switches which contain the information that is being randomized, in particular, the flows to randomize network paths and IP addresses on the edge switches.

It should be noted that when path randomization is enabled, the number of SDN capable switches should be increased as much as possible. As the number of SDN capable switches grows, so does the number of possible paths within the randomized pool, making it more difficult to correlate end points within a network given the additional entropy

introduced. The number of hops should be considered as the source of entropy for this strategy, so the controller or switches themselves are not compromised. As the number of hops available increases, so does the difficulty level for an adversary to correlate endpoints in the network.

Finally, an additional area of interest to our research is the amount of information that can be gained from side channel attacks on the proposed MTD techniques. Specifically, of interest to our research is the information that can be gained from an adversary who obtains knowledge about the parameters of the MTD techniques and what advantages that provides them. One example of a side-channel attack is an adversary learning the frequencies at which the MTD strategies reconfigure the system based on network latency measurements. In such a scenario, our research focuses on investigating possible mitigations to defend against such side-channel based attacks.

The threat model and security protections developed as part of our research do not protect against every possible adversary, but do add an additional layer of defense. There are also a variety of other side channel attacks that may be available to extract information about the computer security defense such as attacking the random number generators that generate the random MTD mappings, but these additional side-channel attacks are outside the scope of this research and is an area for future research. We also assume that the software running in the SDN switches and controllers, such as the packet matching software, is secure. For the purposes of our research, the threat model is used as a basis so that the effectiveness of the MTD techniques can be quantitatively measured based on the criteria outlined in this section.

4.1 Operational Impacts

Each of the MTD techniques introduce additional layers of defense against an adversary who has the goal of gaining reconnaissance information from a network. Without these defenses, network access alone would be enough for an adversary to learn the IP addresses,

port numbers and communication patterns by passively observing the network packets traversing the network. After observing this information passively, the adversary can then plan, research and launch attacks against the IP addresses or services at a later time. One of the goals of our research is to introduce delays into the reconnaissance phase of an attack and measure those delays to determine the effectiveness of each technique. Ideally, the delays will be a significant enough amount of time to detect or deter an adversary from launching a successful attack. The real-time constraints and requirements of ICS environments are also taken into account and those impacts on the operational network are measured. The tradeoff between security and usability as well as finding a balance between maximizing the adversarial workload while minimizing the impact to both the defender and to the operational network is the focus of our research. Some of the operational metrics measured and captured include latency, throughput, bandwidth, network utilization, CPU utilization, and memory utilization.

4.2 Adversarial Models

We have assessed the MTD strategies developed using a variety of adversaries to measure the effectiveness of each technique. A single adversary is introduced into the network that follows the threat model outlined above. The techniques for each of the adversaries follow the strategies for randomized port numbers found in RFC 6056 [100]. These strategies are chosen since they are already established as a standard that is widely adopted to select random port numbers and serves as a baseline measurement for the effectiveness of each MTD approach. Side channel attacks are also taken into account to evaluate each of the MTD techniques. One of the side channel attacks evaluated is the information gained from observing network latency between a pair of end devices. In this case, an adversary can potentially learn and understand how frequently a defender is reconfiguring the system with their deployed MTD strategy. With this knowledge, the adversary would have the necessary information on how quickly their attack must be crafted and delivered to successfully exploit the system.

The same set of tests and evaluations are performed against distributed adversaries. The goal is to simulate what a defender can expect in the event that a DDoS is carried out by a number of adversaries simultaneously. The information gained from the different types of adversaries evaluated are then taken into account to improve and build upon the MTD techniques developed. The improvements on each of the MTD techniques developed are also bounded by environmental constraints and requirements.

Chapter 5

Approaches to Randomization

We implemented and evaluated three MTD techniques to quantify their effectiveness, both individually and in combination of one another. IP modification has the goal of creating uncertainty and increasing the difficulty for an adversary to discover and track the systems existing within a computer network. IP randomization is implemented using an SDN based approach with the flow rules installed at each switch controlling the randomization intervals. Port modification has the goal of hiding the services offered by a system. Port randomization is implemented as a standalone solution that is placed at each individual end point within the network. Path modification supports both of the previous two goals and also has a third goal of preventing an adversary from learning the end points of a network by observing traffic and performing analysis to correlate the end systems that are actively communicating with one another. Path randomization has been implemented in an SDN based approach with the flow rules controlling the next hop switches in the network. Each technique provides its own sets of benefits and are described in more detail in the sections that follow.

5.1 IP Randomization

The first MTD defense we developed focuses on randomizing IP addresses at user configurable frequencies to evade adversarial discovery. The randomization algorithms reside at the network layer, transparent to the end devices themselves, for both usability and scalability purposes. Improved usability comes from the fact that the randomization al-

gorithms are managed at the network level and do not need to be deployed at every end device. The algorithms are built into the SDN framework which consists of several SDN-capable switches and a management controller system. The management burden is reduced since the network security personnel would only have to maintain the network layer devices as opposed to all of the end devices of the network (which typically outnumber the network layer devices by far). The SDN architecture provides a scalable solution where any new end device introduced into the network will automatically have the IP randomization MTD defense activated and enabled, without the end user necessarily having any knowledge that the MTD defense deployed. Additionally, there are typically far fewer end devices than there are network based devices within a network.

An SDN based approach is also used so that routing and switching logic can be customized to control the frequency at which source and destination IP addresses are randomized. The customized logic can also account for the periods of time when a packet is traversing the network and new randomized source and destination IP addresses are installed on each of the switches in the network. The random IP address mappings are programmed by flow rules that are managed by a centralized controller. Each flow rule has a "match" specification and an associated "action" to perform depending on if the match criteria is satisfied. The flow rules for this implementation match a packet based on a combination of the source IP address, the destination IP address, and the incoming physical port of the switch that the packet was received on. If the incoming physical port and source IP address that the packet was received on corresponds to a host that is directly connected to the switch, then the action taken within the flow rule is to rewrite the source and destination IP addresses with a set of newly generated random source and destination IP addresses. Otherwise if the host is not directly connected to the switch (but rather to an interior switch interface), the packet is forwarded to the next hop switch. The location of the next hop switch is specified within the flow rules that matched the randomized source and destination IP addresses for that particular MTD reconfiguration interval. The random mappings are communicated to the SDN controller via a Python wrapper

script that updates the mappings based on predefined user configurable randomization intervals desired.

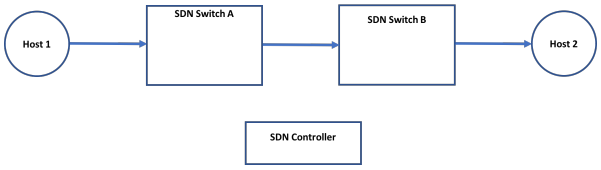
Once the packet reaches the edge switch that is directly connected to the destination host, the original source and destination IP addresses are restored within the packet back to the original source and destination IP addresses. The result of this approach is that an adversary passively observing traffic, on an interior non-SDN capable network switch, will no longer automatically learn the true IP addresses of the end hosts simply by observing network traffic passively; in this scenario, the adversary would instead observe a pair of pseudorandom IP addresses traversing the network. The pseudorandom IP addresses that are managed by the controller are continuously changing at user configurable time intervals and the random mappings are generated using a pseudorandom number generator. For this implementation, the entire 32-bit IP address is randomized since we are analyzing a flat network that contains only layer 2 switches. If routers are included in the topology, a quick solution to deploy this MTD technique would be to only modify the host bits of the IP address. This solution would allow layer 3 devices to appropriately route packets without having to modify the underlying routing protocols within those devices. A similar approach could have also randomized MAC addresses or even set all MAC addresses to the same value since the match criteria of the SDN flow rule does not depend on MAC addresses. Manipulation of MAC addresses was not performed in this research but can easily be adapted to do so. We have developed a prototype that has been tested on topologies of over 300 end devices operating within a virtualized environment using mininet [101].

The algorithms to randomize the IP addresses had to be slightly modified in practice to work correctly and avoid packet losses. The OpenDaylight controller [102] is an open source model-driven SDN controller which communicates to SDN capable devices through the OpenFlow protocol. The OpenFlow protocol [103] is a standardized interface with an internal table that manages communications between controllers and the flow rules of

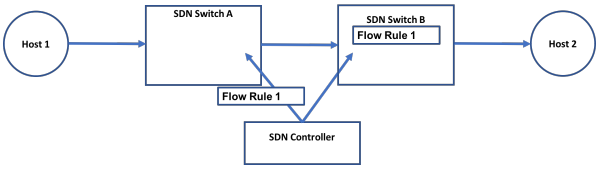
how to switch packets. OpenFlow version 1.3 supports axillary connections to the controller(s), functions to control the rates of packets through meters per flow, and cookies can be added as identifiers to each flow rule to help add, update, and delete flow rules as desired. Most vendors developing SDN capable switches support the OpenFlow 1.3 protocol.

During our experimentation, it was observed that when using the OpenDaylight implementation packets would occasionally be dropped. The dropped packets occured in scenarios where new flow rules were installed slightly before a packet arrived at the last hop SDN switch, which is the switch that is responsible for delivering the packet to the final destination system. This scenario is shown in Figures 5.1(a) - (g). The *hardtimeout* parameter within the OpenFlow protocol is used to configure the time period in which a flow rule is active. The cause for the dropped packets is that the SDN switches are not perfectly synchronized in time with each other when new packets flow rules are installed at each of the switches. These minor variations in flow rule installation time cause the flow rules to expire at slightly different times through the *hardtimeout* value specified. The small window of time where two switches may not have a consistent view of the network, in terms of the active flow rules installed, needed to be addressed and corrected for the solution to be usable in practice.

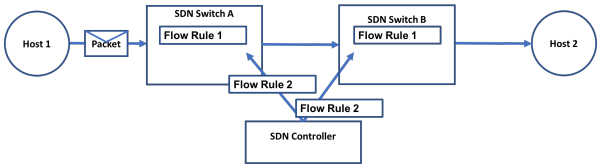
To correct this issue, new flow rules are initialized and installed on each of the SDN-capable switches by the controller. The old flow rules are configured to overlap with the new flow rules at a user configurable period of time, 3 seconds in this case. When new flow rules are installed at each of the SDN-capable switches, they are installed with a lower *priority* field, within the OpenFlow protocol, than the existing flow rule previously installed. After the controller sends the new flow rules to be installed at each of the switches, the controller receives an acknowledgment from each switch that the new flow rule was accepted and installed. The new flow rules, however, are not actively matched at this point since they have a lower *priority* than the previous flow rules installed. The



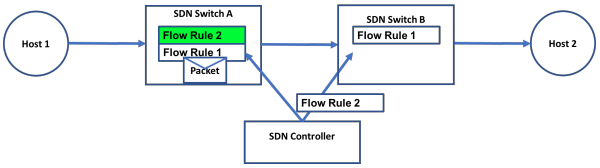
(a) Two hosts would like to communicate over an SDN network.



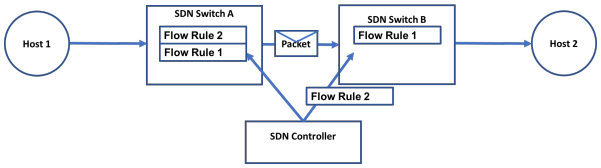
(b) The controller installs Flow Rule 1 on SDN switches A and B to randomize IP addresses between Host 1 and Host 2.



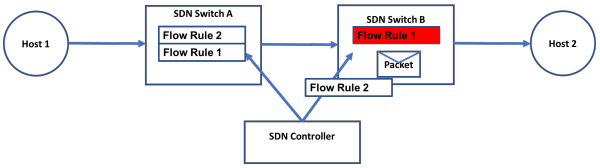
(c) After a period of time, new randomized source and destination IP addresses are generated to send to each of the SDN switches A and B labeled as Flow Rule 2. At the same time Host 1 sends a packet to Host 2.



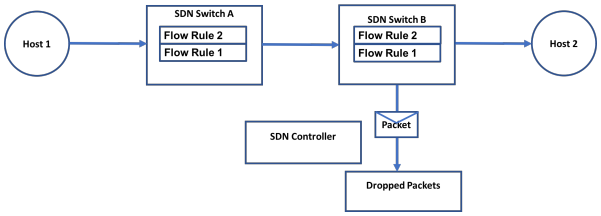
(d) The new flow rule is installed on the SDN Switch A but has not reached the SDN Switch B due to network congestion. The packet from Host 1 is matched with Flow Rule 2 installed at SDN Switch A



(e) The source and destination IP addresses are rewritten according to Flow Rule 2 and are forwarded to SDN switch 2. Flow Rule 2 has still not yet reached SDN Switch B.

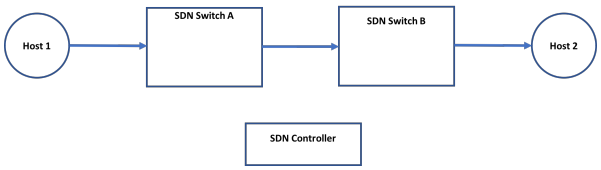


(f) The packet is received on SDN Switch B and since Flow Rule 2 has still not yet reached SDN Switch B, there is no match with Flow Rule 1 which is the only rule installed.

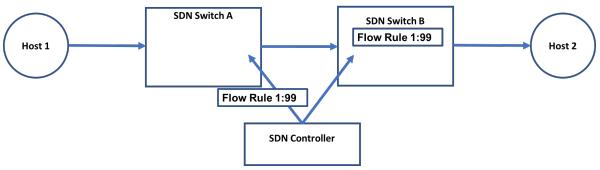


(g) The packet is dropped since Flow Rule 2 has not yet reached SDN Switch B. Flow Rule 2 is now installed on SDN Switch B, but it is too late.

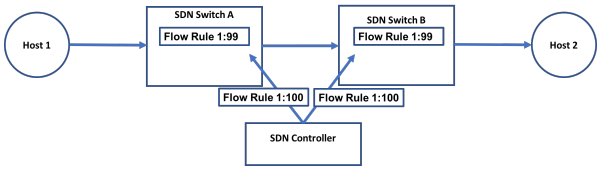
Figure 5.1: The sequence of events that cause packets to be dropped when randomizing source and destination IP addresses within an SDN setting.



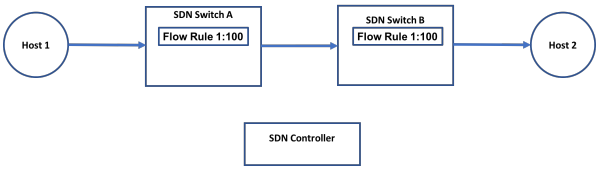
(a) Two hosts would like to communicate over an SDN network.



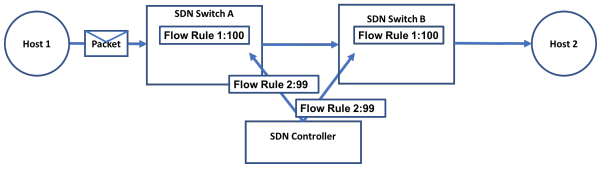
(b) The controller installs Flow Rule 1 with priority 99 on SDN switches A and B.



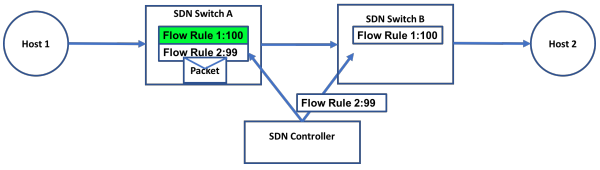
(c) Immediately after Flow Rule 1 is installed, Flow Rule 1 is updated to have priority 100.



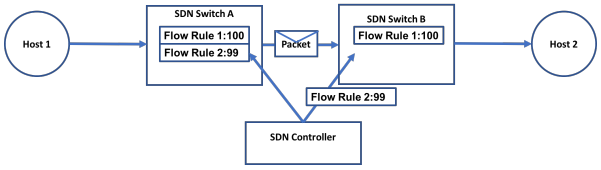
(d) Flow Rule 1 is updated on both SDN Switch A and SDN Switch B to have a priority of 100



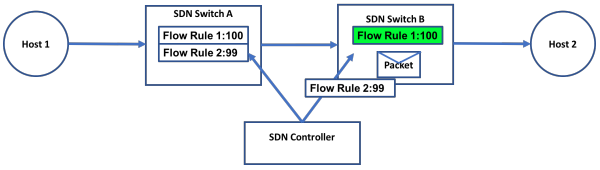
(e) After a given period of time, the controller pushes out Flow Rule 2 with priority 99 and new randomized source and destination IP addresses. Host 1 sends a packet to Host 2.



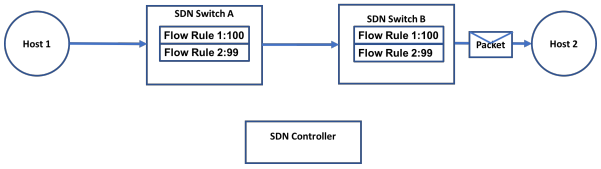
(f) The packet is received on SDN Switch A and matched on Flow Rule 1 since it has a higher priority. Flow Rule 2 has reached SDN Switch A but not SDN Switch B.



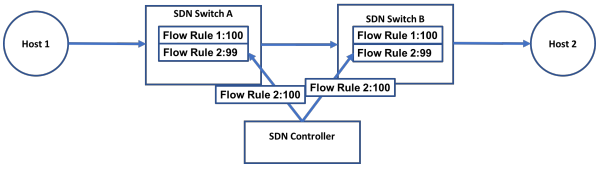
(g) Flow Rule 2 with priority 99 is installed on only SDN Switch A so far. The packet is forwarded to SDN Switch B.



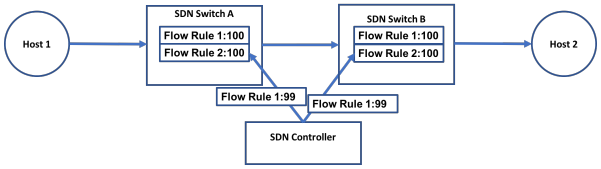
(h) SDN Switch B receives and matches the packet against Flow Rule 1 since Flow Rule 2 has not been received.



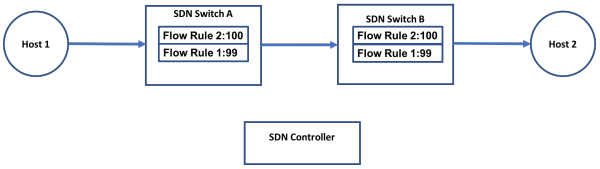
(i) Flow Rule 2 is installed on SDN Switch A and B with priority 99.



(j) The SDN Controller immediately updates the priority of Flow Rule 2 to 100.



(k) The SDN Controller updates the priority of Flow Rule 1 to 99. Flow Rule 2 takes priority.



(l) Flow Rule 1 is updated to priority 99 and Flow Rule 2 has priority 100.

Figure 5.2: The sequence of events to correct dropped packets from occurring when randomizing source and destination IP addresses within an SDN setting.

next step is to swap the flow *priorities* of the old and new flow rules that are installed at each of the switches. Finally, the old flow rules will eventually expire before the new flow rules at specific time periods that depend on the user configurable setting of the overlap window. The process of SDN flow rule installation to prevent packets from being dropped is shown in Figure 5.2(a) - (l). This solution allows old flow rules to deliver packets to the destination device without worrying about the slight variations in timing when the flow rules are installed and expired. The *priority* field is used to determine when flow rules become active in matching packets to randomized source and destination IP addresses.

5.2 Port Randomization

The second MTD defense developed randomizes the application port numbers of services running on each of the end devices within the network. Port randomization was implemented using the *iptables* packet filtering tool, a tool that is typically used to configure and enforce firewall policies on a system. The *iptables* tool has several rule chains, each of which are triggered at different points within the network stack when evaluating packets that are sent and received. The rule chain used to randomize port numbers is the same rule chain that manages firewall rules for network address translation (NAT) [104] based networks. The NAT rule chain evaluates packets just before and just after they exit and enter the network interface card, respectively. If a match is made within the *iptables* rule, then the specified actions are performed on the packet. The actions for port randomization involve rewriting the source and destination port numbers, based on a pseudorandom number generator that is seeded based on time, to random values.

Each host in the network is initiated with the same agent software installed which are all synchronized in time with an Network Time Protocol (NTP) server so that they can generate the same pseudorandom port mappings. Alternative methods exist to synchronize end hosts within the network, but the approach to synchronize on time was chosen to conceptually evaluate host based MTD solutions. The frequency of creating new random mappings is user configurable and, in this case, has been chosen to regenerate new map-

pings every one second. An effect of applying this MTD strategy is that an adversary can no longer automatically learn the services running on a network by passively observing network traffic alone. To defeat this defense, adversaries would be required to have the ability to perform deep packet inspection to identify the protocol and service offered by the end devices within the configured randomization interval. This does not completely eliminate all threats, but does add an additional layer of defense to delay an adversary or alert an operator if previous port mappings that have expired are actively being scanned by an adversary.

5.3 Path Randomization

The third technique developed randomizes the communication paths that packets take within a network. This approach utilizes SDN-capable switches to install flow rules that specify pseudorandom paths into each of the SDN-capable switches. The flow rules are installed into each of the network devices and are replaced with new random mappings at user configurable time periods. The pseudorandom paths are generated by the controller which has complete knowledge of the network topology. The controller first generates all possible paths between all possible pairs of systems when the network is being initialized. After initialization is complete, a randomly-selected path is chosen by the controller and the flow rules associated to that path are installed at each of the SDN switches to appropriately route traffic at user configurable periods. The effectiveness of this technique is based on the amount of entropy available within the network (i.e. the number of possible paths within the network in this case). To achieve a high level of entropy, the number of SDN-capable switches should be increased so that there are more options of paths that are available within the network. The greater the entropy, the greater the workload placed on an adversary who has the goal of correlating and identifying ingress and egress communication patterns in the network.

Without the addition of path randomization, traffic analysis is a concern for each of the approaches described thus far. A passive adversary observing traffic may still be able to

determine the end points in communication by analyzing each of the network communication streams. We have developed two proof-of-concepts, one using a POX controller and another using an OpenDaylight controller, that periodically randomize communication paths using an SDN network. POX [105] is a controller written in the Python programming language which supports the OpenFlow version 1.0 protocol. OpenFlow version 1.0 is very useful for modifying packets through flow rules which is needed to randomize IP addresses and paths within the network. However, later in our work when we discuss fault tolerant algorithms, the requirement for the SDN switches to communicate with multiple controllers is necessary, which OpenFlow version 1.0 does not support.

The algorithm to randomized communication paths assumes that the SDN controller has a priori knowledge of the network topology and that the systems wishing to communicate are part of a connected graph [106]. If the assumptions are valid, then all possible paths between each pair of systems within the network are enumerated and stored within a hash table stored at the controllers for quick path lookups. To determine the communication paths, the controller selects a random path between two endpoints and installs the appropriate flow rules at each of the intermediate switches to enforce that packets will traverse the random communication path currently selected. The high level algorithm is shown below.

The *FindAllPaths* function uses the breadth-first-search algorithm and maintains a stack to enumerate all possible paths within the network. This cost is incurred on only the first time that the POX controller is started. During runtime, a user would pass in a parameter to specify the time intervals when the paths of network flow rules should be re-randomized. A user may also specify a maximum number of hops to help satisfy the constraints of the allowable delay in the network. The maximum number of hops could also tie into the QoS parameters for individual users of the system. If a critical process that must complete within a certain time bound, then a lower number of maximum hops can be configured.

```
// Generate every non-looping network path between each pair of systems
// within the network
GenertePaths() {
    // convert the topology into a graph
    $g = CreateGraph()
    // global hash table of paths from each pair of systems
    $pathhash = {}{}

    // enumerate and store each path between each pair of systems
    for $host1 in g:
        for $host2 in g:
            $paths = FindAllPaths($g, $host1, $host2, [])
    for $path in $paths:
        $pathshash[$host1][$host2].append($path)
}

// When the packet is received at each switch, install the flow rule that
// corresponds to the random path currently selected (which changes
// in time)
PacketIn($packet) {
    InstallRandomPathFlow($pathshash[$packet.src][$packet.dst])
    SendPacket($packet)
}
```

As an example, an ongoing session is shown in Figure 5.3 where packets from one host, h1, sent to another host, h2, originally take the path h1→s1→s2→s3→s4→h2. The network topology, in this example, consists of two hosts, h1 and h2, along with four switches between the two hosts. The hosts are connected in a mesh network and the path

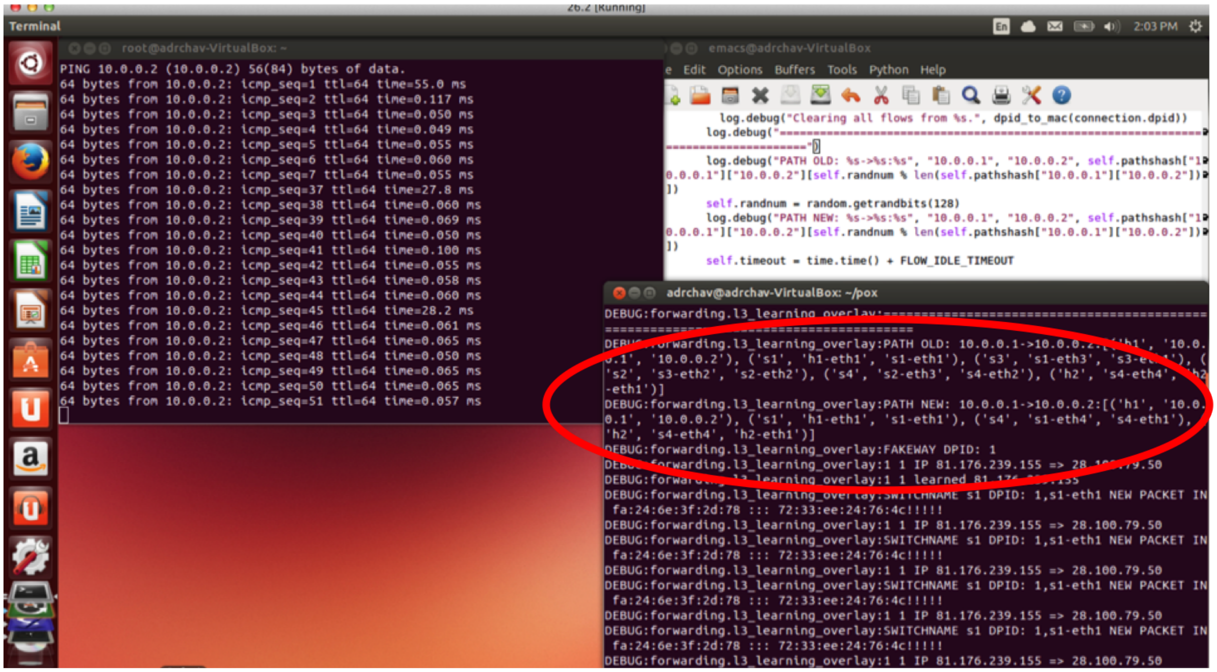


Figure 5.3: An example of two hosts communicating through random paths taken as shown in the red circled text in the command prompt window. The first path taken is h1→s1→s2→s3→s4→h2, while the next random path taken is h1→s1→s4→h2

randomization algorithms select a random path every 1 second interval of time. After a given period of time supplied by the user passes, the new path taken is re-randomized to h1→s1→s4→h2.

Chapter 6

Fault Tolerance Theory

ICS systems must withstand faults and be resilient against attacks to survive a computer security incident. Additionally, ICS systems must also meet several real-time constraints that typically must be within 12-20 ms and cannot tolerate any unnecessary delays within the operational network. Many of the MTD techniques described thus far depend upon a centralized system for coordination and management. An example where a centralized system is needed is when an SDN based solution is deployed, such as the IP randomization protection that was described earlier. Because the IP randomization scheme depends upon SDN, the controller of the SDN system can be viewed as a single point of failure. In the event that an adversary is able to compromise the controller, the IP randomization flows would no longer be pushed out to each of the SDN capable switches within the network. To compensate for this scenario, fault tolerant algorithms can be deployed to achieve a more resilient controller that can withstand system failures or compromises. Similarly, diversity amongst the SDN controllers and SDN switches deployed can also support the fault tolerant algorithms. A diverse set of SDN controllers and switches provided by multiple vendors would increase the difficulty for an adversary to successfully compromise multiple independent implementations simultaneously.

The goal when introducing fault tolerant algorithms is to replicate and distribute the controller so that there is no longer a single point of failure. Coordination and agreement between the controllers is necessary to maintain a consistent view of the network and

to achieve a consensus agreement between the distributed controllers. Distributing the controller increases the workload of the adversary and would require them to compromise several controllers simultaneously instead of an individual controller by itself. The consensus algorithms help protect against adversaries who have compromised a controller with the goal of maliciously corrupting the data or information communicated between the cluster of controllers.

Several approaches exist that can enable systems to mask against crashes or failures of controllers within the cluster of controllers [107]. These approaches are referred to, synonymously, as either crash tolerant or fault tolerant algorithms [108] within this dissertation. Crash tolerant algorithms can detect system failures within the cluster of controllers by maintaining heartbeat communications. As soon as one of the controllers does not respond to a heartbeat communication for a given amount of time, it can be presumed that a controller has crashed. Additional algorithms exist that focus on protecting the data and information communicated from individual controllers within the cluster against arbitrary (including malicious) failures, and not just crashes or disrupted links. These algorithms are referred to as Byzantine fault tolerant algorithms [109]. Byzantine algorithms have the goal of detecting malicious controllers that have the goal of corrupting the other controllers within the cluster. Each of these algorithms help to protect against different types of adversaries who have different goals when attempting to compromise a system.

6.1 Crash Tolerant Algorithms

Crash tolerant algorithms are capable of detecting individual failures within a cluster of systems. The number of systems within the cluster dictates the number of failures or crashes that can be tolerated within the network. After a threshold limit number of failures is exceeded, the crash tolerant algorithm restricts the cluster from continuing to function and process inputs received from clients. In our research, the client system is the IP randomization wrapper software that communicates the flows that will be installed at

each of the SDN capable switches to the controller system. In an SDN setting, the cluster of systems that is required for the crash tolerant algorithms to operate correctly are the distributed SDN controllers that are installed within the network.

A crash in the cluster can be caused by an unintentional event by a legitimate user or can intentionally be caused by a malicious actor. A crash, for the purposes of this discussion, is considered to be a system within the cluster that is no longer responding to network communications or that has been taken offline or is otherwise no longer reachable on the network. Invalid inputs, corrupted information, or abnormal behavior is not considered to be a crash as the crash tolerant algorithms do not protect against these types of failures. One of the main goals of the crash tolerant algorithms is to ensure that there are a minimum number of systems within the cluster that are able to respond and serve accurate requests from a group of clients. As a result, resiliency is improved since crashes of individual controllers would no longer prevent the SDN switches from receiving flow updates. A crashed controller would instead fail over to other controllers that are correctly operating within the cluster.

The crash tolerant algorithms are desirable in scenarios where availability is a primary requirement. ICS systems are ideal candidates for crash tolerant algorithms to be deployed as limiting or eliminating downtime, unintentionally or intentionally caused, is a necessity. In an ICS scenario, it is also a requirement that the crash tolerant algorithms do not limit or negatively impact the operational network in any way. We measured and analyzed the impacts and effects of the crash tolerant algorithms to quantify the operational impacts.

In order for the crash tolerant algorithms to operate correctly, several algorithms have been developed to ensure consistency amongst the cluster of systems. Each of the systems in the cluster must ensure that they all have the same state information regarding the systems that are operational and those that have crashed. The algorithms must also tolerate crashes before, during, and after other failures occur within the cluster. This is

a challenge that the two-phase and three-phase commit protocols, described in the following sections, seek to address. Consistency and consensus amongst the systems within the cluster are the major challenges when developing crash tolerant systems. As stated earlier, the crash tolerant algorithms do not protect against compromised controllers that attempt to communicate false or corrupted information to the other controllers within the cluster.

6.1.1 Two-phase Commit

The two-phase commit protocol is designed to coordinate agreement between multiple systems within a cluster to withstand potential system failures at any moment [110]. The goal of the two-phase commit protocol is to make transactions atomic between systems within the cluster so that all of the systems are synchronized with one another, even in the event of network delays or potential system crashes. The clients that communicate over the SDN network depend on the consistency of the controllers within the cluster when their packets are traversing the network. The dependency exists because each of the SDN switches could potentially be communicating with any of the controllers within the cluster to receive and install the randomized flows. As part of the two-phase commit protocol, a separate system called the "coordinator" communicates with each of the controllers within the cluster when communicating state information regarding the status of each of the controllers.

There are two states that the coordinator system must advance through and two states that the controllers within the cluster must advance through before a transaction can successfully be completed. The two states that the coordinator advances through are prepare and commit. The two states that the controllers in the cluster advance through are prepared and done. These states mark different points in the process of achieving a consensus agreement between the cluster of controllers. These states are divided into two separate phases within the two-phase commit protocol. The two-phase commit protocol is shown in Figure 6.1.

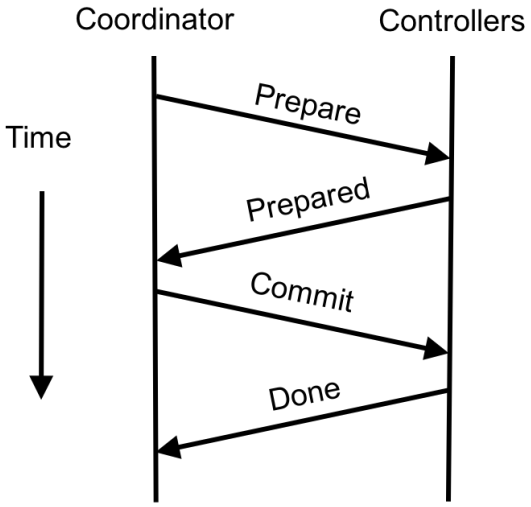


Figure 6.1: The two-phase commit protocol between a coordinator system and a cluster of SDN controllers. The goal is to detect and withstand faults within the SDN controllers and to synchronize internal state information when transactions are executed on all controllers.

The first phase of the protocol is for the coordinator system to send a prepare message to each of the controllers within the cluster. The prepare message notifies all of the controllers within the cluster to prepare for a new transaction to begin. In this phase, the controllers in the cluster save enough state so that they can rollback to the previous state in the event that a failure occurs midway through the transaction. Any changes that occur on individual controllers within the cluster are typically saved to persistent storage locations such as a log file, in the event that a rollback is required. The individual controllers within the cluster then reply back to the coordinator that either they are or they are not prepared to begin the transaction. The coordinator then accepts the responses from each of the systems within the cluster.

The second phase of the protocol depends on the responses received by the coordinator system. If the majority of the controllers within the cluster are prepared, then the coordinator sends a commit message to each of the controllers within the cluster. If the majority of the controllers within the cluster are not prepared, then the coordinator sends an abort message to each of the controllers within the cluster. In either case, the coordinator will log the commit or abort message to each of the controllers. The controllers within

the cluster then will act accordingly by either committing or aborting depending on the result received from the coordinator. The controllers finally will send a done message to the coordinator to acknowledge the commit message. These steps cover the commit and done states of the coordinator as well as the states maintained within the controllers that are in the cluster.

In the event of a failure in any of the states for each of the phases, the goal is for the transaction to be aborted. In the case of an aborted transaction, all of the controllers in the cluster will rollback to their previous states. There are problems that exist within the two-phase commit protocol that cause delays in agreement. One problem that causes delays in the protocol is the requirement that the coordinator and all of the controllers within the cluster be up and responsive in order to successfully advance through states. If the coordinator is not up and running, then there is no way to know if the controllers in the cluster voted to commit or abort the transaction. This scenario occurs when the coordinator fails before logging the outcome of the votes received from all of the controllers in the cluster. If any of the controllers in the cluster crash midway through the protocol, then the coordinator, like the controllers in the cluster, must all wait until a timeout period expires or until the controllers are repaired so that the coordinator can make a decision to either commit or abort the transaction. These problems can be overcome by modifying the algorithms to a three-phase commit protocol.

6.1.2 Three-phase Commit

The three-phase commit protocol [111] solves some of the issues that were identified in the two-phase commit protocol. Many of the issues are solved by adding another phase before the commit phase of the protocol. The new phase added is called the pre-prepare phase and eliminates the time of uncertainty for all participants waiting to receive the result of the votes from the coordinator. The time of uncertainty is the time between the controllers sending the prepared message and the controllers waiting to receive the commit or abort message from the coordinator. The pre-prepare phase helps reduce the blocking period of time while waiting for either the responses from the controllers in the

cluster or waiting for the coordinator to be repaired. The coordinator first sends a pre-prepare message to each of the controllers in the cluster. After the pre-prepare message is received by each of the controllers in the cluster, the controllers will respond with a "yes" message back to the coordinator. If the "yes" responses are not received from the controllers, those non-responsive controllers are ignored going forward in the remaining phases of the protocol as well as the transaction that may potentially be executed on each of the controllers. A timeout parameter is configured to ensure that the algorithm does not block when a new coordinator is needed or when awaiting a "yes" response from a controller in the cluster.

The remainder of the protocol is the same as that of the two-phase protocol. The coordinator sends a prepare message to all controllers in the cluster that responded with a "yes" message. The controllers in the cluster respond with a prepared or abort message. The coordinator then sends the commit message to each of the systems in the cluster that a prepared message was received. The controllers in the cluster wait for the commit message and, when received, acknowledge the commit message with a done message. The coordinator receives all done messages, or times-out waiting for individual requests, and logs the results. Finally, all controllers in the cluster that received a commit message will go forward with the transaction. If a commit message is not received after the timeout value expires, then the transaction is aborted. The full protocol diagram is shown in Figure 6.2.

A problem with both two-phase and three-phase commit protocols is that any communication error can cause a system in the cluster to block in execution. This is the equivalent of a DoS attack on the communication link. A DoS attack has the same effect in that service is denied either through saturating a link, exhausting system resources, causing a system to go into a state where the system becomes non-responsive, causing packets to be dropped. An adversary can achieve the same results if they have physical access to a system by physically removing or cutting network links. A DDoS using the same DoS strategy multiple times against several systems in the cluster would also cause a block

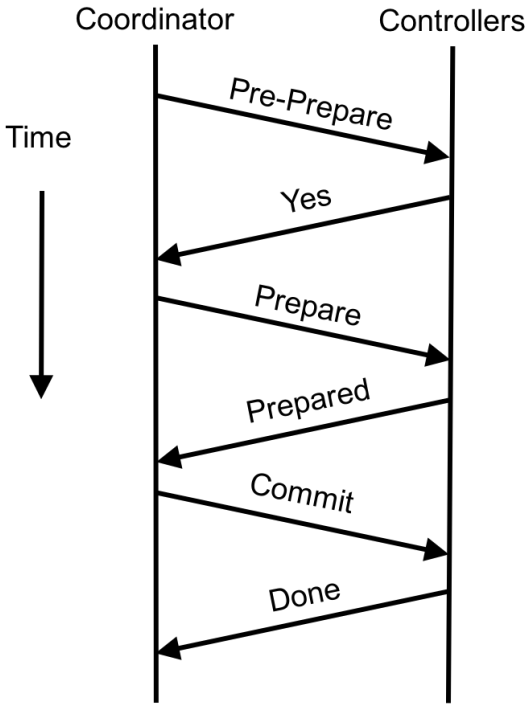


Figure 6.2: The three-phase commit protocol between a coordinator system and a cluster of SDN controllers. The goal is to detect and withstand faults within the SDN controllers and to synchronize internal state information when transactions are executed on all controllers. An additional state, pre-prepare, is added to reduce the amount of time blocking when the coordinator is waiting on controller responses.

in execution, but within a larger subset of the controllers in the cluster. A DDoS is the equivalent of several coordinated adversaries working together to simultaneously attack a system to deny service. Both DoS and DDoS attacks are challenging problems that every communication protocol cannot fully prevent [112] when an adversary has access to the communication channel, but it is noted here for completeness.

There are a number of optimizations that can be made to both the two-phase and three-phase commit protocols to reduce the amount of time blocking and the amount of required communications for the protocols to operate correctly. In read-only transactions, phase one of the protocol is only required before sending the read-only data to the client. One of the messages communicated in the protocol can also be eliminated after an abort message is received from the coordinator. The controllers in this case do not need to respond with

a done message since the protocol will reset and start over. The controllers in the cluster that fail and do not receive the abort message would eventually timeout and request the response from the coordinator, which would have flushed all knowledge of the results and would subsequently send an abort message to the controllers. The coordinator state can also be transferred between systems in the cluster if the coordinator happens to fail in the three-phase commit protocol. The coordinator has an election protocol where a new coordinator can be chosen using the two- or three-phase commit protocols. An additional optimization is when the controllers in the cluster timeout waiting for the outcome to either commit or abort the transaction from the coordinator. The controllers in the cluster can communicate with other controllers in the cluster and abort or commit depending on the outcomes they have received from the coordinator. If no outcome was received from the coordinator or the other controllers in the cluster, then there will be a blocking period until the timeout is reached. This optimization is called the Cooperative Termination Protocol (CTP). Each optimization can be applied to improve both the availability and the efficiency of the controllers in the cluster as well as the coordinator system when using the three-phase commit protocol.

6.1.3 Replication - Paxos

The Paxos algorithm is a practical agreement protocol that relaxes some of the requirements of the two- and three-phase commit protocols [113]. Paxos tolerates controller failures, network failures, and network delays within the cluster. Paxos is a widely used protocol in academia and industry to establish agreement amongst a cluster of systems. Some examples of Paxos deployments include Yahoo's Zookeeper [114] service for coordinating processes of distributed applications, Google's Chubby service [115] which is a distributed locking mechanism to store small files, and The University of Washington's Scatter application [116] which is a distributed key-value storage system.

Some of the properties of the Paxos algorithm are safety, consistency in data, and fault tolerance amongst the controllers in the cluster. Safety is the property that ensures that once an agreement is reached, then all controllers in the cluster have agreed on the same

value and that value was proposed by one of the controllers in the cluster. This property maintains consistency between all controller data within the cluster. Fault tolerance is the property that allows the algorithm to continue to progress and reach an agreement if more than half of the controllers in the cluster are still available. The two-phase commit protocol described earlier could not handle failures from controllers in the cluster midway through the protocol and would block all other controllers in the cluster from progressing through the algorithm. Finally, the Paxos algorithm is not necessarily guaranteed to converge upon a value that is agreed upon by all controllers in the cluster. However, in a practical setting this is considered a rare event and agreement will be achieved in most cases.

Paxos is similar to the two-phase commit protocol but with the potential to have multiple coordinators at the same time. When a transaction is desired to be processed, the coordinator first performs the computation to execute the transaction and then sends the resulting value to all other controllers in the cluster. The other controllers perform the same computation and check the resulting value sent by the coordinator. The coordinator then communicates the agreed upon value if a majority agreement is achieved, or otherwise tries again until there is a convergence on an agreed upon value. As noted earlier, any of the controllers in the cluster can become the coordinator at any time and can send values to the rest of the cluster at the same time. When there are multiple coordinators, there is an order assigned to each coordinator and the values that are sent to the cluster. The order defines the sequence in which the other controllers in the cluster perform their computations.

One other difference from the two- and three-phase commit protocols is that the Paxos algorithm has the ability to run in separate partitioned segments of a network and still achieve agreement. This does not cause any issues since the Paxos algorithms only require a majority vote on a given value produced by a computation that is part of a transaction. Since there cannot be more than one majority in all partitions combined, there is no

ambiguity when the network is partitioned. In the two- and three-phase commit protocol, there could be conflicting votes in each partition which would prevent the algorithm from deciding to abort or commit when the network is partitioned evenly in half and the results are merged together.

For the Paxos algorithm to work correctly, the controllers in the cluster must maintain state variables to track transaction numbers and values that are in the process of being agreed upon. The variables tracked include the highest transaction number observed, the highest transaction number accepted with the corresponding value accepted, and the current transaction number being communicated to the other controllers in the cluster. In the first phase of the algorithm, one of the controllers in the cluster decides to become the coordinator through the two- or three-phase commit protocol. The coordinator then chooses a transaction number higher than the highest transaction number observed so far. This transaction number is then communicated to the other controllers in the cluster. The other controllers in the cluster will either accept or reject the transaction based on if the transaction number is the highest transaction number observed so far. If other controllers accept the transaction, then their internal variable that tracks the highest transaction number will be updated accordingly and that controller will not accept any future transaction numbers that are lower than the one just received.

If the coordinator receives accept messages from a majority of the other controllers in the cluster, then the leader calculates and sets the value corresponding to the highest transaction number that was previously sent to the other controllers. If a majority of accepts is not received by the coordinator, an abort message is sent by the coordinator and the Paxos algorithm is delayed and then restarted. The second phase of the algorithm begins with the coordinator sending the computed value to the other controllers that are a part of the cluster. The other controllers in the cluster again verify that the transaction number matches the highest transaction number observed so far. If it does not match, then the controllers will send an abort message back to the coordinator. If the transaction

number does match, then the highest transaction number observed is updated as is the highest transaction number accepted along with the associated value computed for that transaction number. The controllers in the cluster then send an accept message to the coordinator.

If the coordinator receives a majority of accept messages, then the coordinator sends an accept back to all of the controllers in the cluster along with the value that was agreed upon. This extra accept message is sent to update the value and transaction numbers agreed upon for the controllers that were not part of the majority accept votes. If there is not a majority of accept messages received from the coordinator, then the Paxos algorithms delay and restart again. At this point the protocol concludes communications and repeats the same process for the next transaction received.

In the event of a failure of a coordinator, another coordinator from the cluster of controllers will be elected and will take over the coordinator role. This is managed by ensuring that there is an order enforced on the transactions that occur within the network. The order enforced provides the controllers in the cluster the knowledge of the state variables that are being tracked by the coordinator. As a result, increased resiliency is added to the algorithm that the two-phase commit protocol could not handle.

Although Paxos is a great solution in many applications, it has some limitations. One important limitation is that it cannot handle controllers that intentionally or unintentionally report incorrect information during the replication phase of the value that is being agreed upon in the cluster. This scenario could arise in the event of an adversary who has compromised one of the controllers in the cluster and who is attempting to infect other controllers in the cluster with incorrect information. Another limitation is that the algorithm may not terminate in rare cases. One scenario when this can happen is when multiple coordinators have race conditions. The race conditions are caused by different values associated with different transaction numbers that are being proposed for

acceptance before an accept condition is reached by any of the individual transactions. These limitations must be acknowledged due to the high availability requirements of ICS systems.

6.2 Byzantine Fault Tolerant Algorithms

A Byzantine failure includes classes of attacks where a controller does not necessarily lose service, but the information being produced becomes untrustworthy due to a malicious actor [117]. The main goal of a Byzantine fault tolerant algorithm is to tolerate Byzantine failures from a limited number of the systems, f, and provide reliable results that can be trusted. The Byzantine Fault Tolerant State Machine Replication Technique (BFT-SMaRT) [118] algorithm discussed and used in this section requires $3f+1$ total systems in order to tolerate f failures. If there are anywhere between 0 and f failures, the results can be trusted. The setup of the Byzantine fault tolerant algorithm is similar to those discussed previously. Read and write operations are performed with the goal of having an agreed upon consensus value, even in the presence of f compromised controllers where each of the controllers independently performs the requested calculation. All controllers initially start in the same state and remain synchronized as requests are submitted by a set of client systems.

Controllers in the cluster play two separate roles in the algorithm. There is one leader controller and the remainder of the controllers are considered backups. The leader is elected via a three-phase commit protocol, as described earlier, from the cluster of controllers. After the leader is selected, all backup controllers follow the three-phase protocol with the controller elected as the leader. The messages are digitally signed for the Byzantine failures since malicious actors are assumed to be potentially included in the network. The leader also typically will send multicast messages on all messages received from clients to the backup controllers to improve communication efficiencies. A quorum based approach is applied here where $2f+1$ backup systems are required to produce the same result in order for that result to be trusted. After a quorum number of commit messages are re-

ceived, the backups then apply the changes. Each of the client requests also preserve the order in which the messages are received. This maintains consistency amongst the controllers in the cluster.

The Byzantine algorithms also have the ability to meet practical constraints, such as reducing the amount of space required by each of the controllers in the cluster in order to have the ability to rollback or be restored to previous states. This is handled by regularly checkpointing the controllers in the cluster. Requests are typically stored in logs and will continue to grow as requests are submitted by clients. The increasing length of the log file can be a potential vector for a DoS attack by an adversary attempting to exhaust all memory resources of the controllers in the cluster. To protect against logs from continuously growing, a defender can transfer the log files to a separate system after the log files reach a user configured length limit. Checkpoints are agreed upon by the quorum of controllers in the cluster and can be stored either locally or remotely. In the scenario of a rollback or restore, the time to synchronize a controller with the others in the cluster is reduced.

The Byzantine fault tolerant algorithms described make use of the three-phase protocol to maintain consistency and to arrive at an agreed upon consensus between a cluster of SDN controllers. The applications of Byzantine fault tolerant algorithms can be towards high fidelity systems such as those found in network file shared environments [109], cloud environments [119] where replication occurs regularly and often, or within transactional databases which was the genesis of fault tolerant algorithm research. The goals are to enhance the resiliency of the SDN controllers when in the presence of failures that are caused intentionally or unintentionally. The focus of our research is to evaluate fault tolerant algorithms within an ICS setting. The operational requirements and constraints will determine the feasibility of deploying fault tolerant algorithms to protect these types of systems.

6.3 Adversarial Models

Examples of the goals of an adversary are to negatively affect the operational network or to cause a failure in a system, such as a crash or the injection of malicious data into an SDN controller. The adversary has multiple ways to achieve these goals. The strategy for the adversary will largely depend upon the applications and protocols installed within the ICS environment. The path the adversary takes will also depend upon their goals. The adversary may not take the path of least resistance if they would like to be stealthy and maintain persistence. Alternatively, the adversary may only have the goal of disrupting a system and may not mind being detected by the defender. The adversaries also may not have any goals of disrupting service, but strictly exfiltrating information from the system undetected. The adversaries will vary widely in their goals, approaches, and definitions of success.

In the context of fault tolerant algorithms, the adversary may have the goal of causing a system to crash. The adversary may have physical access where they can easily succeed at accomplishing this goal. If the adversary only has network access, they would have to launch a remote exploit which causes a system failure. The difficulty of these approaches, from an adversary's perspective, also will vary depending on the skill level of the adversary and the security protections applied to the system. In the case of the crash tolerant algorithms, the adversary would have to compromise and cause a crash in at least f of the $2f+1$ controllers in the cluster to succeed.

In the case of the Byzantine fault tolerant algorithms for replication, the adversary would have to compromise the data in f of the $3f+1$ controllers within the cluster simultaneously. $3f+1$ is a lower bound for replication with several implementations available [118, 120, 121, 122] that provide different guarantees. The BFT-SMaRT algorithm was selected for its high throughput and low latency properties when configured with both crash and Byzantine fault tolerant algorithms. When focusing on compromising an individual controller, the adversary may be able to inject false information by first Ad-

dress Resolution Protocol (ARP) spoofing [123] the controller followed by injecting false information into the controller. Alternatively, an adversary may have access to a web interface where an SQL injection [124] can introduce false information into the controller. Regardless of the approach taken, there are a number of ways an adversary can achieve their goals of injecting false information into a controller which the Byzantine fault tolerant algorithms are designed to protect against. However, the difficulty is increased when the Byzantine fault tolerant algorithms are applied because the adversary is then required to compromise f systems to successfully manipulate the data so that a false consensus agreement would be achieved. As the number of controllers in the cluster increases, so does the number of controllers that an adversary would be required to compromise in order to succeed.

Another approach an adversary may pursue to achieve their goals is to attack the fault tolerant algorithms themselves. In this scenario, the adversary can disrupt the communications of the fault tolerant algorithms to cause latency delays. These latency delays in communication may indirectly translate into disruptions in service. The adversary can also attack the implementation of the fault tolerant algorithms. This vector of attack should be considered with any security protection software deployed in any system or environment even outside of ICS. If the fault tolerant algorithms implementations are vulnerable, the adversary may be able to compromise each of the controllers in the cluster by exploiting the fault tolerant algorithms themselves, which are intended to be the security protections.

6.4 Operational Impacts

There are costs associated when introducing any security protection into an environment. ICS networks have a low tolerance for any new delays introduced since they are time sensitive systems. Minimizing the amount of latency in these systems is critical for ensuring the operational network will not be negatively impacted. One area of interest is the performance impacts to the end devices. These metrics are important since ICS end

devices may have very limited resources, such as strict memory or CPU constraints. The devices under consideration may be inverters, PLCs, RTUs, or IEDs. Bandwidth and throughput metrics are important, but typically not a major concern in an ICS setting. In most cases, there are not high demands on bandwidth or latency for these systems.

The two time periods of interest when deploying fault tolerant algorithms are when there are no faults occurring and also at the instances in time where the faults occur in the network. When there are no faults occurring, the algorithm introduces additional communications into the network to verify all systems are responsive and consistent with one another. When there are faults occurring, there are also additional communications introduced into the network. These faults can be system failures or malicious manipulations of information communicated by controllers within the cluster. When the controllers in the cluster lose connectivity or have a fault in their data, the fault tolerant algorithms generate increased amounts of network communications. A fault in the coordinator would also increase the network communications because a new coordinator would need to be elected using the three-phase commit protocol which would require each of the controllers to communicate with one another. If there were an intermittent failure of a controller that was later restored, there would be a period of time where a new controller would be elected which would increase communications within the cluster. There are multiple ways to recover, for example BChain [125] prioritizes recovery by using a chain structure rather than requiring the broadcasting that BFT-SMaRT performs. Because of these additional communications and potential delays that occur during failures, the latency metrics during these intervals are of particular interest.

The goal of our research is to determine if the operational impacts of the fault tolerant algorithms are acceptable in the context of an ICS environment. The strict time constraints for latency in ICS settings are typically 12-20ms [15]. Both the crash tolerant and Byzantine fault tolerant algorithms will have to meet these constraints in order to be introduced into an operational ICS environment. The Byzantine algorithms will require

additional communications as compared to the crash tolerant algorithms but have protections built-in that defend against data manipulations. The crash tolerant algorithms require less communications and can tolerate system crashes but do not protect against malicious data modifications. The fault tolerant algorithm applied will depend upon the ICS constraints and the security requirements. It is a trade-off between security and usability to determine which type of fault tolerant algorithm to select.

Chapter 7

Overview of Experimental Setups

We have completed several experiments to quantitatively measure the effectiveness of each of the MTD strategies described thus far. The initial set of experiments were conducted within a simulated environment on a stand-alone system. The next set of experiments were performed within a virtualized environment. The final set of experiments were performed within a representative control system environment with actual end devices integrated. Each experiment consisted of a suite of MTD technologies deployed along with a variety of adversaries attempting to learn the information that the MTD techniques were hiding, such as IP addresses or application port numbers. The level of difficulty for each of the varying levels of adversaries to succeed is strongly correlated with the amount of entropy available to the MTD strategy that is enabled. We performed and repeated each experiment in each environment using 10,000 trial runs for the metrics we captured. The metrics collected for each MTD technique include throughput, bandwidth and latency measurements within each of the environments.

The simulated experimentation was performed on a standalone system where both the defender and adversary were modeled. The defender and adversaries are implemented as separate Python programs that run in separate processes to simulate the MTD strategies and the attacks competing against one another. As the MTD strategies were started, the adversaries were also started and configured to attempt to defeat the MTD protections. In this case, the adversary had the goal of learning the randomized MTD parameters.

The simulated results included a pair of end hosts with a single adversary attempting to exploit the defenders. The simulations were part of our early phases of research to determine the feasibility of the IP address and the port randomization MTD approaches developed. The initial theory for the success rates of the adversary was also verified with this set of experimentation.The specifications of the standalone system that performed the simulations were as follows:

- 2.8 GigaHertz (GHz) Intel® Core i7 CPU processor
- 16 GigaBytes (GB) Random Access Memory (RAM)
- 250 GB Serial Advanced Technology Attachment (SATA) Disk Drive
- Mac Operating System (OS) X Yosemite 64-bit

We developed the virtualized tests within the mininet environment [101]. Two virtual machines were configured to communicate over a mesh network of four Open vSwitch instances with an additional virtual machine representing the adversary's system. The reason for the mesh network of switches was to test the randomized network communication paths. The virtualized network was configured on a standalone system where the virtual machines were Ubuntu installations. The difference from the simulated environment is that the network stack and the operating system overhead were included in the virtualized environment. The network overhead was also measured, but since the virtual machines were all located on a single system, a local bus was used to communicate between the virtual machines and the links were virtually configured to communicate at a rate of 100 Mbits/sec. The virtual machines were installed on the same machine used for the simulated experiments discussed previously. The specifications for each of the virtual machines were as follows:

- 2.13 GHz Intel® Xeon® CPU X3210 quad core processor
- 2 GB RAM
- 40 GB SATA Disk Drive
- Quad port Peripheral Component Interconnect Express (PCIe) Intel Gigabit Ethernet card
- Ubuntu 14.04 64-bit
- Linux Kernel 3.13.0-46

There were two separate environments used to test the "representative" environments. One environment is a public testbed available for security researchers to allocate physical systems that can be configured and customized as desired. Network settings and topologies are also configurable in this testbed through Network Simulator (NS2) [126] scripts. The testbed is named Cyber-Defense Technology Experimental Research Laboratory (DETERLab) [127]. In these experiments, we configured four end hosts with 16 adversaries added to the network. We then captured performance metrics on the effectiveness of each MTD technique developed when a number of adversaries were attacking the defenses.The systems allocated within DETERLab for the IP randomization experiments consisted of the following specifications:

- 2.13 GHz Intel® Xeon® CPU X3210 quad core processor
- 4 GB RAM
- 250 GB SATA Disk Drive
- Quad port Peripheral Component Interconnect Express (PCIe) Intel Gigabit Ethernet card
- Ubuntu 16.04 64-bit

The second representative environment developed was used to model an ICS system that consisted of both physical and virtualized systems. The physical and virtual systems included common ICS devices such as inverters, PLCs, historian systems, Human Machine Interfaces (HMIs) as well as the networking devices required for the end devices to communicate with one another. Actual network communication protocols were present and active during the experimentation. The Modbus protocol was used in this case, but other ICS protocols such as (Distributed Network Protocol) DNP3 could also be included if desired. The ICS network consisted of 24 end devices, five Open vSwitch instances and one adversarial system. We also captured the same performance metrics to verify and validate both the simulated and virtualized environments. Each of the experiments and results are described in more detail in the chapters that follow.

Chapter 8

Simulation Environments

We performed simulations on a standalone system to capture performance metrics and evaluate the effectiveness of several MTD strategies. We implemented simulations in the Python version 2.7 programming language [128]. We implemented the IP randomization and port randomization algorithms as two separate programs that were designed to run in separate processes on the same system. We developed an additional program to simulate an adversary attempting to find the randomized values assigned to the source and destination IP addresses as well as the application port numbers. In order for the adversary to learn if they have successfully discovered the randomized source and destination IP addresses, the adversary process would communicate with the MTD process which would indicate a success or failure to the adversary. The specifications of the standalone system that performed the simulations are as follows:

- 2.8 GigaHertz (GHz) Intel® Core i7 CPU processor
- 16 GigaBytes (GB) Random Access Memory (RAM)
- 250 GB Serial Advanced Technology Attachment (SATA) Disk Drive
- Mac OS X Yosemite 64-bit

Each simulation was run with only the minimum required system processes active in the background. This precaution was taken in order to limit the chance of external processes affecting the experimental results. We captured performance metrics from each of the simulations every one second with a total of 10,000 simulation trials performed.

8.1 Adversary Guessing Strategies

The first set of experiments simulates an adversary attempting to guess the specific network parameters (IP address or application port number) that have been randomized. We created a stand-alone program to simulate a network parameter first being altered uniformly at random followed by an adversary attempting to discover that randomized network parameter. In the case of an application port number, the program selects a 16-bit value uniformly at random and then allows an adversary to take a limited number of attempts or probes to discover the correct application port number chosen by the defender. The number of attempts allowed for an adversary vary from 1 attempt to 2^{21} attempts. The limit was placed on the adversary to model a defender who has the ability to detect an adversary after a certain number of attempts are made. For each of these experiments, we assessed adversaries with different guessing strategies for their success rates in correctly discovering the randomized network parameter in question. Each of the four guessing strategies evaluated are taken from the Internet Engineering Task Force (IETF) Request For Comment (RFC) 6056, which outlines the strategies taken for port randomization [100] selection when a client connects to a server. The results of each guessing strategy are shown in Figures 8.1, 8.2, and 8.3 the sections that follow. In the experiments we performed, we assume that the adversary can search the state space before the port numbers are re-randomized.

8.1.1 Serial Guessing

The simplest strategy an adversary can deploy is to begin guessing application port numbers starting at port number 1 and incrementally guessing subsequent port numbers until the correct 16-bit randomized port number is found. This is a brute force approach that works well when the attack space is small, such as the case here with a 16-bit number. As

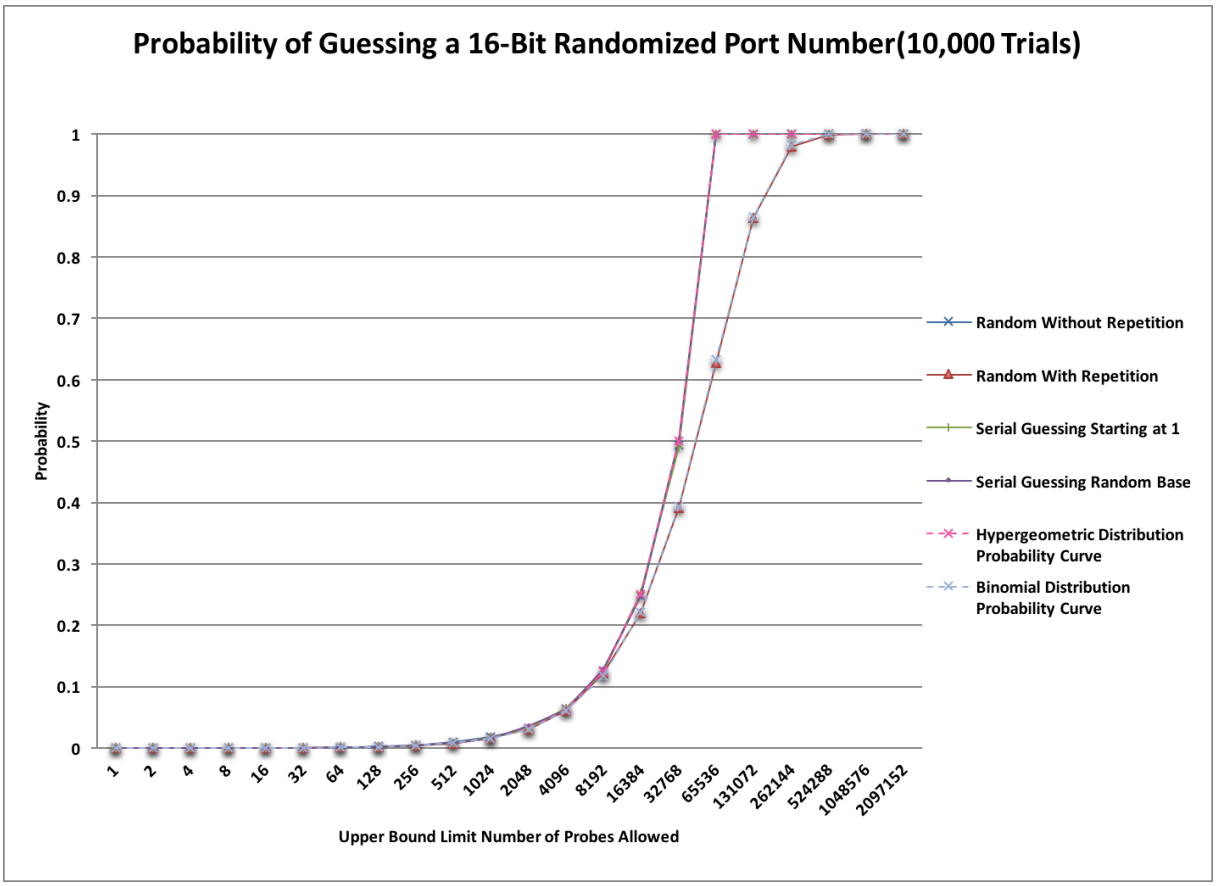


Figure 8.1: The probability of correctly discovering a randomly-selected 16-bit port number using different guessing strategies given a limited number of probes.

shown in Figure 8.1, the number of probes that are configured as the upper limit for the adversary are shown on the x-axis and the probabilities of success by an adversary are shown on the y-axis. As the number of probes afforded to an adversary increases, so does the adversary's probability of successfully discovering the randomized application port number. Since previously failed attempts at discovering the application port numbers are not repeated and the two outcomes are either success or fail, the data captured fits into the definition of a hypergeometric distribution:

$P(X = k) = \frac{\binom{K}{k}\binom{N-K}{n-k}}{\binom{N}{n}}$ [129]

where N is the population size, K is the number of success states in the population, n is the number of probes allowed by the adversary, and k is the number of successes desired. Considering that $K = 1$ and $k = 1$, the probability simplifies to:

$P(X = 1) = \frac{n}{N}$

As shown in Figure 8.1, the data collected for serial guessing follows the hypergeometric curve that is also plotted as a dashed line on the same plot. There is a strong correlation as the hypergeometric destination closely matches and overlaps the experimental results collected. The effectiveness of the port randomization technique can be evaluated based on the probabilistic results obtained for an adversary successfully discovering the randomly-chosen port mapping given a certain number of probes allowed. For example, allowing more than 2^{15} probes would not be in the defender's best interest since serially guessing port numbers would give the adversary a probability of success above 50%. If it is tolerable to allow a less than 5% chance of success, then the defender should consider allowing 2048 probes as the upper bound limit placed on the adversary. Any amount of probes above this limit would then be flagged and an operator would be alerted to take the appropriate action to mitigate the threat. One example of a mitigation strategy an operator can take would be to blacklist the adversary in a firewall rule so they can no longer communicate on the network.

We also collected metrics on the average number of probes needed for an adversary to learn the randomized port number. This average number is obtained when only considering the cases where the adversary successfully learned the correct randomized application port number and is summarized in Figure 8.2. Since the serial guessing strategy follows the hypergeometric distribution, the average number of attempts will continue to grow until the expectation value is approximated (when there are $\geq 2^{16}$ probes allowed by the adversary). After that point, the number of attempts required remains constant as the upper limit number of probes continues to increase. The expectation formula for the hypergeometric distribution is as follows:
$E(X) = \frac{N+1}{k+1} = \frac{N+1}{2} = 32{,}768.5$

The average amount of time required per success, taken over all 10,000 trials, is shown in Figure 8.3. For the serial guessing strategy starting at port number 1 and incremen-

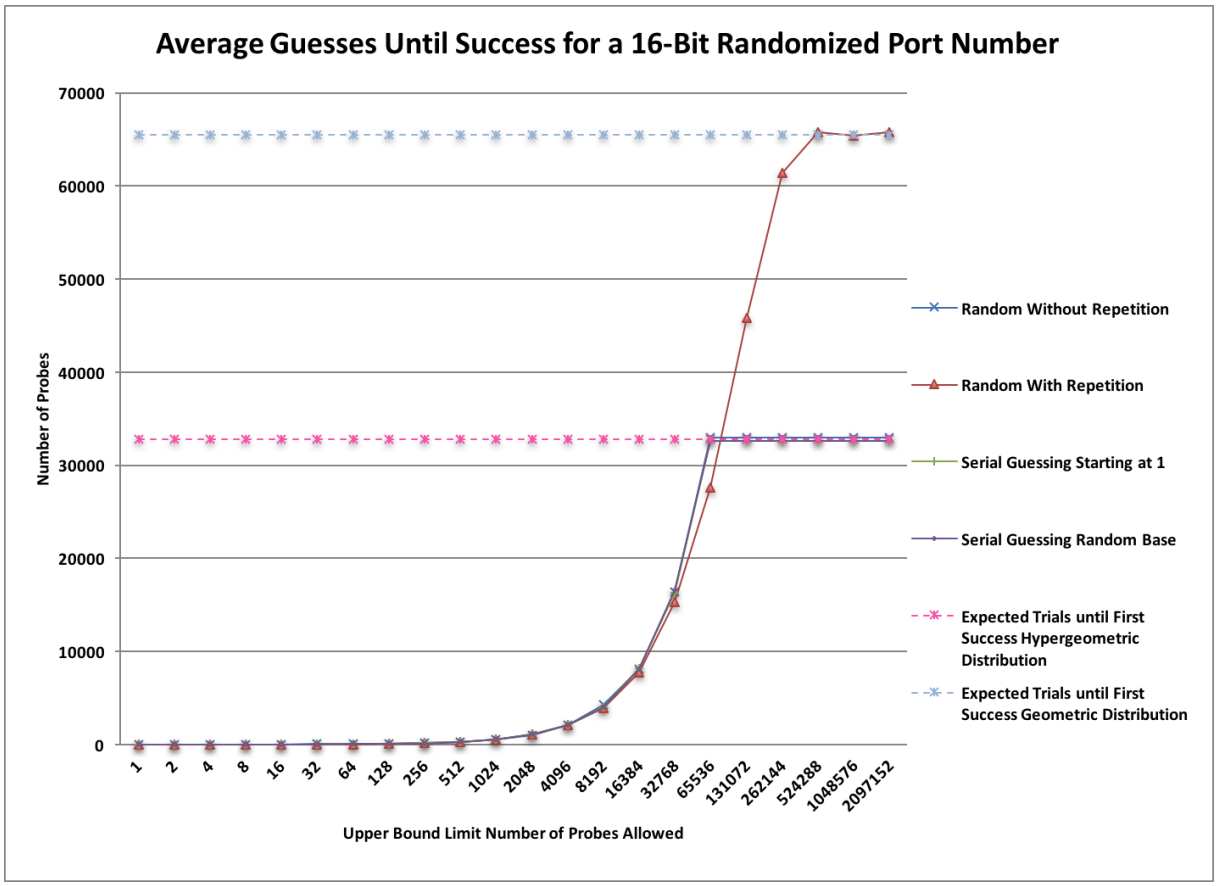


Figure 8.2: The average number of attempts expected before correctly discovering a randomly-selected 16-bit port number using different guessing strategies where the adversary is given a limited number of probes.

tally probing subsequent port numbers, the average time for an adversary to successfully find the randomized port number is under 0.03 seconds when the entire state space is explored. This upper bound time limit is attributed to the limited amount of entropy within a 16-bit space. *Given the minimal amount of time required for an adversary to discover the application port number by brute force, the frequency at which a defender should re-randomize port numbers should be based on the number of probes observed instead of solely based on time units alone.* Within the small 0.03 second window, ~16,000 probes are injected by the adversary, which is a very noisy adversary that can quickly be detected if the defender is monitoring the number of probes observed. Additionally, the number of probes observed provides information to the defender on the likelihood of success for an adversary, depending on how frequently the application port numbers are being re-

randomized as shown from Figure 8.1. *Combining the information on the success rate of the adversary along with the time required by an adversary until a success can be expected provides the defender with the parameters necessary to protect against adversaries who follow the strategies described.*

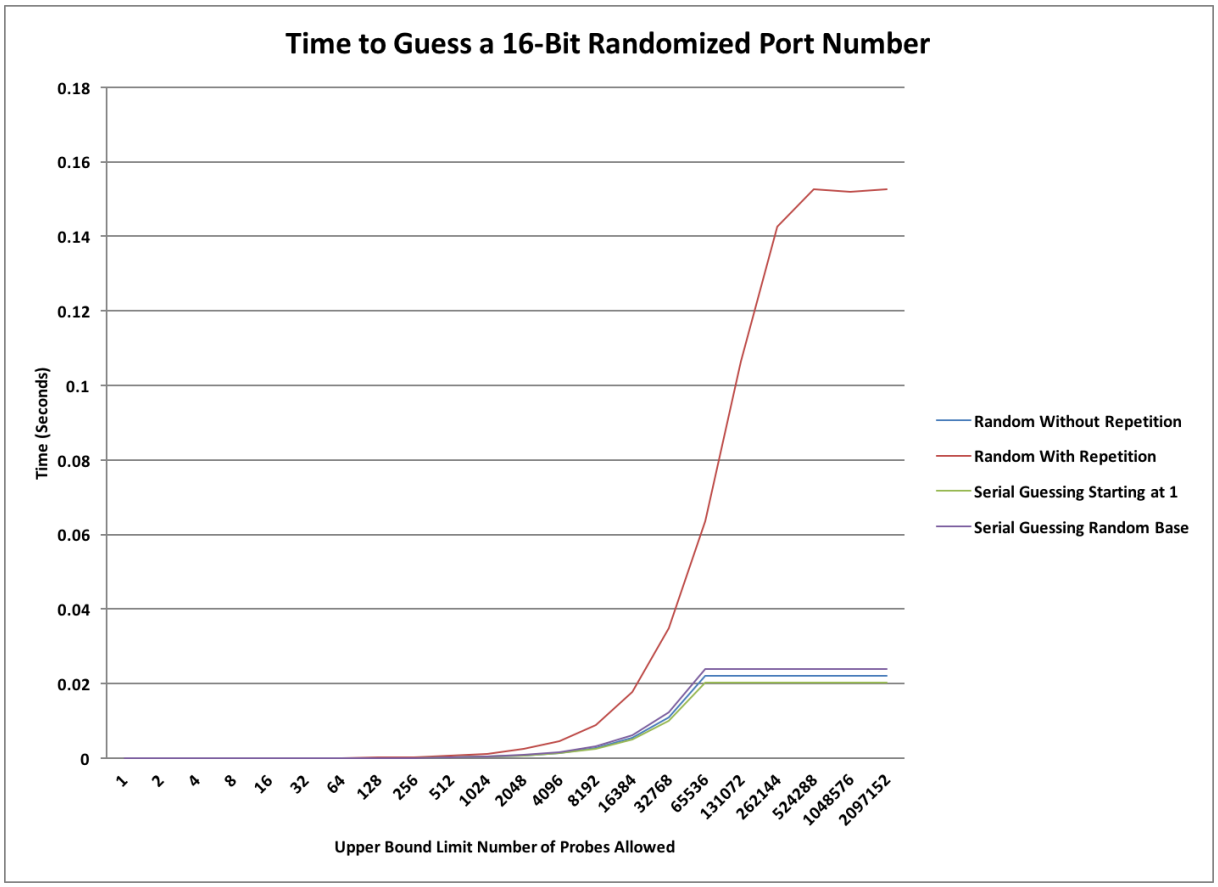


Figure 8.3: The average amount of time needed before correctly discovering a randomly-selected 16-bit port number using different guessing strategies where the adversary is given a limited number of probes.

8.1.2 Random Start, Serial Guessing

A similar adversarial strategy to discover application port numbers is where an adversary starts at a random port number within the range of 1-65,536 and then incrementally attempts subsequent port numbers until the correct randomized application port number is found. Once the maximum port number value is reached by the adversary (65,536 in this case), the port number overflows back to 1 and the adversary incrementally continues

guessing until the correct port number is found or until the original starting port number is reached. The results of this strategy follow a similar pattern as the serial guessing strategy since the defender chooses the random mapping uniformly at random and because the adversary starts scanning from an initial application port number chosen uniformly at random. Because the application port number is chosen uniformly at random by the defender, this adversary guessing strategy is equivalent to the case where the adversary starts at application port number 1. Thus, there is no advantage from either the adversary nor the defender when this guessing strategy is chosen. The success rates are shown in Figure 8.1 verifying this result and also follow the hypergeometric distribution. The hypergeometric plot significantly overlays the experimental results obtained and is strongly correlated.

Since the serial guessing strategy with a randomly-chosen starting base for the application port number also follows the hypergeometric distribution, the average attempts needed until success similarly continues to grow until the expected value is approximated (when there are $\geq 2^{16}$ probes allowed by the adversary as shown in Figure 8.2). At this point, the success rate remains constant as the number of attempts permitted by the adversary continues to grow beyond the expectation value. The average amount of time per success taken over all 10,000 trials also resembles the serial guessing strategy starting at application port number 1 as shown in Figure 8.3. For the serial guessing starting at a random base strategy, the average time for an adversary to successfully find the randomized port number is also under 0.03 seconds when the entire state space is explored. The minimal amount of time required for an adversary to successfully discover the application port number, again, provides guidance on the frequency at which a defender should re-randomize application port numbers. The randomization frequencies should be based on the number of probes attempted by the adversary instead of solely based on time units alone. The number of attempts that can be made within a 0.03 second period is $\sim$16,000 attempts which is a large number of attempts. The defender can detect a high number of probes such as these by monitoring the incoming and outgoing network traffic observed.

8.1.3 Random Guessing with Repetition

The next adversary strategy evaluated is when the adversary continuously probes application port numbers selected uniformly at random until the correct randomized port has been found. When using this strategy, it is possible that the adversary repeats previous incorrect probes that were already made. Since previously failed probes can be repeated, the probability of discovering the correct application port number from one attempt to the next does not change. This is in contrast to the serial strategies discussed earlier where the probability of success improved with each attempt since the pool of available application port numbers continues to shrink with each attempt to find the correct application port number. In this case, the probing strategy follows a binomial distribution. As shown in Figure 8.1, the binomial distribution curve closely follows the experimental results obtained for the random with repetition application port probing strategy and the results are strongly correlated to the theoretical results. The probability function for the binomial distribution is:

$P(X = k) = \binom{n}{k} p^k (1-p)^{n-k}$ [35]

where N is the population size, p is probability of success, n is the number of probes allowed by the adversary before the defender detects their presence, and k is the number of successes desired by the adversary. In this case, it is of interest to find the probability of at least one success which is equivalent to taking the complement of exactly zero successes to simplify the formula above ($k = 0$):

$P(X = k) = 1 - \binom{n}{0} p^0 (1-p)^{n-0} = 1 - (1-p)^n$

$P(X \geq 1) = 1 - (1-p)^n$

Of the four strategies evaluated, this strategy is the least likely to be successful for an adversary since repeating previously failed attempts are a possibility. The average number of probes needed for an adversary to learn the randomized application port number, when only considering the successful cases, is summarized in Figure 8.2. Since the random guessing with repetition strategy follows the binomial distribution, the average number of attempts needed until a success occurs continues to grow until the expectation value is

approximated. In this case, the curve levels out to a constant value when there are $\geq 2^{20}$ probes permitted by the adversary. The expectation formula for the number of attempts before the first success is as follows:

$E(X) = \frac{1}{p} = \frac{1}{\frac{1}{2^{16}}} = 65{,}536$

The average amount of time required per success, taken over all 10,000 trials, is shown in Figure 8.3. The average amount of time for an adversary to successfully find the randomized application port number is under 0.16 seconds when the entire state space is explored. Comparing these results to the other strategies which take on average 0.03 seconds, this strategy is 433% times slower until the first success is encountered. However, this upper bound time is fairly minimal at 0.16 seconds and again is attributed to the limited amount of entropy available within the state space of a 16-bit application port number. Given the small amount of time needed by an adversary to successfully discover the randomized application port number, the frequency at which the defender should re-randomize port numbers is advised to be based on the number of probes observed rather than on the amount of time that has passed. Monitoring the number of probes ($\sim$30,000 in this case) would provide sufficient information to detect the presence of an adversary.

8.1.4 Random Guessing without Repetition

The final guessing strategy analyzed is when an adversary randomly guesses application port numbers without repeating any previously failed random probes. To implement such a strategy, the adversary must track previously failed attempts to avoid repetition. To succeed in this scenario, the adversary must discover the application port number before it is remapped by the MTD strategy, based on a user configurable randomization frequency parameter. This strategy once again maps to the definition of a hypergeometric distribution and the data collected from the experimental results obtained verifies this mapping.

The three guessing strategies for an adversary that follow the hypergeometric distribution (Serial Guessing; Random Start, Serial Guessing; and Random Guessing without Repetition) perform similarly with one another in terms of their success rates. The data collected

for each of these three strategies overlap one another significantly and are summarized in Figure 8.1. The average attempts required until a successful attempt is encountered by an adversary grows until the expectation value is approximated. This occurs when there are $\geq 2^{16}$ probes allowed by the adversary as shown in Figure 8.2. When permitting more than the expectation number of attempts by the adversary, the success rate remains constant. The average amount of time per success taken over all 10,000 trials also resembles both of the serial guessing strategies as shown in Figure 8.3. For the random guessing without repetition strategy, the average time for an adversary to successfully find the randomized port number is again under 0.03 seconds when the entire state space is explored. The small amount of time required for an adversary to discover the application port number again provides guidance on the frequency at which a defender should re-randomize the application port numbers. The re-randomization intervals should be based on the number of probes observed rather than solely based on time units alone. If a relatively short amount of time is configured to re-randomize application port numbers, such as every 1 second, then a rather noisy adversary could easily probe the network 65,536 and could effectively defeat the MTD strategy. Since the results depend on the entropy available to a defender, randomizing IP addresses produces similar results when 8 bits of both the source and destination IP addresses are randomized.

8.2 Summary

The simulated environment we developed provided us with the ability to quickly collect theoretical results during the early phases of our research on the feasibility of each MTD approach. We were able to simulate four adversarial strategies and the MTD techniques with stand-alone programs. The stand-alone programs allowed us to easily modify the network parameters being simulated as part of each MTD technique as well as the adversary strategies. Our findings were that an adversary can brute force a 16-bit application port number (or 16-bits from a pair of IP addresses) in under 0.03 seconds with three of the adversary strategies and within 0.16 seconds when one of the adversary strategies is applied. This is a minimal amount of time for any of the four strategies but what works

against the adversary is the number of probes required to be successful. The adversary must search at least half of the attack space before the first successful discovery of a randomized 16-bit application port number can be discovered. Also of note, is that the adversary and defender are communicating through inter-process channels which is much faster than through an IP network. Considering that there are at least 16-bits of entropy available to the defender, the adversary must make 2^{15} probes before the first success is expected. Figure 8.1 and Figure 8.2 show the two curves that provide information on the success rates of an adversary given a variable number of probes and the number of probes an adversary must attempt before the first successful randomized mapping is discovered. Combining the information on the success rate of the adversary along with the time required by an adversary until a success can be expected provides the defender with the parameters necessary to protect against adversaries who follow the strategies described. These results were later verified in both the virtualized and representative environments developed that are discussed in the following chapters.

Chapter 9

Virtualization Environments

We developed a virtualized environment to validate the prior results obtained from the simulated environment. The virtualized environment introduces the network communications into the experiments that were not present in the simulated environment. OpenFlow version 1.3 is the protocol used to facilitate the communications between the SDN controller and the SDN capable switches. A separate wrapper program manages the randomized flows that are sent to the SDN controller which are then inserted into the network. The mininet tool was used to build a network of virtual machines representing the end hosts of an ICS environment as well as the SDN capable switches. This environment included the MTD strategies built-in to each of the virtual machines to demonstrate the concepts beyond simulation. Open vSwitch was the software package we chose to implement the SDN capable switches within the virtualized environment. Open vSwitch provides the same functionality of a physical network switch in hardware, but it is implemented in software where the randomization algorithms have been placed. It has previously been shown that OpenFlow has the ability to randomize IP addresses within a network as a standalone solution in a small scale network [20]. Additionally, it has also been shown that overlay networks can be used to mitigate DDoS attacks [32]. One of the goals of our research is to build upon those results by merging IP randomization, port randomization, and overlay networks to counter the reconnaissance phase of an attack all contained within a single solution.

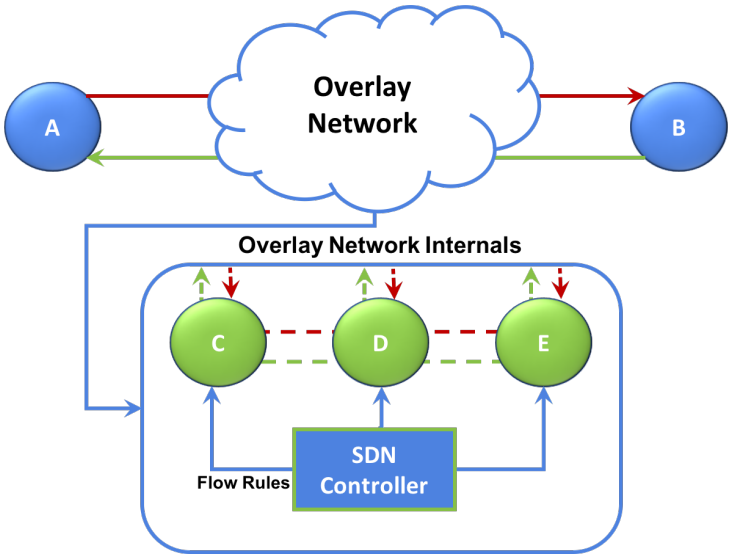


Figure 9.1: A diagram of an example network where host A wishes to communicate with host B. The OpenDaylight controller inserts flows within the overlay network so that packets have randomized source and destination IP addresses, randomized port numbers, and take random paths (shown as the red and green lines passing through the overlay network) through the network.

The SDN network we used for our experiments operated under the open source OpenDaylight controller [102]. The OpenDaylight controller communicates to the Open vSwitch instances through the OpenFlow version 1.3 protocol to install the necessary flows to manage the randomized network parameters. The OpenDaylight controller is responsible for installing flows that translate real IP addresses into randomized IP addresses when a packet is traversing each of the Open vSwitch instances within the network. The OpenDaylight controller also manages the randomized paths that the packets take through the overlay network. Figure 9.1 depicts an example network where the OpenDaylight controller is communicating with the Open vSwitches in the overlay network. The OpenDaylight controller installs randomized source and destination IP addresses, randomized port numbers, and randomized paths into the SDN overlay network when packets originating from host A are sent to host B. The randomized source and destination IP addresses are translated back to the original source and destination IP addresses at the last hop switch before reaching the final destination host B. Since the true IP addresses are mapped to randomized IP addresses when entering the network and then re-mapped back from

the randomized IP addresses to the true IP addresses when the packets are leaving the network, the solution is completely transparent to the end devices within the network.

9.1 Application Port Randomization Overhead Cost

Port randomization is implemented using the *iptables* [130] firewall tool that is built into most Linux base installations. The performance impacts that result from using the *iptables* rule chain to randomize application port numbers increased the latency by an average of 0.015 ms and did not interrupt active communication sessions that were already in progress. The results over a 10,000 second (∼2.77 hours) interval are shown in Figure 9.2. It should be noted that there is little to no performance impact of enabling port randomization given that the maximum impact to the Round Trip Time (RTT) was within 1.2 ms of when port randomization was disabled which is well within the constraints of a typical ICS environment. The strict timing constraints used within ICS environments are noted to be no more than between 12-20 ms of additional delay.

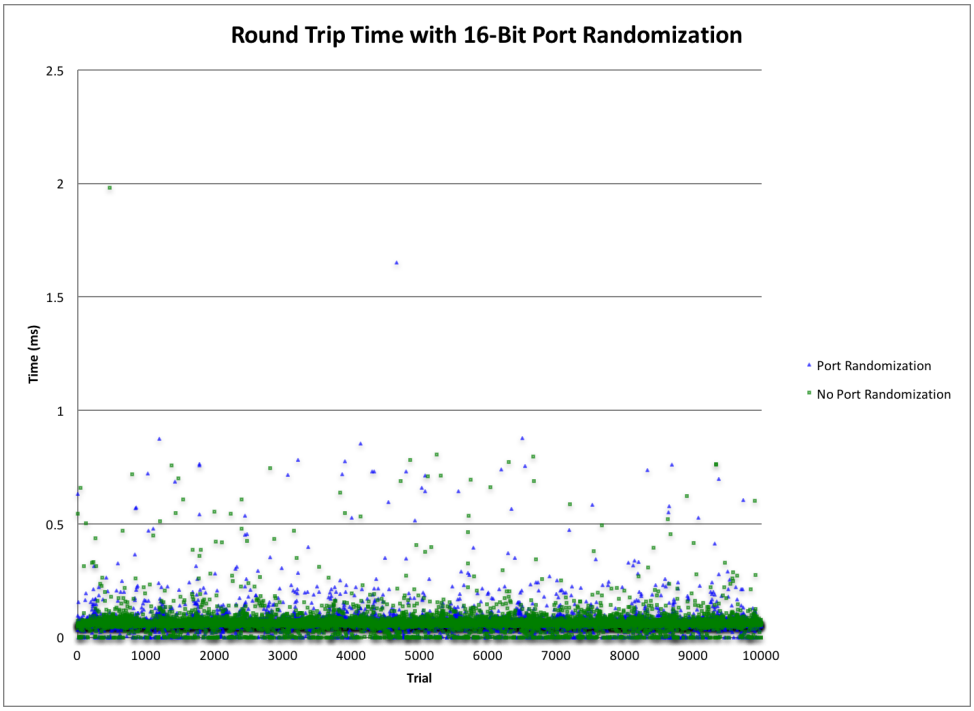


Figure 9.2: The RTT measured across 10,000 pings with port randomization disabled and enabled.

The impacts on bandwidth when port randomization is enabled and disabled are shown in Figure 9.3. We configured the port randomization updates to re-randomize all application port numbers ranging from port numbers 1-1024 at a frequency of once every 10 seconds. The *iperf3* tool was used to gather the resulting data points over a 10,000 second (~2.77 hours) interval. We observed a 9.91% reduction in bandwidth when port randomization was enabled. The increase in overhead is attributed to the time to process each packet in software and rewrite the application port numbers before forwarding and receiving packets. There are typically not strict requirements on bandwidth and throughput measurements within ICS environments since the communications usually require minimal amounts of bandwidth.

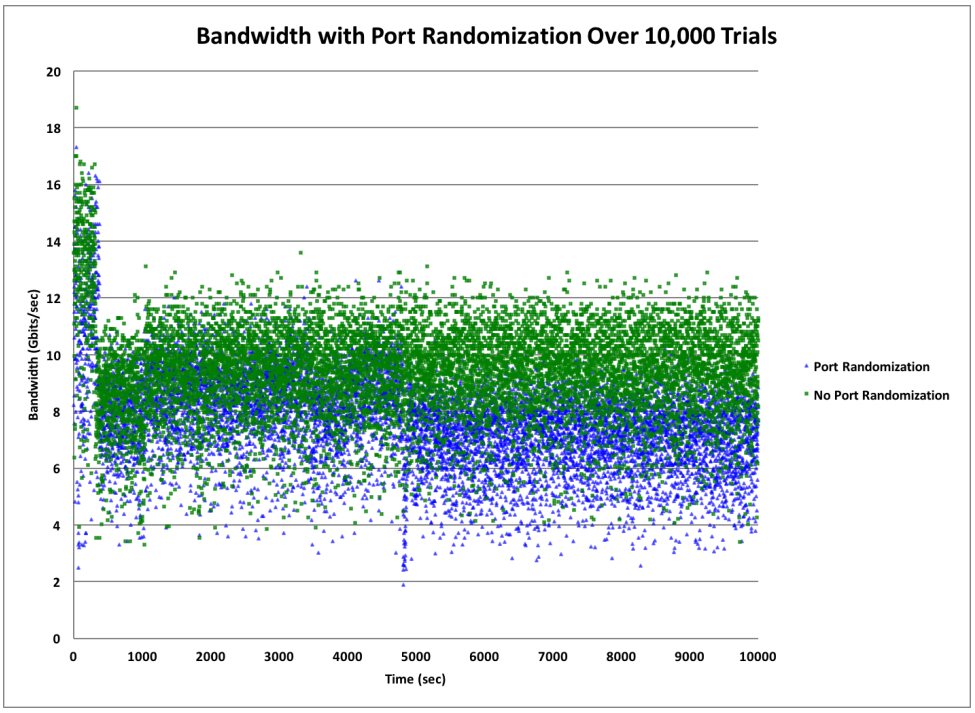


Figure 9.3: The bandwidth measured across a 10,000 second (~2.77 hours) period of time when application port number randomization is disabled and enabled.

9.2 IP Randomization Overhead Costs

The overhead cost incurred by the SDN switches to lookup the appropriate flow rules and make the appropriate routing decisions (and rewriting source and destination IP ad-

dresses) resulted in an average of 0.04 ms of additional delay. We configured these lookups only at the edge switches so that the operational impacts are well within the constraints of a typical ICS environment of 12-20 ms [131]. We also performed experiments to validate that the connectivity was maintained and uninterrupted between hosts actively communicating before, during and after each of the randomization periods. The verification of the uninterrupted communication channels is important since high availability is one of the primary requirements and concerns for an ICS environment. Availability is a concern when introducing any new technology, security related or not, into the system. The results of sending 10,000 ping packets across a network are shown in Figure 9.4. We took measurements when IP randomization was disabled and then again when it was enabled on the network. The majority of the measurements collected overlap one another, in both cases of when IP randomization was enabled or when it was disabled. The increases in RTT that occur every 500 seconds when IP randomization is enabled typically do not increase the RTT to more than 15 milliseconds and in the worst case do not increase more than 30 milliseconds. The latency introduced falls within the bounds of the more strict constraints (that range in milliseconds) the majority of the time and are well within relaxed constraints (that range in seconds) of ICS environments.

We also captured bandwidth measurements with and without IP randomization enabled. The results are as expected in that when IP randomization is enabled, the bandwidth measurements observed slightly decreased. This decrease is a result of the overhead involved in the SDN flow rules, that when matched, must rewrite both the source and destination IP address fields at the ingress and egress points in the network instead of simply forwarding packets as a traditional switch would. However, traditional switches occasionally require layer 2 traffic, such as ARP traffic, to learn about the locations of new hosts that are introduced into the network. The overhead associated with rewriting the IP address fields in an SDN deployment degrades the bandwidth as shown in Figure 9.5. The $iperf3$ tool was used to measure and capture the results over a 10,000 second ($\sim$2.77 hours) period of time.

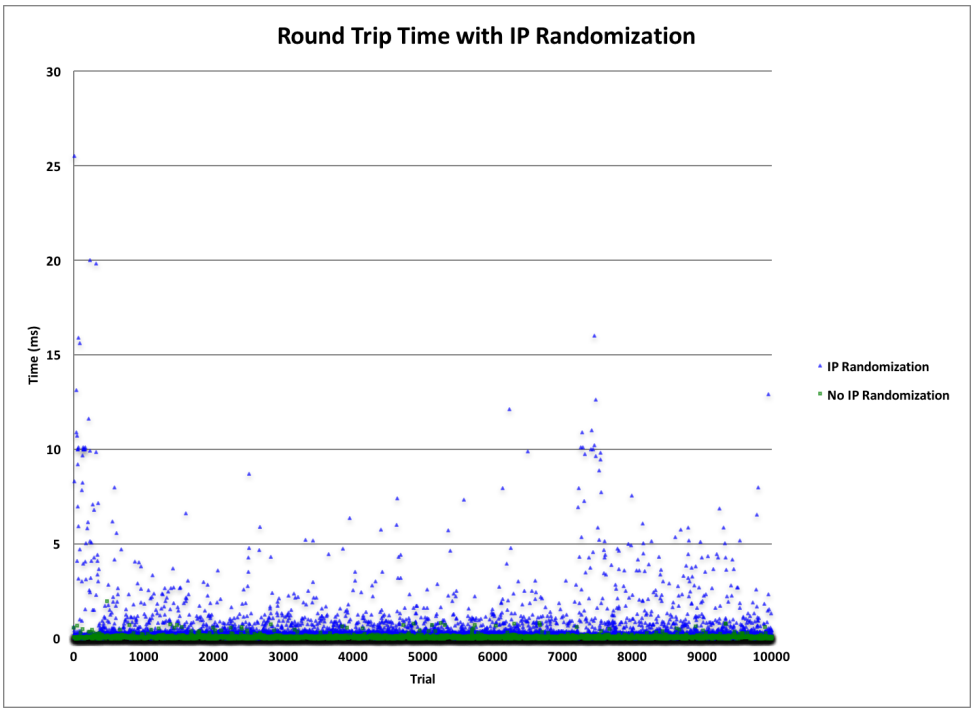


Figure 9.4: The RTT measured across 10,000 pings when IP randomization is disabled and enabled.

The average bandwidth was reduced from 9.31 Gbits/sec to 9.14 Gbits/sec, or a 1.79% decrease in performance. There is a significant amount of overlap when comparing IP randomization being enabled and disabled. Also of note are the fluctuations when IP randomization is enabled that occur every 500 seconds. This is attributed to purge-times within the OpenDaylight controller (the purge-times flush all flows and are part of the default configuration) that happen every 500 seconds. When all rules are purged, there are slight increases in delay because the Open vSwitch instances are forced to consult with the SDN controller on how to appropriately route the packet. The purge-time is a user configurable parameter that can be adjusted if desired, but the default value was not modified for these experiments. Although ICS environments are typically not driven by bandwidth and throughput measurements, those metrics are captured here for potential ICS scenarios where high bandwidth and throughput are desired, such as the case when communicating synchrophasor data.

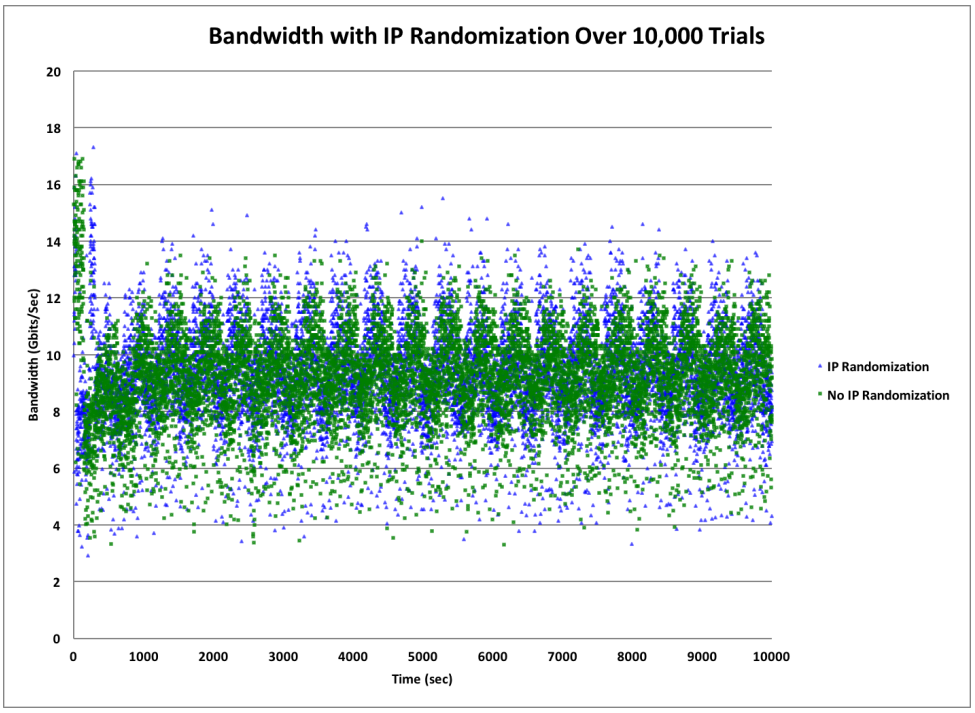


Figure 9.5: The average bandwidth measured over a 10,000 second (∼2.77 hours) period when IP randomization is disabled and enabled.

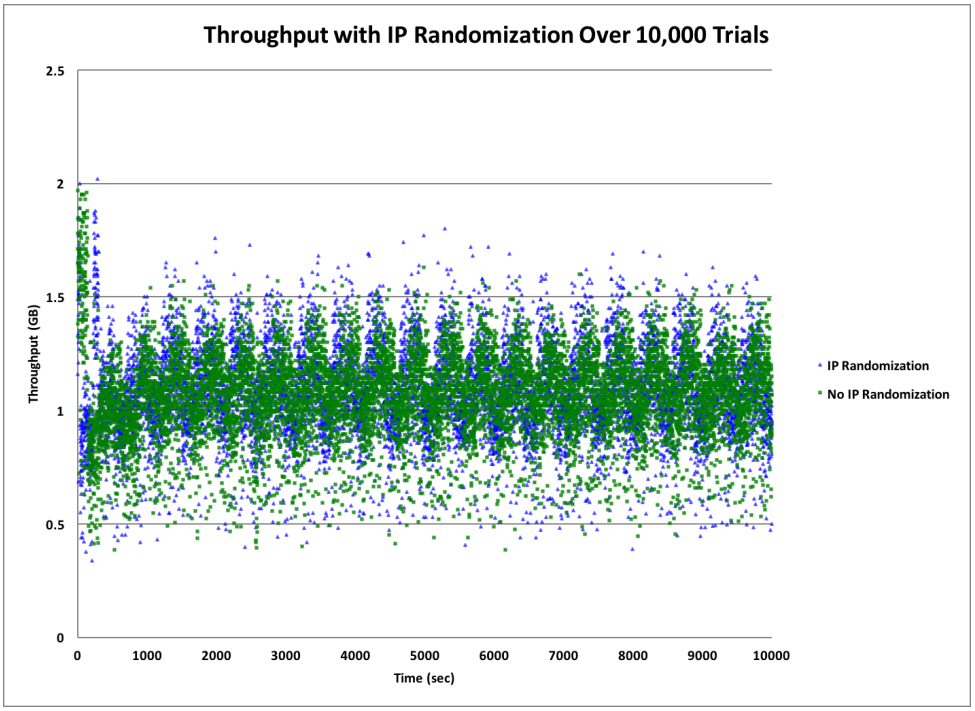


Figure 9.6: The average throughput measured over a 10,000 second (∼2.77 hours) period of time when IP randomization is disabled and enabled.

We also evaluated the impacts on the total amount of data transferred over 10,000 second (∼2.77 hours) intervals using the *iperf3* tool when IP randomization was disabled and then when it was enabled. As shown in Figure 9.6, the impacts on the amount of data transferred are similar to the bandwidth measurements captured and described above. The total data transferred provides another way to look at the bandwidth measurements previously captured, but in terms of the amount of total data transferred over each 1 second interval. The total amount of data transferred without IP randomization enabled over the 10,000 second (∼2.77 hours) period is 10,834 GB. This number drops to 10,649 GB when IP randomization is enabled, or a 1.79% drop in performance. The drop is attributed to the added time to overwrite the source and destination IP address fields of the flow rules that are installed at each of the Open vSwitch instances.

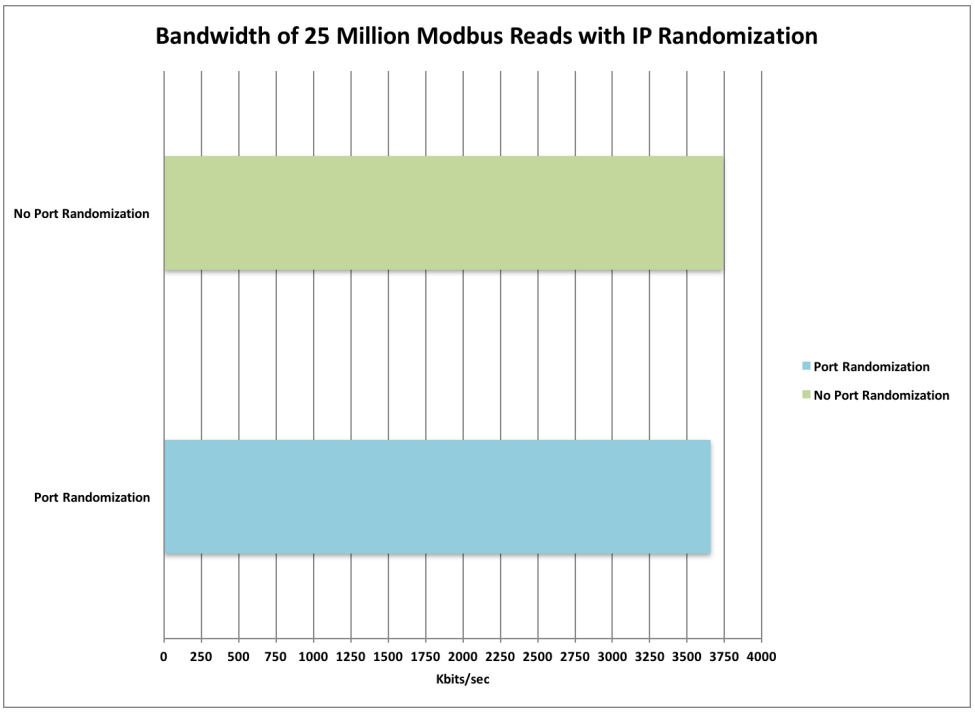


Figure 9.7: The average bandwidth measured over a 10,000 second (∼2.77 hours) period when IP randomization is disabled and enabled.

We also captured bandwidth metrics when using the Modbus protocol, a widely used protocol within ICS environments. In this scenario, a Modbus server was running on a single system and a Modbus client was running on a separate system that is programmed

to request 25 million reads of data. The results of the bandwidth metrics captured when using the Modbus protocol are summarized in Figure 9.7. When IP randomization is not enabled, the bandwidth on the 25 million reads is an average of 3,737 Kbits/sec. When IP randomization is enabled, only a small decrease in bandwidth results in 3,525 Kbits/sec, or a 5.67% decrease in performance. The delays observed are within the bounds of an ICS environment and make the techniques feasible for deployment when using the Modbus protocol.

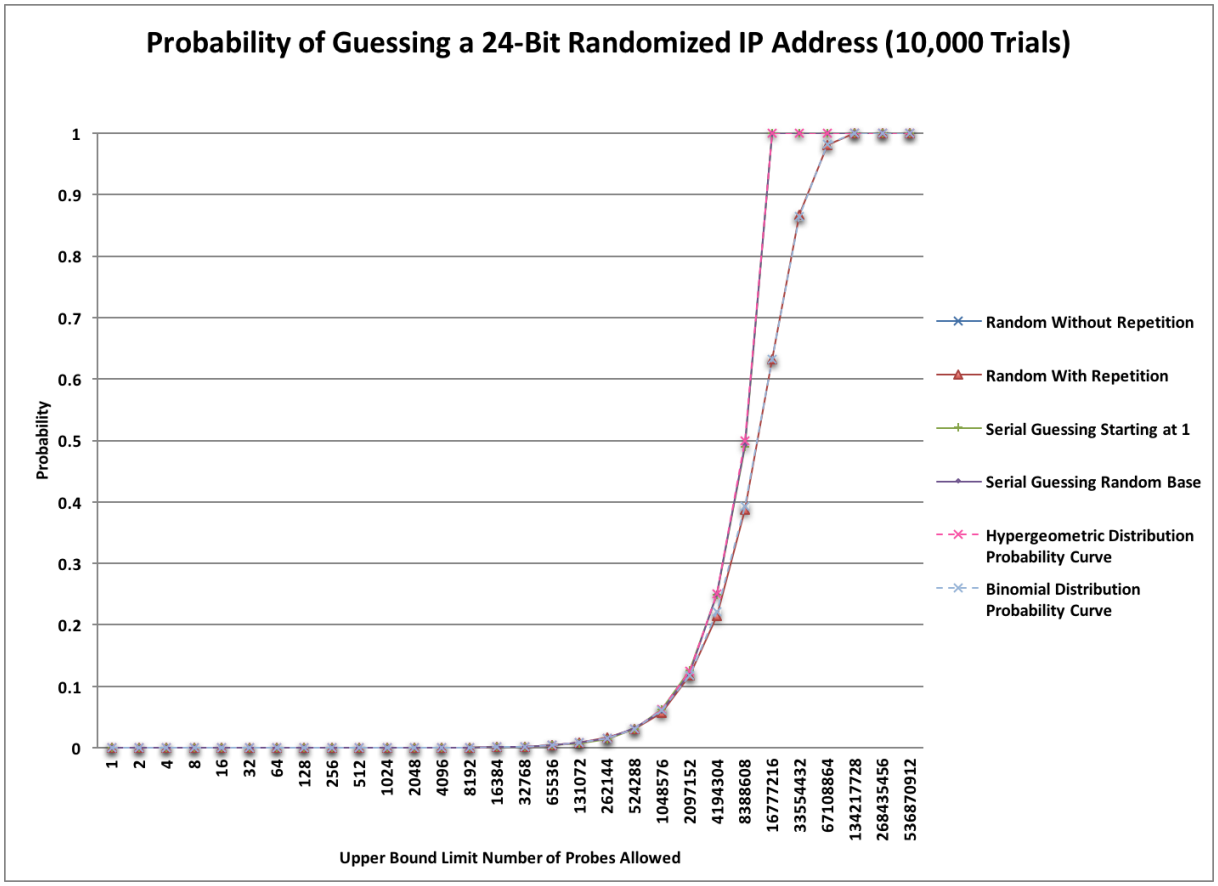


Figure 9.8: The probability of correctly discovering a randomly-selected 24-bit number (a CIDR class A IP address) using different guessing strategies given a limited number of probes.

Finally, we captured the probability distributions for adversaries who have the goal of discovering the randomized source and destination IP addresses using different strategies similar to the application port randomization techniques described earlier. The results

are shown in Figure 9.8 and are similar to those shown for the port randomization test performed in Figure 8.1. We have verified that all strategies, except for the random guessing with repetition strategy, follow the hypergeometric distribution over 10,000 trials of experiments that model an adversary attempting to guess both of the randomized source and destination IP addresses. In these sets of experiments, the assumption is that 24-bits are available to use as host bits. Using 24-bits of the IP address as host bits provides an upper bound of the effectiveness of the IP randomization technique given that it is unlikely, in practice, to have a Classless Inter-Domain Routing (CIDR) class A network available within an IPv4 address space. However, well above 24-bits, typically 64-bits, of entropy would be available when using IPv6 addressing. The random guessing with repetition strategy follows the binomial distribution and again is verified through the experimental results obtained. As shown in Figure 9.8, the adversary gains a better than 50% chance of success when allowed more than 2^{23} attempts. This is much improved from the application port randomization technique, however as previously mentioned, it is difficult to obtain a CIDR class A address space with 24-bits of entropy available within an IPv4 environment. Conversely, within an IPv6 deployment, IP randomization becomes much more valuable since the IP space is much larger at 128 bits.

The expected number of probes required for an adversary to successfully discover the 24-bit host portion of the IP address behaves similarly to the port randomization. For the random with repetition strategy, the binomial distribution curve matches the experimental data captured. The average number of probes needed for an adversary to find the randomized source and destination IP addresses, when only considering the success cases, is summarized in Figure 9.9. In the binomial distribution, the average attempts needed until success continue to grow until the expectation value is approximated, in this case, when there are $\geq 2^{24}$ probes allowed by the adversary:

$E(X) = \frac{1}{p} = \frac{1}{\frac{1}{2^{24}}} = 16{,}777{,}216$

When the adversary is allowed to make attempts beyond the expectation value, the success rate of finding the randomized source and destination IP addresses remains constant.

The remaining strategies evaluated all follow the hypergeometric distribution and the average grows until the expectation value is approximated. The expected number of guesses until success for the remaining strategies is thus $\geq \frac{2^{24}+1}{2}$ probes. If the adversary is allowed additional attempts beyond the expectation value, their success rate will again remain constant. The defender should limit the adversary well below the expectation number of probes when deploying each MTD technique. The result of the expectation value leveling out the experimental data captured can be seen in Figure 9.9.

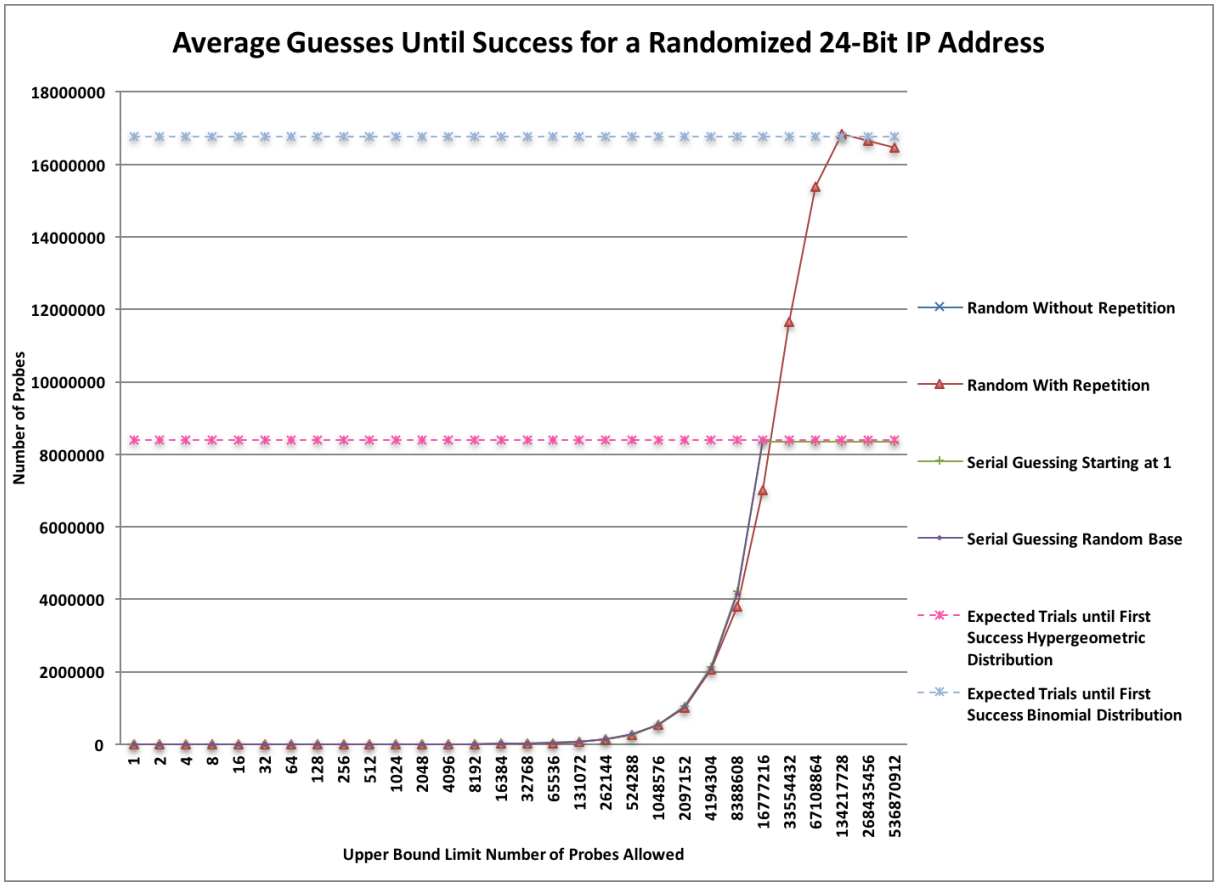


Figure 9.9: The expected number of attempts to randomly find a 24-bit number (a CIDR class A IP address) using different guessing strategies given a limited number of probes.

9.3 Path Randomization Overhead Cost

We implemented the path randomization technique by first capturing the network topology and configuration. The topology and configuration knowledge required to initialize

the path randomization algorithms are the IP addresses of each host, the connections of each host, the ports of the SDN switches, and the datapath identifiers that uniquely identifies each SDN switch in the network. The next step was to learn all possible paths between each of the pairs of nodes using the Breadth First Search (BFS) algorithm [132] on the network topology. Once all possible paths are known, the SDN controller then selects each of the paths randomly from the exhaustive list of all paths and install the appropriate flows to activate those paths so that all endpoints can communicate. The randomized paths remain active for user configurable intervals at which point a new randomized path is installed. The intervals for the results shown as part of our research are configured to install new random paths every 10 seconds.

The path randomization MTD approach introduced the most latency of the three chosen MTD techniques, as shown in Figure 9.10. The RTT increased from 50 ms in a normal configuration to 61 ms with path randomization enabled. When we enabled path randomization, data transfer rates and bandwidth rates were not affected but these parameters are usually not of concern in ICS settings since these networks typically communicate small messages. The time to transfer a 1 MB file had the largest increase in time from 70 ms using traditional switches to 100 ms when path randomization was enabled within an SDN deployment.

The delays observed are attributed to the additional hops that are taken in the randomly-chosen path that go beyond the optimal path in the network. In practice, this technique would have to be throttled, similar to a QoS type of service to meet the potential real-time constraints of the system that the technology is being applied towards. One of the main goals of this MTD strategy is to prevent an adversary from discovering the endpoints within a network by performing traffic analysis. The path randomization implementation was developed using the POX controller since we developed these algorithms in the early stages of our research. We also implemented the IP and port randomization schemes in the POX controller to compare the same metrics against the path randomization metrics.

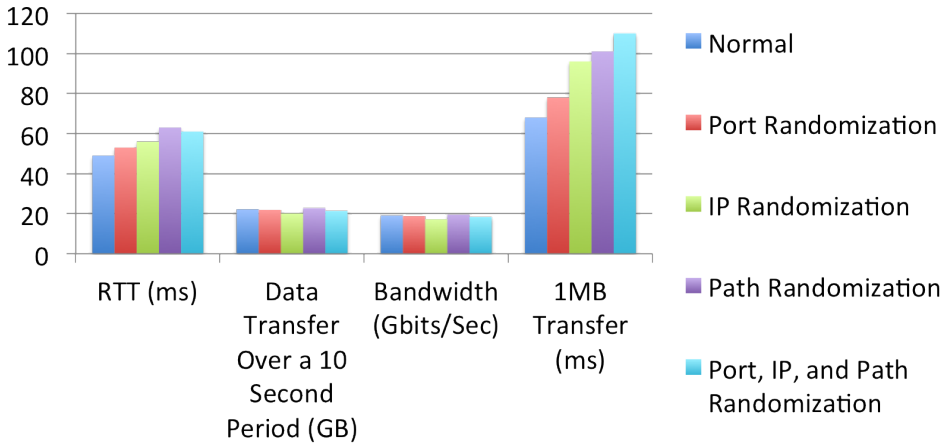


Figure 9.10: Performance metrics of a normal network without randomization techniques introduced, with the three randomization algorithms implemented independently, and finally with all three algorithms combined and applied.

Our goal was to further reduce the overhead costs of each of the MTD techniques, which the OpenDaylight controller satisfied as is shown later in Chapter 10 in Figure 10.7. The path randomization algorithms can also be developed so that only a specific or a limited set of desired paths are available to the defender to deploy, but this feature was not included as part of our research. This could help support load balancing and could also enforce a QoS policy to meet the requirements of the given environment.

9.4 Port, IP and Path Randomization

We combined the proof-of-concept POX and OpenDaylight implementations of the three randomized schemes into a single solution. We set the period of time to re-randomize each MTD defense to 1 second intervals and the SDN-capable switches were all synchronized together in time. This implementation choice of synchronizing the MTD techniques simplified the process of gathering consistent performance metrics across multiple trials of experiments. For example, if two of the three MTD techniques re-randomized at different points in time, the results would vary from one run to the next. Since all three implementations are synchronized to re-randomize at the same time, the results are repeatable. We have also compared the performance metrics collected against a baseline network without any randomization applied. The results are shown in Figure 9.10.

The RTT is the round trip time retrieved from sending an Internet Control Message Protocol (ICMP) ping message from one host to another and receiving back a response. The baseline network without any of the MTD techniques enabled was the fastest, followed closely by each of the individual MTD schemes enabled. The differences when each MTD technique is individually enabled and disabled is the time it takes to lookup the random port mappings, the time to overwrite the source and destination IP addresses, the time to take additional hops through the network, and the management overhead of the algorithms in a single centralized POX or OpenDaylight controller. The amount of data transferred, in the second set of measurements, which we measured over a ten second period were similar for each of the scenarios evaluated. The large amounts of data transferred that we observed are due to the small scale network that mininet simulated, all residing on a single machine with minimal network latency. Also, the Open vSwitch instances did not have to ARP to repopulate internal tables to learn the locations of the systems in the network which saved time when comparing against traditional switches. The bandwidth reported also had similar results to the data transferred over a ten second period. The 1 MB file transfers varied in latency when combining the three randomization schemes. Port randomization increased in time because of the management required to maintain and remap application port numbers within *iptables*. The IP randomization further increased in time due to the fact that each packet had to be matched for the source and destination IP addresses and the source and destination IP addresses had to be rewritten if a match was made. The path randomization scheme, individually, increased the most due to the additional hops required to be taken through the network. The combination of all three randomization techniques yielded the largest amount of time increases required for an attacker due to the cumulative overhead costs of each independent technique combined. The metrics we collected, outside of the RTT, were produced using the $iperf3$ tool.

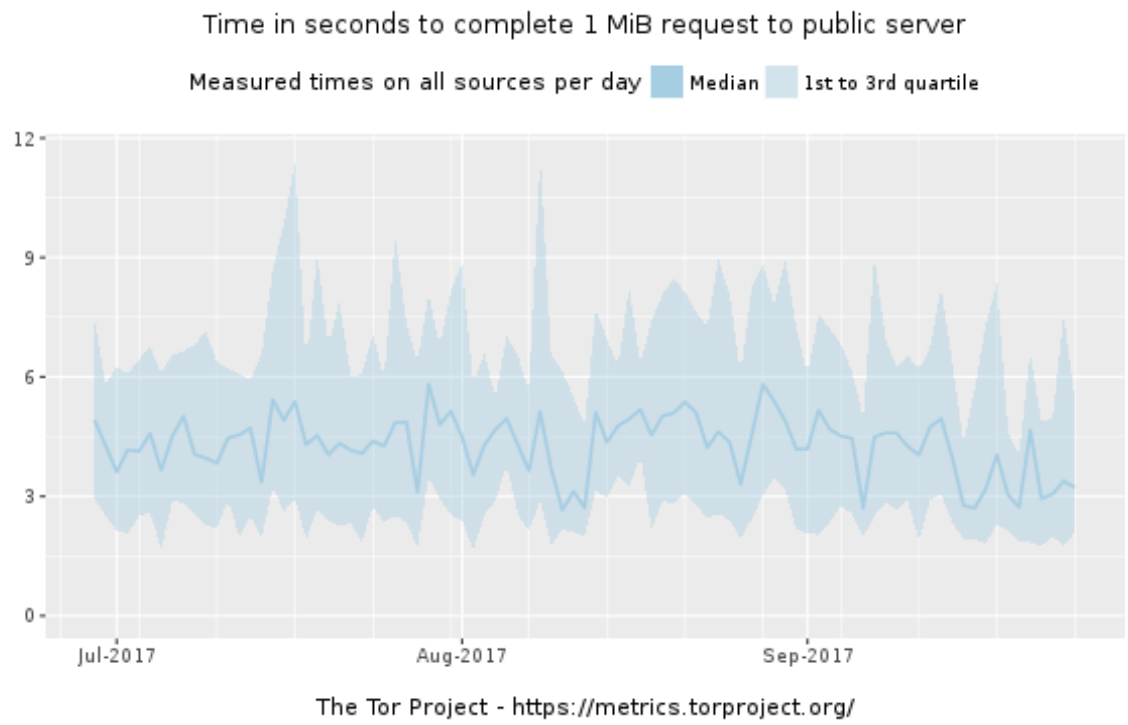


Figure 9.11: Performance metrics when transferring 1 MB files within the Tor network over a three-month period of time.

Although the performance was impacted for each individual approach (as well as the combined approaches), the transfer times of a 1 MB file are still faster than the average rates that the Tor project is reporting, shown in Figure 9.11. Tor is a traffic anonymizer which is an alternative to introducing IP randomization into a network. Tor is reporting approximately five seconds to complete a 1 MB transfer on average, while the randomization schemes proposed as part of our research are all completed for the same transfer in under one second. This difference comes from the fact that Tor requires additional processing time for the extra hops taken in the Tor network plus the encryption and decryption overhead of each encapsulated portion of a packet. The Open vSwitch instances must only make a match on the fields within the header of a packet, then potentially rewrite the source and destination IP addresses, and finally forward the packet. The Open vSwitch costs shown as part of our research are much lower than the cost of an encryption or decryption routine that the Tor tool is reporting.

9.5 Summary

The virtualized environment we developed served as an intermediate step between the simulated and representative environments. It was not known that we would have access to a representative environment until later in our research, so we developed a virtualized environment. We created virtual machines with the necessary software installed to create a virtualized SDN network with the MTD techniques built-in. We then captured operational metrics to evaluate the impacts to latency, bandwidth, throughput, and to a communication channel using the Modbus protocol. We observed the latency impacts of IP randomization to be within 1.2 ms of the baseline latency impacts. This increase in time is well within the constraints of a typical ICS environment, which are between 12-20 ms. Although most ICS systems are not bandwidth and throughput driven, we captured these metrics in the event that there are large bursts of traffic, such as when synchrophasor data is being communicated. We measured the decreases in bandwidth and throughput when IP randomization was enabled which both had the same 1.79% decrease in performance. The percentages are not large and show the potential for these concepts to be applied within other environments outside of ICS. We observed the impacts on Modbus communications to drop by 5.67% on the number of reads and writes that could be performed.

We again evaluated the four types of adversaries and we observed similar results as the simulated results, but this time using virtual machines. It was verified that the adversary would have to search, at a minimum, half of the attack space as was shown in the simulated results. We also measured the application port number, IP address, and communication path randomization schemes individually and in combination of each other. The MTD scheme that incurred the largest amount of latency was the path randomization scheme. This is due to the fact that the optimal path is not guaranteed to always be taken in the network. The time for the additional hops taken in the network increased the latency but also help prevent an adversary from correlating endpoints based on traffic analysis. The path randomization technique can also be further developed to restrict the

maximum number of hops taken to provide QoS guarantees to the users of the network who depend on real-time communications to operate. We observed that each of the MTD techniques applied were feasible and well within the bounds of many ICS systems within our virtualized environment.

Chapter 10

Representative Environments

We developed two representative environments to test and evaluate the MTD techniques discussed previously in order to model different operational environments. The primary goal is to capture effectiveness measurements of the MTD protections while also accounting for the operational traffic and processes running together that are difficult to reproduce in simulated and virtualized environments. The two test environments include the DETERLab testbed and an ICS testbed developed with both virtual and physical devices that interact with each other. The DETERLab testbed provides physical systems and network equipment that security researchers can allocate, customize, and configure for security experiments. The environment is in a controlled isolated network so that the tests can be made repeatable. The second environment is an ICS environment that is also customizable and includes both physical and virtualized systems within the network. The environment modeled is a virtual power plant that consists of ICS end devices and protocols frequently deployed in operational ICS networks. Each environment and the test results will be described in the sections that follow.

10.1 DETERLab Testbed

The cyber DEfense Technology Experimental Research Laboratory (DETERLab) testbed hosts a network of physical computers and network devices where approved security researchers around the world can test and evaluate new security technologies within a controlled environment. The DETERLab testbed consists of over 600 physical computers

that can be allocated by security researchers to conduct computer security focused experiments. Each computer can further instantiate up to 23 virtual systems per physical system if larger experiments are needed. The computers vary in their processing power, available memory resources, disk size, and number of Network Interface Cards (NICs). The network link speeds vary in capacity with a maximum of 10 Gigabits per Second (Gbits/Sec) capable links. DETERLab[1], based on the Emulab framework, is operated by the University of Southern California (USC) Information Sciences Institute (ISI) for the purpose of performing security research experiments and is under active development. The DETERLab project is currently funded under the Department of Homeland Security (DHS) within the Science and Technology (S&T) Directorate.

The DETERLab was used to evaluate and analyze the tradeoffs between the increased amount of adversarial workload incurred and the increased amount of operational impacts imposed when IP randomization was enabled. We varied the frequencies at which IP addresses are randomized and also the number of adversaries attacking the IP randomization scheme. The systems allocated within DETERLab for the IP randomization experiments consisted of the following specifications:

- 2.13 GHz Intel® Xeon® CPU X3210 quad core processor
- 4 GB RAM
- 250 GB SATA Disk Drive
- Quad port Peripheral Component Interconnect Express (PCIe) Intel Gigabit Ethernet card
- Ubuntu 16.04 64-bit

We configured each of the link speeds to 100 Megabits per second (Mbps) for all network connections. In all experiments, the legitimate systems participating and supporting the IP randomization are referred to as "*operational* nodes". The systems attacking the

[1]DETERLab: `https://www.isi.deterlab.net/`

IP randomization scheme are referred to as "*adversarial* nodes". For each experiment, there are 4 *operational* nodes allocated to manage and run the IP randomization MTD strategy and there are between 1 and 65,536 (or 2^{16}) *adversarial* nodes that have the goal of defeating the IP randomization MTD scheme. We ran the experiments within the DETERLab testbed with up to 32 physical *adversarial* nodes. The experiments that had more than 32 *adversarial* nodes were simulated in our standalone system, since the simulated results from Chapter 8 were consistent with the DETERLab results. Another reason we chose to simulate the experiments that had more than 32 *adversarial* nodes allocated was because of the DETERLab testbed physical resource limitations on the number of nodes that had the same specifications at the time that the experiments were performed. DETERLab currently supports a total of 64 nodes with the specifications listed above, and each experiment was configured to allocate 4 *operational* nodes plus 2^n *adversarial* nodes, where $0 \leq n \leq 16$. Thus, the maximum number of physical nodes that can be allocated given the constraints of 2^n *adversarial* nodes plus 4 *operational* nodes are experiments that consist of 32 *adversarial* nodes and 4 *operational* nodes. An example of an experiment with 16 *adversarial* nodes and 4 *operational* nodes is shown in Figure 10.1 for reference.

In Figure 10.1, each experiment network includes links that connect all of the nodes to a single switch, labeled lan0. The switch supports the SDN technology to manage the flows within the network. The network flows are the rules applied to each SDN switch that are responsible for routing packets based on the criteria that is specified by the end user. In this case, the rules specify to first randomize the source and destination IP addresses and then to correctly route the packets to their destination. The system responsible for managing the network flows is called the SDN *controller* which is labeled as *nodeD* and is shown on the left side of Figure 10.1. The nodes labeled *nodeA*-*nodeC* are *operational* nodes that represent the end users that are connected to the network. In this case, all end users have a direct connection to the SDN *controller* so that IP addresses can be randomized and de-randomized as packets leave and enter their NIC, respectively. Each

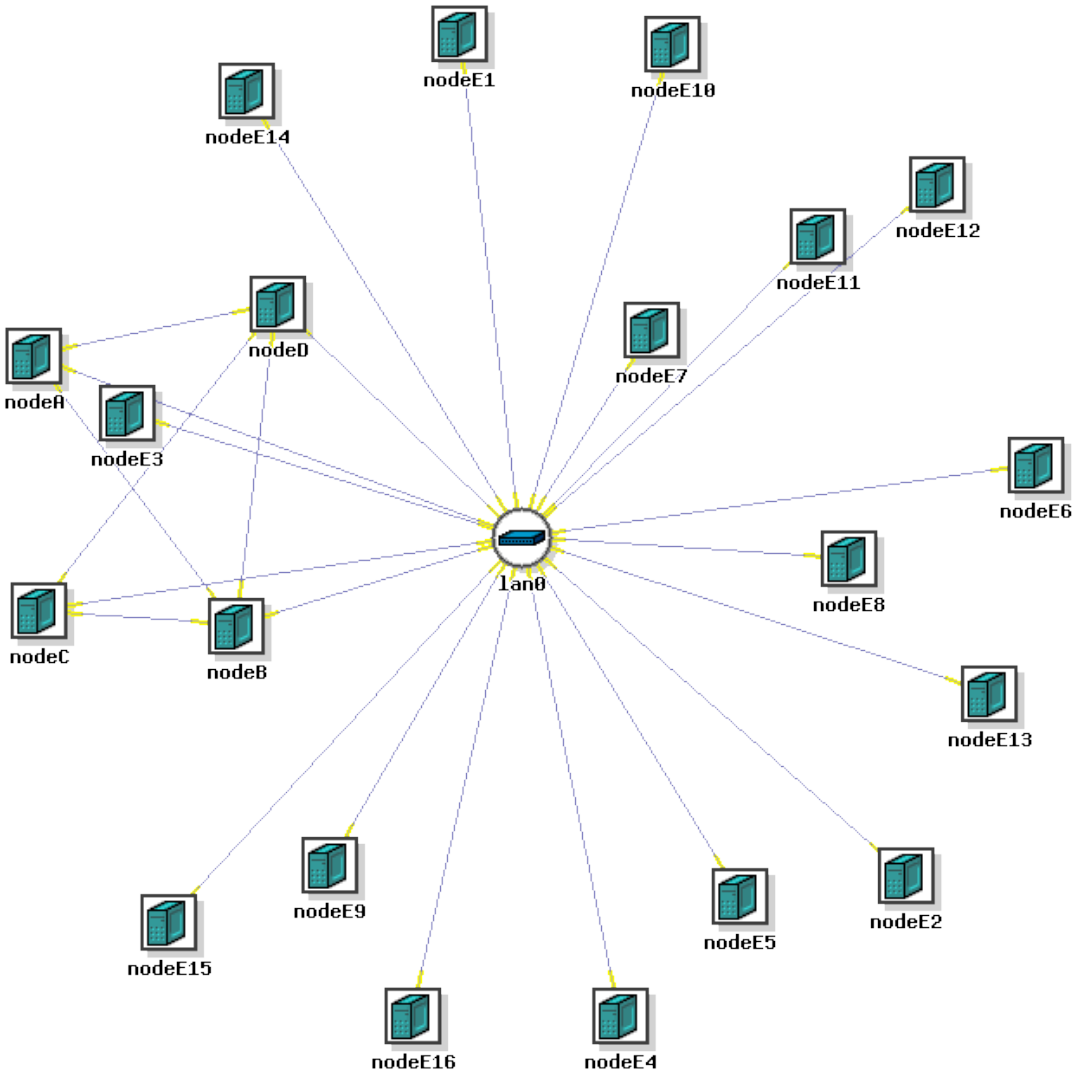


Figure 10.1: An experiment allocated within the DETERLab testbed consisting of 16 *adversarial* nodes labeled *nodeE*1-*nodeE*16 and 4 *operational* nodes labeled *nodeA*-*nodeD*.

of the *adversarial* nodes has the goal of evenly dividing up the IP space evenly between all adversarial nodes. Each adversary will then probe their appropriate partition of the network to attempt to determine all of the random IP address mappings of the nodes within the network. The network is configured as a CIDR class C network, leaving 8 host bits for randomization, while the remaining 24 bits are static and unchanged at each of the endpoints. The network bits are left unchanged so that routers could also be introduced into the network and the packets would still be able to reach their destination without requiring any changes to the existing routing algorithms.

10.1.1 Software Defined Networking

SDN is a technology that can be deployed to programmatically manage and control how computer networks operate and route packets. Within the SDN framework, management of the network(s) is achieved by separating the "control plane" (called the Southbound Application Programming Interface (API)) from the "data plane" (called the Northbound API). In traditional networks, these two planes are combined and hidden from the user and not accessible for modification. The separation of the two planes is done in a manner that is transparent to the end users of the network. The SDN framework allows users to programmatically define how network devices route and switch packets by installing network $flows$ directly into the network devices control plane. The network $flows$ result in *actions* that the network devices perform based on the match criteria that is specified by the network administrators. Each packet entering and leaving the NIC is inspected for a possible match, and if a match is successful, then the action is enforced. As an example. the actions may specify to send the packets out of a particular physical port of the network device, drop the packet, modify the packet fields directly, or a combination of the three.

In the SDN architecture, the *controller* is responsible for installing network flows into the SDN-capable network devices. The controller communicates over a TCP connection and can optionally establish a Transport Layer Secure (TLS) connection for secure communications to each of the SDN-capable network devices. The specific controller used for

the experiments within the DETERLab testbed was the OpenDaylight controller. OpenDaylight is an open source project that is under active development and supports the OpenFlow 1.3 protocol standard. The OpenDaylight controller communicates to each of the SDN-capable network devices via the OpenFlow 1.3 protocol and the OpenDaylight "Boron" release version 5.1 SR1 was used for this testing.

The SDN-capable network devices that we used were software implemented switches. Each of the *operational* nodes had the appropriate software installed so that the *controller* could communicate with them as if they were traditional network switches. The software switches used for this portion of research comes from the Open vSwitch project [133]. Open vSwitch version 2.6 was used because it communicates using the OpenFlow 1.3 specification which encompasses much of the SDN features including IPv4/IPv6 compatibility and IP modification actions. Previous versions of OpenFlow may not be compatible with commercial SDN products as many of them require the use of at least OpenFlow version 1.3.

10.1.2 Threat Model

Given the use of SDN, and the ability to randomize IP addresses, we assume that the goals of an intelligent and motivated attacker would be to commandeer the IP randomization scheme and inject spoofed packets into the network with a valid pair of *operational* source and destination IP addresses. The adversary may or may not wish to be stealthy depending on their objective. Additionally, the adversary must find the correct source and destination IP addresses before the IP addresses are again re-randomized at user defined frequencies. The adversary must correctly learn both the source and destination IP addresses since the network $flows$ installed at each SDN-capable network device must match on both addresses to correctly route traffic. The match criteria could be further restrictive by also matching on the physical port that the packet was received on in addition to the IP source and destination addresses. The extra match criteria would then require an adversary to tap into the link that is between the *operational* node and the SDN-capable network switch to succeed. The physical port was not specified as part of

the match criteria in each of these tests to simplify the DETERLab experiments that demonstrate the concept of an adversary injecting an unauthorized packet into the network. The adversary is assumed to have network access and an unlimited number of network probes to inject into the network. The adversary, again, is not required to be stealthy in this setup.

The adversary can take a number of approaches to accomplish their goals of correctly identifying randomized source and destination IP addresses within the network. One approach may be to leverage a side-channel attack to learn the randomization frequencies by observing and analyzing network latencies while randomization intervals are passing. After learning the randomization frequencies, the adversaries would know the amount of time required to discover the source and destination IP addresses of the *operational* nodes before the IP addresses are re-randomized again. Once the adversary determines the source and destination IP addresses, they can then craft and inject an unauthorized packet into the SDN-capable network device. When this strategy is combined with multiple adversaries attacking the IP randomization defense at the same time, the result is a DDoS attack with up to 65,536 total adversaries which significantly reduces the required amount of time for an adversary to learn the true IP address mappings. In the scenario of a DDoS attack, each adversary would evenly divide the attack space of possible IP address pairs and continuously probe the network devices individually until one of the adversaries successfully injects a spoofed packet with the correct source and destination IP addresses into the network. We performed experiments within the DETERLab testbed to evaluate the success rates of an adversary with varying IP randomization intervals applied.

10.1.3 Adversary Evaluation

We evaluated four adversarial strategies for their effectiveness in defeating the IP randomization defense. Each strategy was evaluated individually with 2^n adversaries, where n varied from 0 to 16. Additionally, we varied the IP randomization frequencies from never randomizing IP addresses to randomizing IP addresses every 0.5 seconds. The four adversarial strategies are based on the Request For Comment (RFC) specification 6056 [100].

Each of the strategies represents an adversary who does not gain any additional knowledge beyond a packet successfully or unsuccessfully being injected into the network, depending on if the correct source and destination IP address pairs were used. The *hping*3 tool was used to craft and inject spoofed ICMP echo request messages into the network. If an ICMP echo reply is observed in the network after the spoofed ICMP echo request is sent, then the adversary would know that the source and destination IP addresses were correctly spoofed, otherwise the IP addresses were incorrectly spoofed and they would make another attempt with a different source and destination IP address pair. We used the same adversary strategies that were presented for finding the application port numbers in Chapter 8 to find the IP addresses. The four strategies are summarized below, for reference, along with the specific attacks that we crafted according to each strategy.

10.1.3.1 Random With Repetition

The first strategy evaluated is meant to model an adversary with minimal resources available who is attempting to avoid detection by a defender that can observe patterns in the sequence of IP addresses being spoofed. For this strategy, an adversary would first craft an ICMP echo request packet with spoofed random source and destination IP addresses (selected uniform at random) and then inject that packet into the network. If that attempted packet injection fails to generate an ICMP echo reply from the spoofed destination system, then the adversary would attempt to randomly probe the network again with a new set of randomly selected source and destination IP addresses. The next random probe does not take into account the previous attempts that have already failed, so it is possible that the source and/or destination IP address will be repeated in this strategy. When there are multiple adversaries attacking the IP randomization defense, the IP address space is divided evenly into disjoint sets amongst all adversaries. Once a single adversary succeeds, the successful adversary sends a message to all other adversaries indicating success and for them to stop probing the network.

10.1.3.2 Random Without Repetition

The second strategy is similar to the first but does not repeat previously failed attempts of incorrect source and destination IP address pairs. To avoid repeating previous failed

attempts, an internal table is maintained with all possible source destination IP address pairs. A random permutation of that table is then generated and the adversary iterates through the table to inject packets with the current spoofed source and destination IP address pairs within the table. If the attempt fails, then the adversary injects a packet with the next pair of spoofed source and destination IP addresses into the table. This process is repeated until a packet is successfully injected into the network. When multiple adversaries are involved, the IP address attack space is again divided up evenly into disjoint sets amongst the adversaries. Each adversary follows the same strategy of first generating a random permutation of the disjoint IP address space assigned to them followed by probing the network with the current source and destination IP address pairs inserted into a ICMP echo packet. All adversaries follow this strategy and simultaneously inject spoofed packets until one of the adversaries is successful. An adversary knows when they are successful because they will receive an ICMP response back after the spoofed packet is injected into the network. If no successes are encountered before the adversary(ies) exhaust the permutation table, then a new permutation is generated and the adversary(ies) restart the process as before. This process continues until at least one adversary is successful.

10.1.3.3 Serial Probing

The serial probing strategy is another strategy that starts by initializing a 16-bit number to 0. The first 8 bits of the 16-bit number represent the source IP address and the second 8 bits represent the destination IP address. Packets are spoofed and injected into the network with the supplied source and destination IP addresses based on the value of the 16-bit number. The 16-bit number is continuously incremented until the correct randomized source and destination IP address pairs are found. If the correct source and destination IP address pairs are not found due to the IP randomization scheme re-randomizing values of source and destination IP addresses during the network probing process to a value that was previously attempted by the adversary, then the adversary will be required to restart the same strategy from the beginning. When there are multiple adversaries participating in a DDoS attack, the 16-bit number will be divided evenly into

disjoint sets amongst all adversaries, and the same process will be repeated until one of the adversaries succeeds in finding the correct randomized source and destination IP address pairs.

10.1.3.4 Serial Probing Starting at a Random Base

The final strategy is similar to the serial probing strategy, but instead of always starting the 16-bit number at 0, a randomly-chosen 16-bit value is chosen as the starting point. From the random starting point, the same process is continued where the adversary incrementally probes the network for source and destination IP address pairs sequentially by splitting the 16-bit value in half. If the source and destination IP address pairs are not found after exhaustively searching the entire attack space for IP addresses (due to the IP randomization scheme re-randomizing values to a previously probed source and destination IP address pair), then the adversary would restart the process by selecting a different randomly-chosen starting point. Similarly, if multiple adversaries exist, then the attack space for IP addresses would be divided into disjoint sets for each adversary to attempt to inject spoofed source and destination IP address pairs into the network. If a response is received after the spoofed packet is injected, then the adversaries would know that they have succeeded in spoofing a valid source and destination IP address pair. The same process would continue until one of the adversaries successfully discovers the correct randomized source and destination IP address pairs.

10.1.4 Results

We performed experiments within the DETERLab testbed using the previously described adversary strategies. These are, of course, not the only adversary strategies that can be developed, but these strategies were used as a baseline. Each experiment consists of *operational* nodes with IP addresses that are randomized and *adversarial* nodes that have the goal of discovering the randomized IP addresses assigned to a pair of nodes so that a spoofed packet can be injected into the network. Because an SDN deployment is used and flows are installed to match on both the source and destination IP addresses, the adversary must find the combination of both addresses in the spoofed packet to be successful. The experiments are performed so that an adversary continues to probe the

network using one of the four adversarial strategies until the correct source and destination IP addresses are found. Once the correct pair of IP addresses are successfully found, the number of attempted probes is recorded and the experiment is repeated for another trial. Each experiment is performed over 10,000 trials.

While each probe is being injected into the network, the IP addresses are at the same time being re-randomized periodically by the defender. The frequencies at which the IP addresses are being re-randomized by the defender range from never randomizing (the minimum frequency that can be chosen) to randomizing every 0.5 seconds (the maximum frequency chosen for our research). The specific intervals chosen for these experiments include re-randomizing IP addresses every 0.5 seconds, 5 seconds, 10 second increments starting from 10 and going all the way up to 260, and finally every 2^m second intervals where $0 \leq m \leq 20$. The number of adversaries is also varied for each randomization interval tested to evaluate the effects of a DDoS attack.

During a DDoS attack, the *adversarial* nodes will stop probing the network once a single adversary succeeds. Since DETERLab makes use of the Network File System (NFS), all *adversarial* nodes communicate, if they have succeeded, to the other *adversarial* nodes by writing a "1" to a specific file on the NFS share. Each of the *adversarial* nodes checks if this file has a "1" before injecting each new probe into the network. Once all *adversarial* nodes learn that one of the other *adversarial* nodes have successfully found the correct source and destination IP address pairs, they wait until they can synchronize with each other to repeat the same test in another trial. Each experiment was run through 10,000 trials to ensure that a high enough statistical significance was achieved to yield a 99% level of confidence with a $\pm$ $\sim$1.3% margin of error in the experimental results obtained. The formula used to calculate the statistical significance of a sample size needed to achieve a 99% confidence level with a $\sim$1.3% margin of error:
$n = \frac{z^2 \times p(1-p)}{e^2} = \frac{2.58^2 \times 0.5(0.5)}{1.29^2}$ =10,000
where n is the sample size, $z = 2.58$ is the normalized value of where 99% of the cumula-

tive normal distribution lies, $p = 0.50$ is the proportion of values above the mean number of probes, and $e = 1.29\%$ is the margin of error. The value of p was chosen as 50% since the distribution of the resulting number of probes needed until success is normally distributed and there is an equal chance that the number of probes will be either above or below/equal to the mean number of probes. The error rate was determined based on the number of probes, 10,000, that was used for the number of trials performed on each of the experiments.

Experimentally, we determined that each *adversarial* node can make approximately 310 probes per second with the given NICs of the DETERLab testbed. Each probe consists of crafting an ICMP packet, substituting in the spoofed source and destination IP addresses, and injecting the packet into the network. The links within the DETERLab testbed are all set to 100 Mbps. As the number of probes per second increases for the adversary, the time required until the first success occurs decreases.

10.1.5 Analysis

The adversarial strategies discussed above follow two distributions that we have validated by the test results within the DETERLab testbed and will be presented in this section. The random with repetition strategy follows the binomial distribution and the remaining three strategies follow the hypergeometric distribution. The binomial distribution fits the random with repetition strategy because probes are continually repeated, with the possibility of repeating previously failed probes, with a constant probability of $p = \frac{1}{65536}$ until a successfully spoofed packet with the correct randomized source and destination IP addresses is injected into the network. The hypergeometric distribution fits the remaining three adversarial strategies because failed probes are not repeated until a spoofed packet is successfully injected. In the hypergeometric distribution, the probability changes with each probe, slightly improving ($\frac{1}{65536}$, $\frac{1}{65535}$, $\frac{1}{65534}$, ...). The number of probes needed for each success follow the expectation curve for each of the adversarial strategies.

10.1.6 Binomial Distribution

The least successful of the four strategies evaluated was the random with repetition strategy. In this strategy, probes may potentially be repeated that have already been known to fail. This strategy follows the binomial distribution since the probability of success with each attempted probe does not change. Since there are 8 bits of randomness in each of the source and destination IP addresses, the total number of bits of entropy available are 16 bits. In this case, the adversary(ies) has a $\frac{1}{65,536}$ chance of success on each and every probe. If the entropy increased by using a CIDR class B network, the same curve would result, but requiring more attempts by the adversary until a successful randomized source and destination IP address is found.

The graph in Figure 10.2 shows the results of varying numbers of adversaries probing the network with varying frequencies of randomization on the IP addresses. We performed these tests within the DETERLab testbed. Each of the solid line curves represents a different number of adversaries probing the network and the average number of probes (per adversary) needed before their first success across 10,000 total trials. The dashed lines that follow the curve are the expectation curves that are validated from the experiments performed within the DETERLab testbed. Because the distribution here is binomial, it follows that the expected number of probes for the random variable x until the first success follows the formula:
$E(x) = \frac{1}{p}$

When a single adversary is probing the network, the adversary must probe the full 16-bit IP space before the first success is expected to occur. This is attributed to the fact that the probability is constant across all probes, in this case $p = \frac{1}{65,536}$, no matter how many probes have already been injected into the network. Thus, the expectation is $E(x) = \frac{1}{p}$ =65,536. When there are two adversaries probing the network, the IP space can be divided in half ($p = \frac{1}{32,768}$) making the expectation curve become $E(x) = \frac{1}{p}$ =32,768. As the number of adversaries double, the expectation constant curve requires half the

total number of expected probes per adversary. This process was repeated until there was a total of 65,536 adversaries, in which case only a single probe is needed by each adversary until a success is found since there is one adversary assigned to each of the possible IP address assignments.

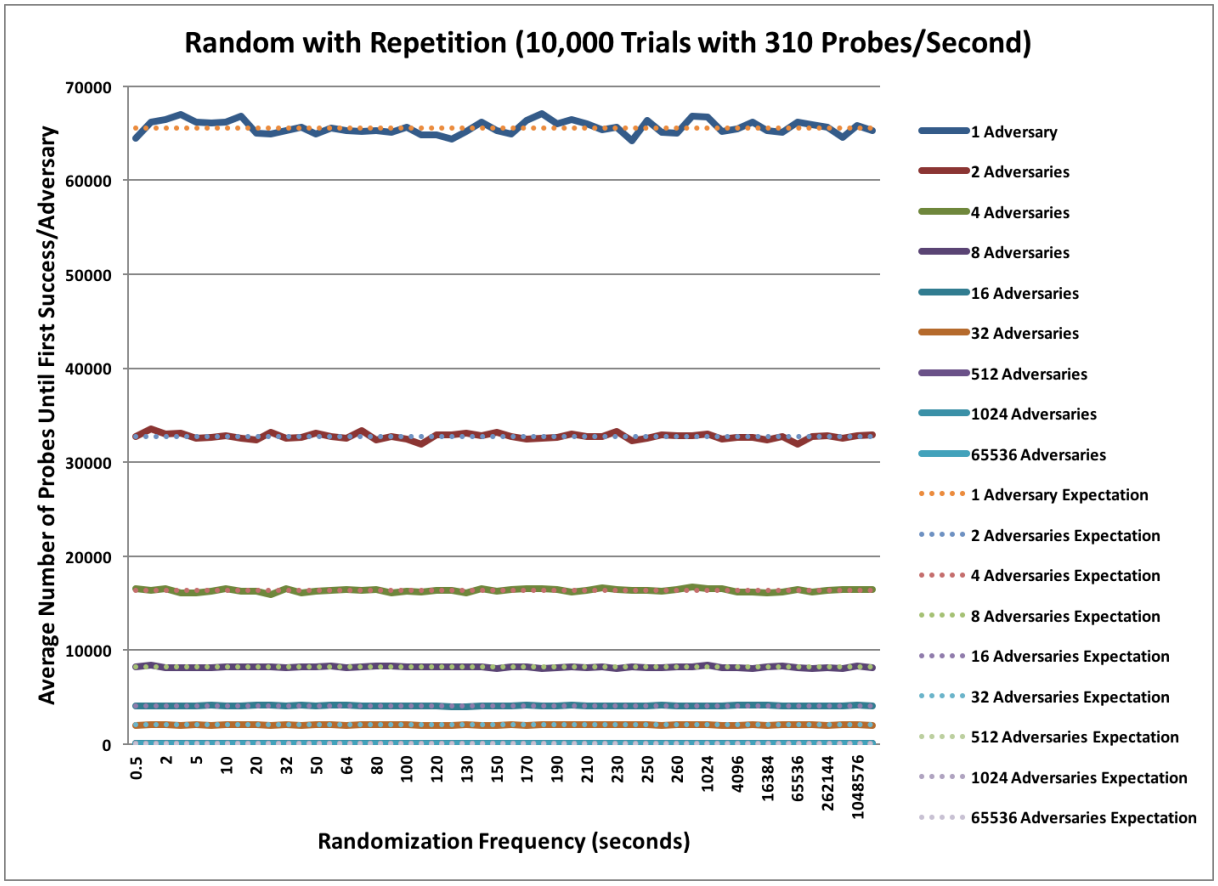


Figure 10.2: The solid lines represent the number of attempted spoofed packets that need to be injected into the network with varying frequencies of re-randomized IP addresses. As the randomization frequencies increase in time, the number of required attempted adversary spoofed packets before a successful packet is injected remains constant. The dashed lines represent the theoretical expectation results of the binomial distribution, which match the experimented data closely. Each of the curves represents the total number of adversaries, varying from 1 adversary to 65,536 adversaries. The frequency intervals vary from 0.5 seconds to a static configuration. We performed 10,000 trials with an adversary that was capable of injecting 310 packets per second in the test environment provided.

10.1.7 Hypergeometric Distribution

The most successful adversarial strategies followed the hypergeometric distribution. The probes of the adversaries in these strategies either repeatedly select source and destination IP addresses randomly without repetition, serially guess IP addresses starting from 0, or serially guess IP addresses starting at a random base. Since the definition of the hypergeometric distribution states that previous failed attempts are not repeated, it follows that each of the strategies fits the definition of the hypergeometric distribution. The graphs in Figures 10.3 - 10.5 show the results obtained from the DETERLab testbed. All of the graphs are similar to one another and are strongly correlated with each of the associated hypergeometric expectation curves, shown as dashed lines.

Focusing on Figure 10.3, the top curve shows the data obtained for a single adversary probing the network and attempting to inject a packet into the network with a forged randomly-chosen source and destination IP address. Since our experiments operate within a CIDR class C network address space, there are 8 bits of entropy for each of the source and destination IP addresses. Because the adversary must successfully guess the correct source and destination IP addresses in order to successfully inject a packet into the network, the problem is equivalent to an adversary finding a randomly-chosen 16 bit number without repeating previously failed attempts as shown in the simulated results in Chapter 8. If the adversary does not guess both correctly, the packet will be dropped since the network is an SDN based environment that requires flow rules to match both the source and destination IP addresses in order to route a packet. The values along the x-axis of the graph show the increase in the amount of time for the defender to re-randomize the current set of active IP addresses within the network. The y-axis shows the average number of probes needed by the adversary, over 10,000 trials, until the first successful packet is injected into the network. When randomizing IP addresses frequently (between 0.5 seconds to 10 seconds), the adversary must attempt $\sim$65,535 probes before the first success occurs (on average). As the defender randomizes IP addresses less frequently ($>$ 210 seconds), the adversaries' number of probes is cut in half to $\sim$32,768 (on average)

probes before the first successful packet is injected into the network. The curve is linear and is dependent upon the frequency at which an adversary can re-randomize IP addresses and the number of probes/second an adversary can inject into the network.

In the DETERLab testbed we observed that ∼310 packets/second can be crafted, forged with newly generated random source and destination IP addresses, and then injected into the network. These metrics come from the open source tool *hping*3. The network connections all operate with 100 Mbits/second capacity links. Therefore, when randomizing IP addresses every 0.5 seconds, the adversary is capable of injecting ∼310×0.5 ≡ 155 packets

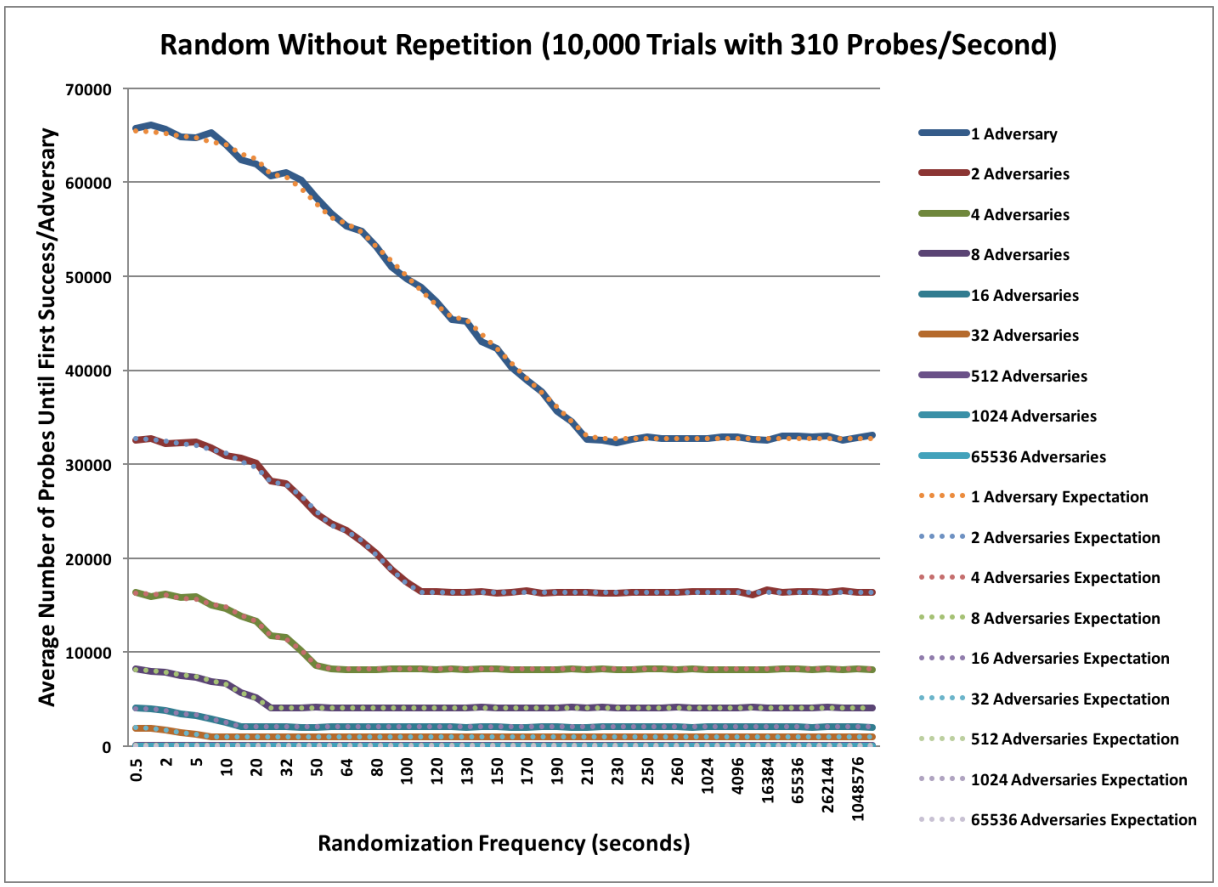


Figure 10.3: The hypergeometric distribution is followed when the adversary randomly spoofs the source and destination IP addresses until a success occurs without repeating previous failed attempts. The results captured experimentally match those of the expectation curve (dashed lines) when varying the number of adversaries and the frequencies at which the defender re-randomizes the network IP addresses.

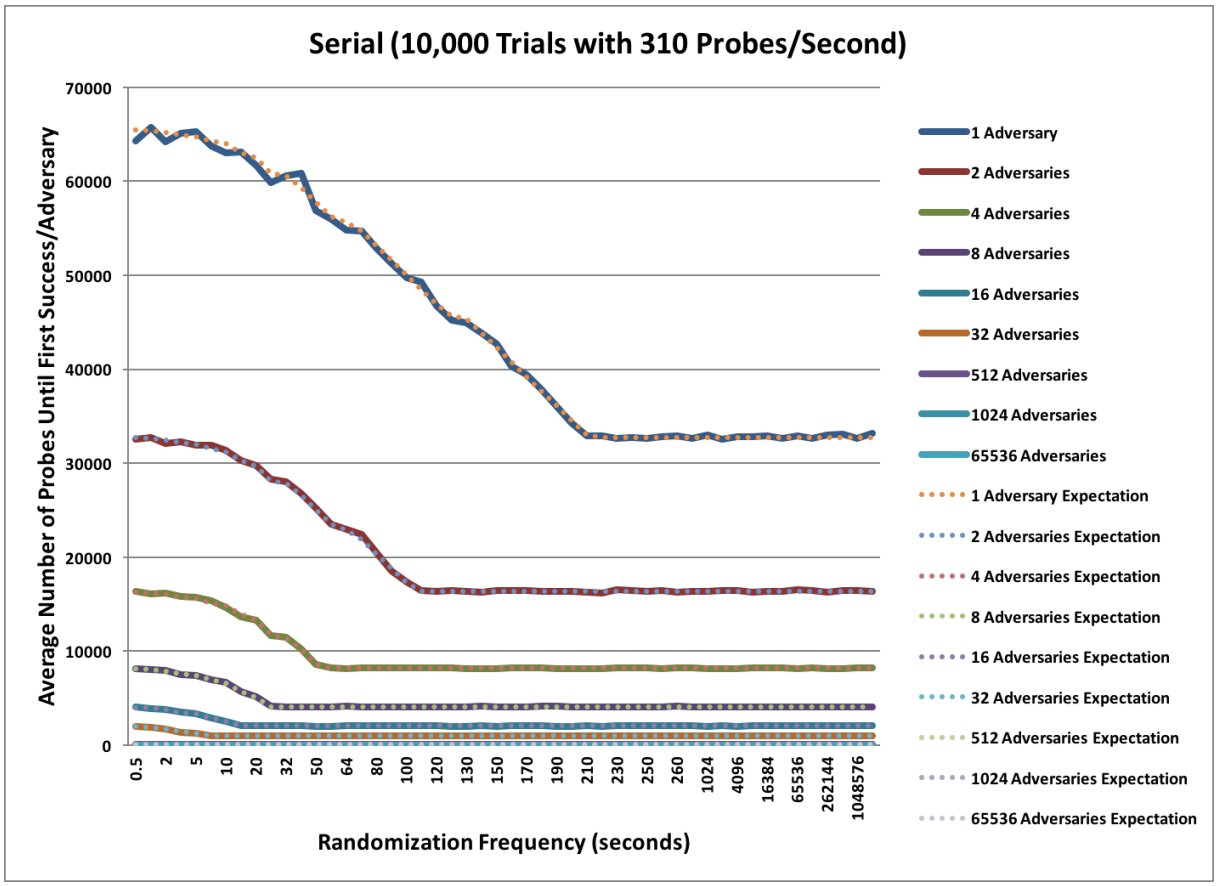


Figure 10.4: The hypergeometric distribution is followed when the adversary serially spoofs the source and destination IP addresses (starting at IP addresses X.Y.Z.0-X.Y.Z.255, where X, Y and Z are 8 bit octets of an IP address) until success. The results captured experimentally match those of the expectation curve (dashed lines) when varying the number of adversaries and the frequencies at which the defender re-randomizes the network IP addresses.

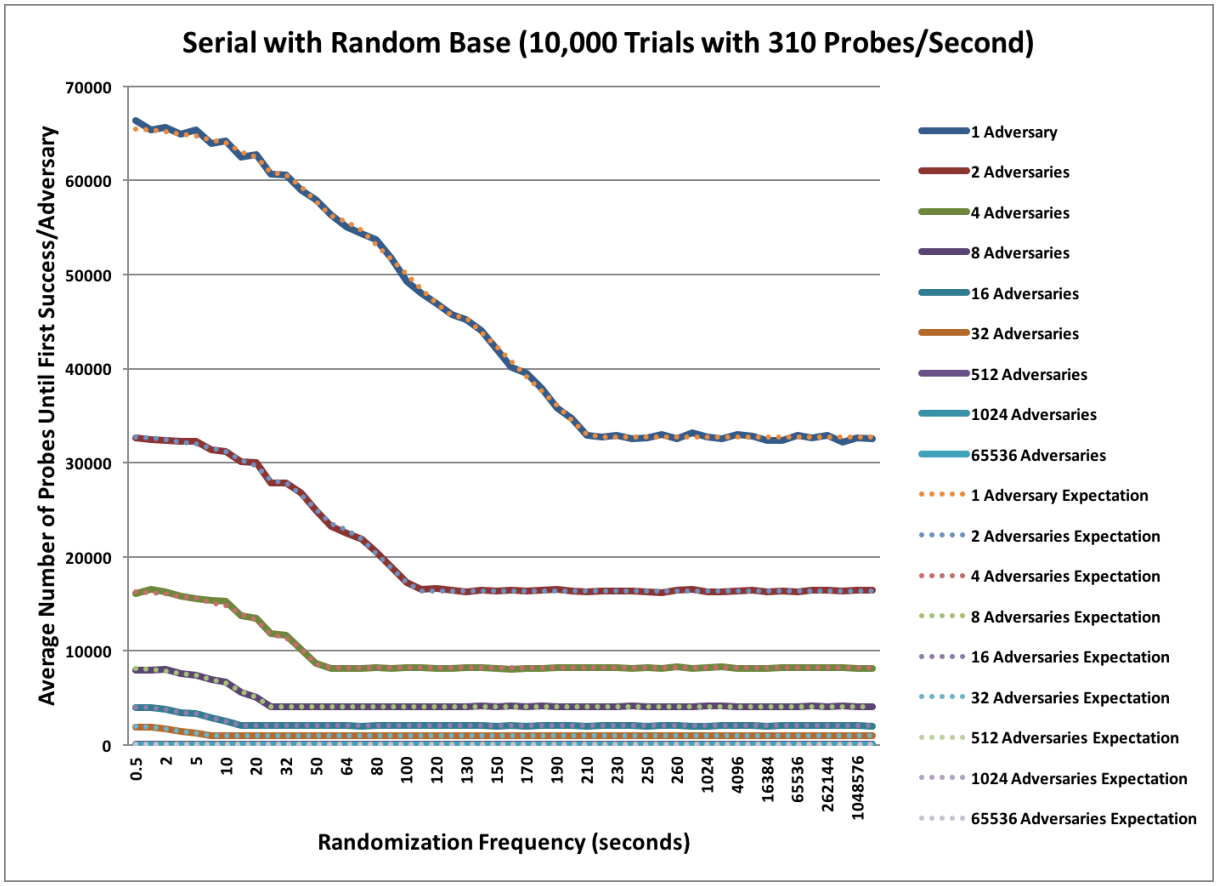


Figure 10.5: The hypergeometric distribution is similarly followed when the adversary serially spoofs the source and destination IP addresses (starting at IP addresses X.Y.Z.[random mod 256]-X.Y.Z.[random mod 256-1], where X, Y and Z are 8 bit octets of an IP address and random mod 256 is a randomly-chosen number between 0 and 255 through the modulo operator) until success. The results captured experimentally match those of the expectation curve (dashed lines) when varying the number of adversaries and the frequencies at which the defender re-randomizes the network IP addresses.

per second into the network. Given the expectation formula from the hypergeometric distribution, the first success would be encountered after $E(X) = \frac{N+1}{2} = \frac{65{,}536+1}{2}$ =32,768.5 probes, where N is the population/attack space. Since the adversary cannot make unlimited probes into the network before the IP addresses are re-randomized, the expectation formula must be modified to model the IP address targets that are periodically changing as well as the continuous stream of probes coming from the adversary. The probability of success, with a restricted number of probes before the IP address changes is $p = k/N$, where k is the number of packets injected into the network with spoofed source and destination IP addresses. Thus, the probability of failing to inject a packet with the correct pair of source and destination IP addresses given k probes is $\hat{p} = 1 - p = 1 - k/N$. To find the expectation of an adversary after repeatedly probing the network k times over and over again before the first success occurs, given that the IP addresses are re-randomized every k probes, the expectation function then becomes: the original expectation of the hypergeometric distribution plus the original expectation of the hypergeometric distribution multiplied by the number of failed attempts before the first success. The second part of the formula accounts for the number of failed attempts before the first success is found when limited to k probes before IP addresses are re-randomized. More simply put, the formula can be written as:

$E(X) = \frac{N+1}{2} + \frac{N+1}{2} \times (\hat{p}) = \frac{N+1}{2} + \frac{N+1}{2} \times (1 - k/N) = \frac{N+1}{2} \times (1 + \hat{p})$.

This expectation formula is shown in the curve as a dashed line in Figure 10.3. As shown, the expectation curve has a strong correlation with the data collected from within the DETERLab testbed. The shape and pattern of the curve continues regardless of the number of adversaries probing the network. The only change in the formula is the attack space since the adversaries are evenly dividing up the workload.

10.2 Virtual Power Plant

The Virtual Power Plant (VPP) environment, developed at Sandia National Laboratories [134], is a representative ICS system that includes several virtual machines as well as physical systems found within an ICS setting. The network topology of the VPP envi-

ronment is shown in Figure 10.6. The virtual machine systems are shaded in red and the physical systems are shaded in blue. The operating systems of the virtual machine instances we used were Linux Ubuntu installs running control system software. The network includes several inverters (systems that changes direct current (DC) to alternating current (AC)), power generators, smart meters, battery energy storage systems (BESS), servers that would be found within a control system, and the necessary routing and switching equipment for end devices to communicate over the network. We applied the IP randomization, port randomization, and fault tolerant algorithms towards this environment in order to measure the effectiveness of each MTD strategy within a representative ICS environment and to validate the simulated and virtualized results captured in Chapter 8 and Chapter 9, respectively.

In this scenario, we used the systems labeled as Engineering Workstation, Historian, SCADA Server, General HMI, and OPC to manage the MTD techniques. We placed the SDN controller instances on each of these systems to push and install flows to each of the SDN-capable switches in the network. The SDN-capable switches in the network were configured to be Open vSwitch instances. A wrapper program with knowledge of the network topology was written to communicate with the controller to install new flows into the network. The protocol used to communicate between the controller and the Open vSwitch instances is OpenFlow version 1.3.

We implemented each of the virtual machine instances in the environment as separate isolated virtual machines as shown in red. The physical systems and inverters that were connected with the virtual environment are shown in blue. The end hosts configured to communicate with each other in this scenario were the systems labeled as Inverters and the BESS systems. These systems communicated over the SDN and Open vSwitch fabric. This was done so that no additional configuration on the end hosts were needed and so that the solution could be transparent to each of the end hosts. The IP randomization was enabled, using IPv4 and IPv6 protocols. We then captured the performance metrics

while these systems communicated with one another in a similar manner to an operational ICS environment.

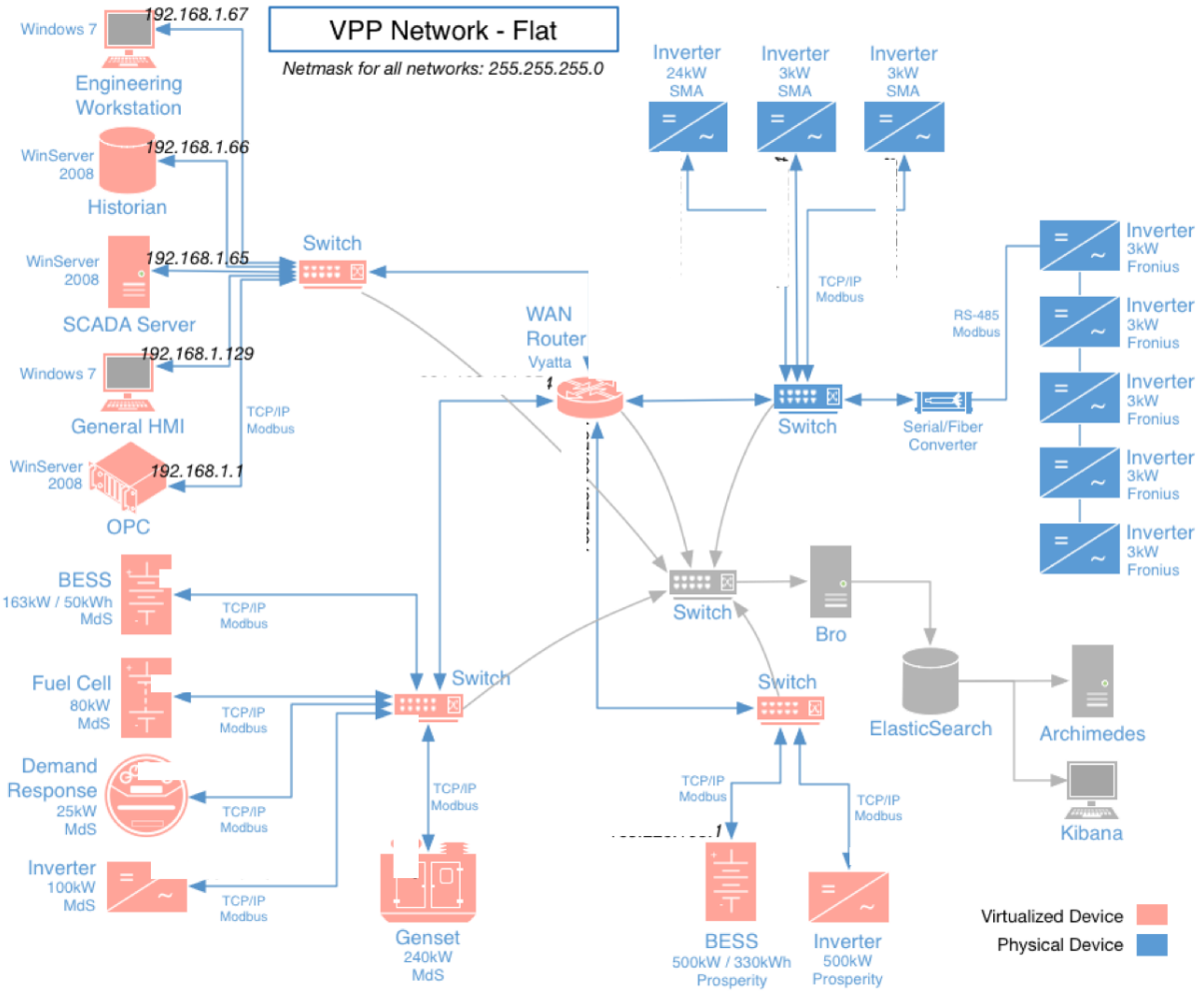


Figure 10.6: A representative ICS environment that combines both virtual and physical environments to model a power plant using ICS-based systems and protocols.

The second set of tests we performed to evaluate the resiliency of the controller were in the events of either a crash or a maliciously modified Open vSwitch instance to incorrectly route traffic to a location of the adversaries choosing. We applied crash tolerant and Byzantine fault tolerant algorithms to show that the single point of failure found in SDN deployments with a single controller could support failover controllers without downtime and with minimal impacts to the operational network. Performance metrics

were then captured to demonstrate the feasibility of applying the fault tolerant algorithms to improve the resiliency of the SDN controllers. The OpenDaylight controller was used for these experiments, but any controller could have been substituted as long as it implemented the OpenFlow 1.3 protocol. The Byzantine Fault Tolerant State Machine Replication (BFT-SMaRt) [135] algorithm was used to proxy the fault tolerant algorithms to protect the flows that were being installed from attempted compromises on any of the individual controllers.

We performed all experiments while the systems in the VPP environment continuously communicated with one another using standard ICS protocols including the TCP/IP Modbus protocol. We observed that the normal ICS protocol communications were maintained and simulated the same levels of communication seen within an actual operational ICS environment. Metrics such as bandwidth, throughput, latency, memory utilization, and CPU utilization were captured for each of our experiments. The primary metric of concern whenever any new hardware or software product is added to the system, in many instances for ICS, is the latency impacts. The other metrics captured also demonstrate the approaches are still usable in the rare cases where bandwidth and throughput are top priorities within ICS environments. An adversary was also deployed in the VPP to attempt to inject packets into the network by spoofing source and destination IP addresses and then submitting those packets to the Open vSwitch instances. We simulated both DoS and DDoS attack strategies in the VPP environment to measure the effectiveness of the MTD strategy deployed.

10.2.1 Metrics

We captured metrics when deploying IPv4, IPv6 and the fault tolerant algorithms within the VPP environment. The experiments we performed were done independently from one another to avoid skewed results. The results we captured were, again, strongly correlated to those obtained in both the simulated and the virtualized environments. The metrics we captured were focused on quantitatively measuring the amount of time required for an adversary to understand and reverse engineer the randomization algorithm mappings.

The adversarial strategies we applied determined the frequencies at which the defender should configure the MTD techniques to re-randomize the IP addresses to evade the adversary. We also captured metrics on the success rates of the adversary given a varying number of probes. These metrics can help support the defender in understanding the level of confidence that the adversary has in succeeding to inject spoofed packets into the network given the adversarial strategies applied and the randomization frequencies configured.

The adversaries follow the same threat model as described in Chapter 4. The adversary has the ability to observe network traffic and is capable of injecting traffic into the network, either via an SDN switch or a network tap. The adversary may also work in parallel with other adversaries to create a DDoS attack to more efficiently attack the system. The defender also has the ability to observe and react to noisy adversaries. This is handled by modeling the number of probes afforded to an adversary before detection. After a certain configurable number of attempts are made by the adversary, the defender has the ability to prevent the adversary from continuing to make progress in their exploits.

The results obtained help determine the feasibility of the MTD approaches being introduced into the ICS environments and also help learn the tradeoffs associated with each approach. We have parametrized each of the MTD approaches developed so that the MTD techniques negative impact on the operational ICS environment are minimized. The MTD parameters can be adjusted according to the unique sets of constraints and requirements that are required for each ICS environment. The implementations and results for each of the MTD approaches are described in the sections that follow.

10.2.2 IPv4

The VPP environment supports both IPv4 and IPv6 protocols. The majority of tests we performed using IPv4 addresses were consistent with the simulated and virtualized results. Additionally, we captured latency, throughput, CPU, and memory metrics for the IPv4 sets of experiments. In these experiments, we integrated physical switches such as the HP-

2920 and the SEL-2740 SDN capable switches into the environment to measure latency, bandwidth and dropped packets within a representative environment. We configured the switches to interoperate with the OpenDaylight controller and received flows with randomized source and destination IP addresses to be installed at each of the SDN-capable switches.

10.2.3 Operational Impacts

One of our primary goals in applying the MTD techniques to the VPP environment was to introduce a minimal or zero amount of additional latency into the system. High availability is typically the top priority for an ICS environment. We captured latency metrics within the VPP environment when varying the frequencies at which IP randomization occurs. The round trip times were also captured over a 1,000 second interval and those times were averaged separately for each of the randomization frequencies applied.

The results are shown in Figure 10.7. The randomization frequencies varied between a static environment (IP randomization disabled) to randomizing IP addresses as frequent as every 1 second. The static configuration of IP addresses without using SDN had the largest amount of latency out of the group of experiments that we performed. This has been attributed to the additional amount of time that is required to periodically communicate Layer 2 protocols, such as ARP, for hosts within the network and because the proactive (instead of reactive) flows are installed on each switch. With proactive flow rule installation, the flows being pushed to each of the switches is initiated by the SDN controller. If the SDN network was configured in a reactive flow rule installation setting, then the controller would be consulted on each packet received. The proactive flow rule installation process provides each switch, immediately, with the knowledge of how to route each packet received and is responsible for the speed-up observed. The SDN implementation did not have the overhead of looking up and populating an ARP table when sending and receiving packets. As shown in the metrics captured, the more frequent the randomization intervals become, the more delay there is on latency. Randomization intervals of 1 second resulted in a $\sim$0.65 ms delay whereas randomizing every 1000 sec-

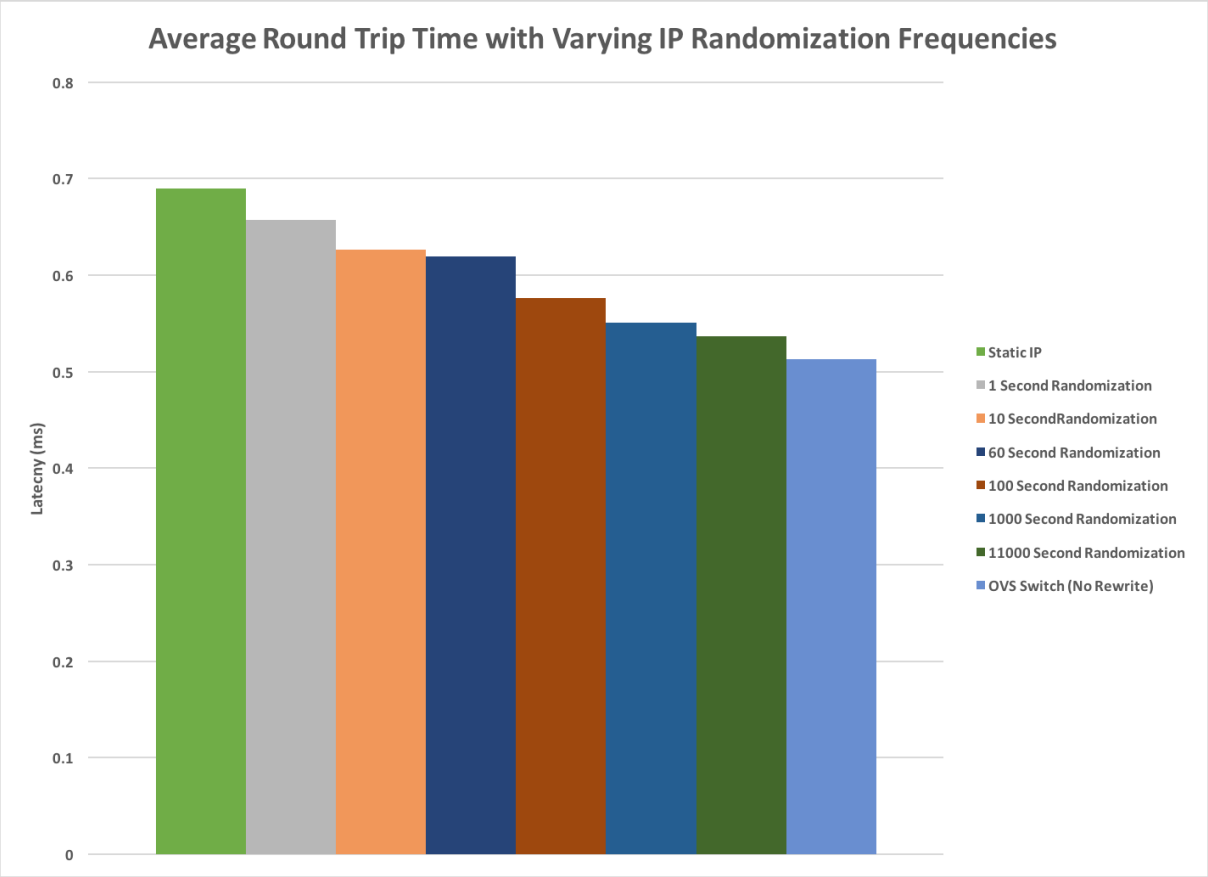


Figure 10.7: The latency impacts of varying the frequencies of randomization from a static configuration to randomizing once every second. As the randomization frequencies increase in time, the latency measurements decrease.

onds incurred a ∼0.55 ms delay. All results we captured were within 1 ms of each other which demonstrates the feasibility of these approaches to be applied within several ICS environments.

We also captured the TCP retransmits when varying the frequencies of randomization from a static configuration to randomizing once every second as shown in Figure 10.8. The retransmits were captured over a 10 minute interval where 500,037 packets in total were transmitted. In general, as the randomization intervals increase, so do the rates of TCP retransmits. The number of retransmits are attributed to the workload placed on the Open vSwitch (OVS) instances during the randomization intervals where flows were being added, removed, and updated.

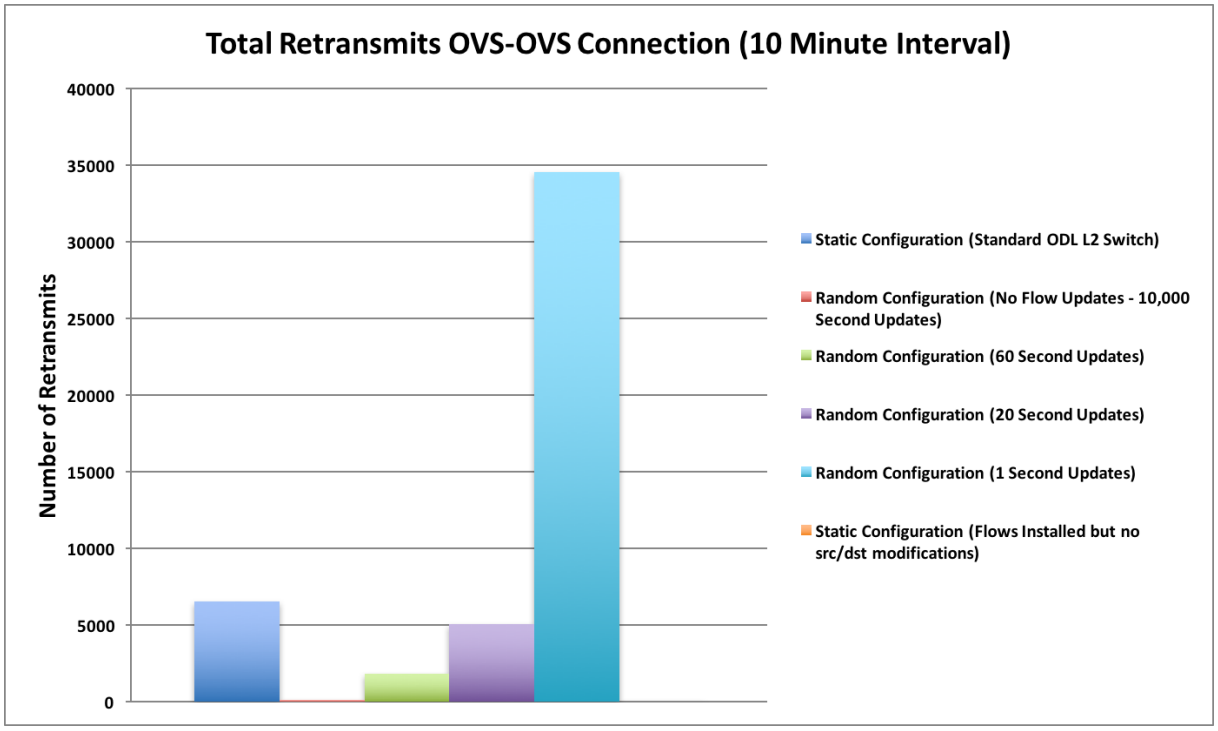


Figure 10.8: The TCP retransmits we captured when varying the frequencies of randomization from a static configuration to randomizing once every second. As the randomization frequencies increase in time, the number of retransmits also increased. A total of 500,037 packets were transmitted in each of the tests over a 10 minute interval. The resulting percentage of retransmits were ∼6.84%, ∼1.01%, ∼0.36%, ∼0.03%, and ∼1.30% when randomizing every 1 second, 20 seconds, 60 seconds, 10,000 seconds, and a static configuration, respectively.

For each of these metrics, two hosts (the BESS and the Inverter in the bottom left of Figure 10.6) were communicating with one another through two Open vSwitches. All other systems within the VPP environment continued to communicate with one another normally to increase the load on the network. The network continued to operate as expected throughout these experiments and we observed no interruptions in connectivity between any hosts within the network while the IP randomization strategy was enabled. The IP randomization technique was configured to re-randomize source and destination IP addresses every 1 second. An overlap window of 10 seconds was configured so that each flow would remain on the Open vSwitches for an additional nine seconds after the 1 second period that they were active. After the 1 second active period expired, a new flow

with a new random source and destination IP address pair was installed. This was done to accommodate packets that were still in flight during the time a flow update occurred containing new random source and destination IP addresses. If packets with previous random IP address mappings are in flight while new mappings are being installed, the old flow rules remain available on each Open vSwitch instance so that they can still appropriately route the packet to its final destination for a user configurable period of time, if needed.

10.2.3.1 HP-2920

The HP-2920 is a commercial SDN capable switch that is publicly available and has been shown to successfully operate within cloud based environments [136]. We have performed an evaluation of the effectiveness of applying the MTD techniques towards the HP-2920 within an ICS environment. The HP-2920 supports the OpenFlow 1.3 protocol with 20 gigabit ports. The switch was evaluated in the test environment described above and substituted in for one of the Open vSwitch instances in Figure 10.6. The HP-2920 switch works by processing the flow rules in software when any packet modifications are desired. The processing of the flow rules in software is performed on flows that have action rules that go beyond simply forwarding packets out of a port. For example, rewriting source and destination IP addresses would be performed in software since those flows make packet modifications before forwarding the packet. Flows that only forward packets out of a port are processed in hardware with significant performance improvements.

We measured the performance impacts of the software based implementation when the IP randomization MTD technique is enabled. A comparison when two Open vSwitch are routing traffic versus when an Open vSwitch and an HP-2920 switch route traffic has been performed. Varying the frequency of randomization from a static configuration to a 1 second randomization interval is shown in Figures 10.9 and 10.10. All frequencies are within 10 ms of each other and are well within the bounds of an ICS environment.

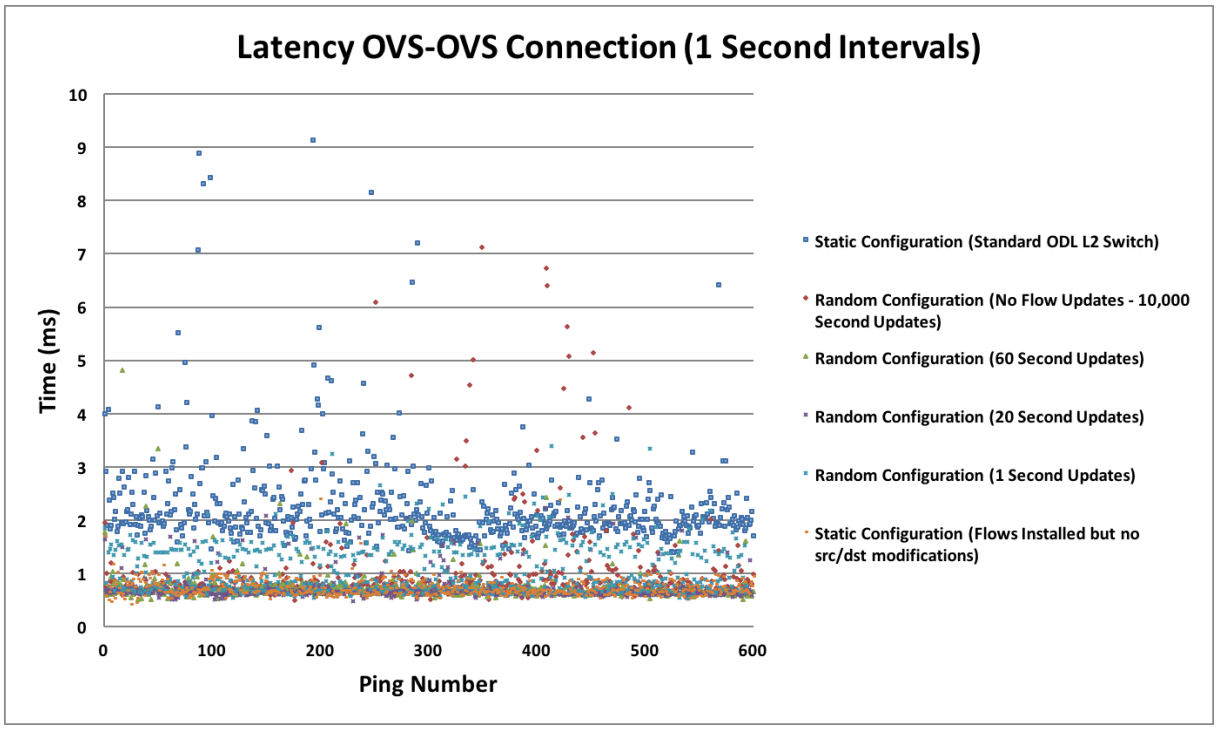


Figure 10.9: We captured latency measurements when sending traffic between two hosts using two traditional switches forwarding traffic in the middle. Latency measurements were also captured when two Open vSwitch instances replaced the traditional switches with varying randomization frequencies of IP addresses.

The traditional switches, labeled "Static configuration (Standard ODL L2 Switches)" incurred, on average, 2.309 ms of latency when using two Open vSwitch instances and, on average, 1.562 ms of latency when introducing the HP-2920 switch. The HP-2920 switch improved the latency metric in this case because the switching is performed in hardware. When focusing on the data points obtained when the SDN configuration was initialized to route traffic and matching rules are made without source and destination IP address rewrites performed (the data points labeled "Static Configuration (Flows installed but no src/dst modifications)"), the HP switch begins processing packets in software because flow matching is performed on IP fields instead of MAC addresses only. The average latency for the two Open vSwitches scenario is 0.740 ms and the average latency for the HP switch paired with an Open vSwitch instance is 4.404 ms, or a 494% increase in latency, on average. The Open vSwitch instances begin switching traffic faster in this scenario because ARPs are no longer needed to be communicated between endpoints. The increase

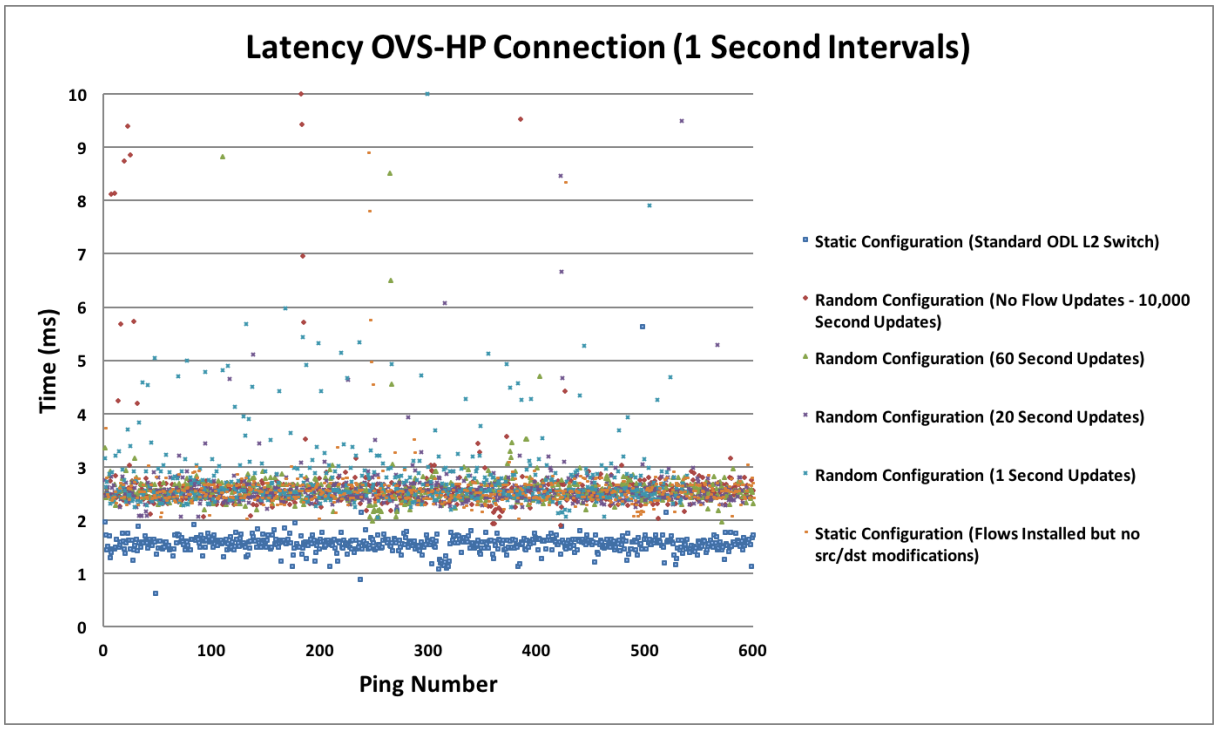


Figure 10.10: Latency measurements captured when sending traffic between two hosts with two traditional switches forwarding traffic in the middle. Latency measurements were also captured when one Open vSwitch instance and one physical HP-2920 switch replaced a traditional switch with varying randomization frequencies of IP addresses.

in time is not, however, significant enough, in this scenario, to impact an ICS network beyond the desired limit of 12-20 ms.

When randomizing IP addresses and rewriting source and destination IP addresses at 10,000 second intervals, the average latency when using two Open vSwitch instances is 1.026 ms and 4.714 ms when using one Open vSwitch instance with the HP-2920 physical switch. The 360% increase is again attributed to the software matching of the flow rules performed within the HP-2920 switch. When randomizing at more frequent intervals, the average latency for both cases of using two Open vSwitch instances or one Open vSwitch instance paired with one HP-2920 switch are similar. In the scenario where two Open vSwitch instances are deployed with randomization frequencies of 60 seconds, 20 seconds, and 1 second, the average latencies are 0.728 ms, 0.711 ms, and 1.091 ms, respectively. In the one Open vSwitch and one HP-2920 switch case with randomization frequencies of

60 seconds, 20 seconds, and 1 second, the average latencies are 4.366 ms, 3.941 ms, and 4.993 ms, respectively. The 1 second randomization frequencies have the largest impact on latency, but are still within range of the desired 12-20 ms.

10.2.3.2 SEL-2740

We evaluated another publicly-available, commercial switch, the Schweitzer Engineering Laboratories-2740 (SEL-2740) SDN network switch has been evaluated for latency impacts in a standalone network. The tests were performed on-site at SEL so the only tests performed at the time were latency tests and dropped packets. The Open Daylight controller was used and a secure Transport Layer Security (TLS) [137] connection was established between the controller and both of the SEL-2740 switches. The two SEL-2740 switches were directly connected to each other. Each of the SEL-2740 switches had several end systems directly connected to them and communicated using ICS specific protocols such as DNP3 and Modbus TCP.

We performed experiments with randomization frequencies of 60 second and 1 second intervals. In each scenario, we configured 100 Mbits/second links with separate tests performed using 1% and 99% link utilizations configured. With the 60 second randomization frequency configured and 1% link utilization, the latency introduced was 25.6 microseconds. When 99% link utilization was configured, the latency introduced was 80.6 microseconds. The large improvement in speed compared to the Open vSwitch and HP-2920 switches is attributed to the flows being processed in hardware as opposed to software.

When the randomization frequency was adjusted to 1 second intervals, the results were similar to those obtained when randomizing every 60 seconds. When the link utilization was set to 1% saturation, 25 microseconds of latency were incurred on the communication channel. When the saturation level was increased to a 99% link utilization, the latency increased to 87.8 microseconds. All latency metrics captured using the SEL-2740 switch, which is specifically tailored towards ICS environments, were well within the constraints

of an ICS environment. Given the results of less than 1 ms of latency, the SEL-2740 can be applicable to a wide range of environments that have even more strict latency constraints than a typical ICS environment.

We also examined the number of dropped packets in our experiments. The IP randomization, with all varying frequencies, did not cause any packets to be dropped. All switches evaluated including the HP-2920, the SEL-2740, and the Open vSwitch did not drop any packets during our experiments. This is an especially important metric within an ICS setting because dropped packets can have severe consequences. Dropped packets may cause delays or major outages within the power grid, depending on if TCP or UDP communications are used, respectively. These directly affect the general public and in some cases, such as when hospitals depend on the power grid and energy delivery systems, can be a cause for public health and safety concerns. This is one of the reasons why high availability is so important in ICS environments.

10.2.4 Fault Tolerance

The controller of an SDN network can be considered a single point of failure since it is responsible for managing and installed the flows that specify how packets should be routed on each of the SDN-capable network devices. If the controller fails or is compromised, then the SDN controller would no longer be able to communicate with the SDN switches and the MTD randomization would no longer continue to function. The network would then return back to a static configuration and would lose the benefits of the MTD protections. To protect against the SDN controller from becoming a single point of failure, intentional or not, we have designed fault tolerant algorithms into the SDN controller. The effectiveness of each algorithm has been measured using latency and bandwidth metrics experimentally captured within the VPP environment.

We integrated both of the crash tolerant and Byzantine tolerant algorithms into the SDN controller to protect it from having a system failure or from experiencing a compromise within the flow configurations. To ensure that an operational SDN controller will still

be available in the event of SDN failures, we integrated the Paxos algorithms into the SDN controller. The improved resiliency has been accomplished by allocating a cluster of controllers to serve as failover systems and also by having consensus agreements on the flows installed in the network. In this deployment, the single point of failure for the SDN controller is eliminated when the Paxos algorithms are applied to track the status of all of the controllers in the cluster. If an adversary is attempting to compromise the SDN controller with the fault tolerant algorithms enabled, they now must compromise a majority of the controllers in the cluster to be successful.

Similarly, we have integrated Byzantine fault tolerant algorithms into the SDN controllers to protect the flows that they are communicating to the SDN-capable switches in the network. In the event that one of the controllers is compromised and attempting to communicate false information to the other controllers of the cluster, the Byzantine fault tolerant algorithms will not only detect the false information but will prevent the other controllers from trusting the false information. The Byzantine fault tolerant algorithms can ensure a consensus agreement and can tolerate f failures when there are $3f+1$ controllers installed within the cluster.

The fault tolerant algorithms combined with enabling the MTD techniques in an SDN setting will have performance costs associated with them. ICS environments can only tolerate minimal amounts of delay to the operational network and any new technology introduced, including security protections, must be evaluated to meet the strict time constraints and requirements. We have captured latency, throughput, CPU, and memory measurements for each of the fault tolerant algorithms combined with the MTD techniques.

Figure 10.11 shows the VPP environment running as a traditional ICS network without the SDN framework, the MTD strategies or the fault tolerant algorithms enabled. The

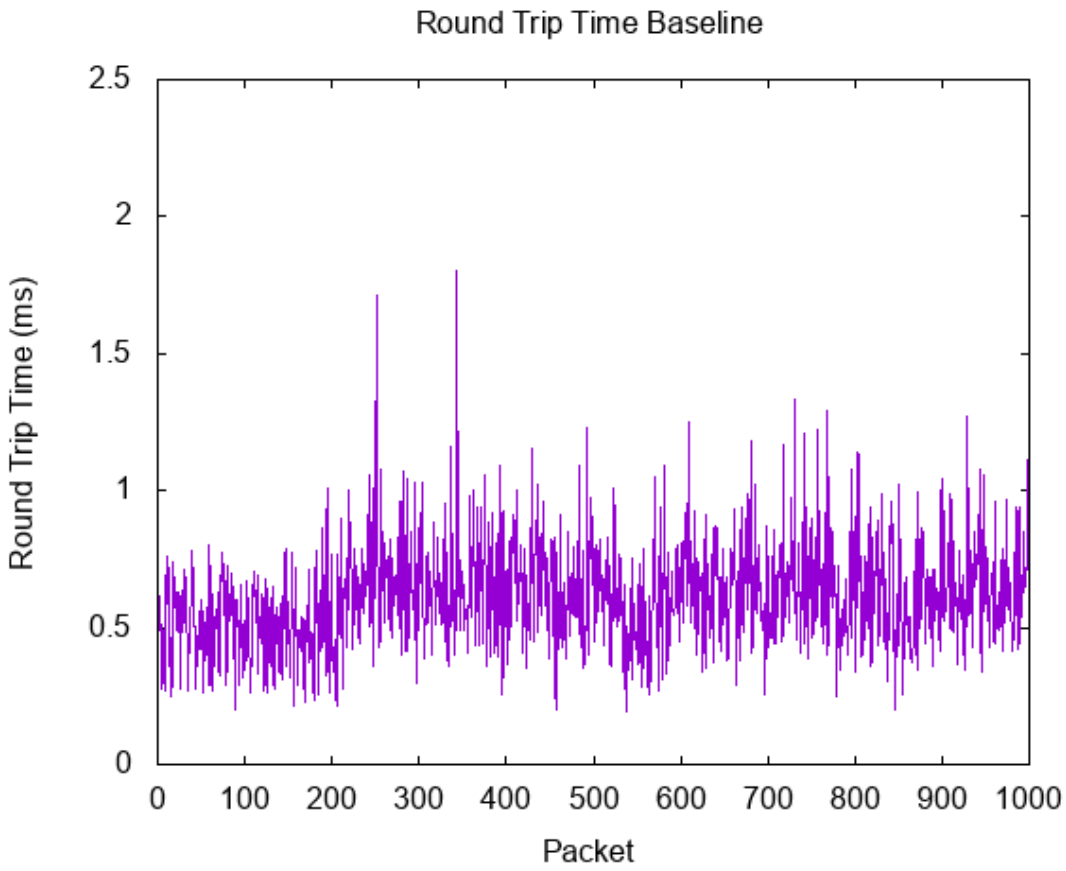


Figure 10.11: Latency metrics we captured within the VPP environment over a 1,000 second interval of time. We captured these results to measure a baseline for the VPP environment.

average latency measured experimentally over a 1,000 second period of time is 0.612 ms. We captured this baseline measurement of latency independently to compare against the latencies captured when enabling each of the security protections separately within the VPP environment.

Next, we captured performance metrics when the IP randomization techniques were enabled within the VPP environment. The latency results captured over a 1,000 second interval are shown in Figure 10.12. We configured the randomization frequencies to generate new random source and destination IP addresses every 1 second. The average latency over the 1,000 second period of time improved from the traditional network base-

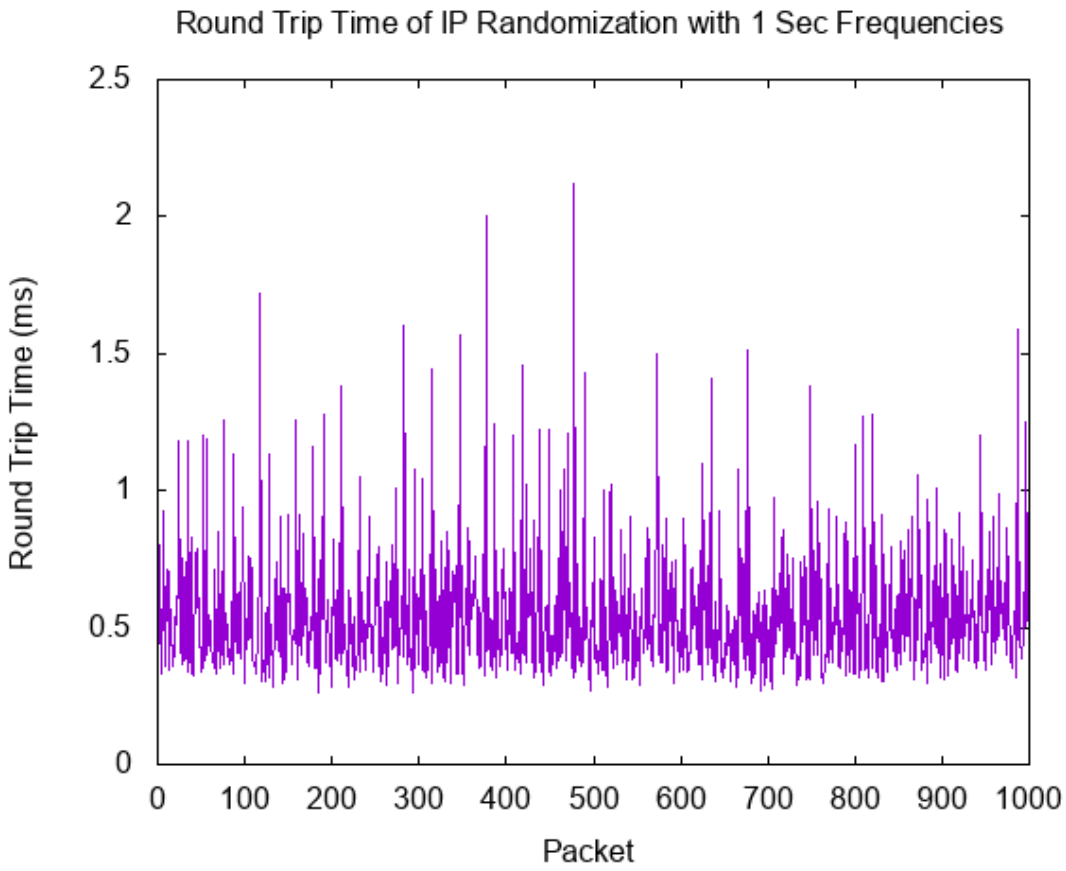


Figure 10.12: Latency metrics captured within the VPP environment over a 1,000 second interval of time. The results show the effects of applying an SDN framework combined with the IP randomization MTD technique.

line that was previously captured since the SDN network does not require ARP requests and replies to operate and because the proactive (instead of reactive) flows are already installed on each switch before each packet is first observed. The latency captured for the round trip time of an ICMP message was observed to be 0.546 ms, a 10.78% improvement in performance.

To determine the performance impacts of the fault tolerant algorithms, we enabled the crash tolerant algorithms and captured latency metrics within the VPP environment. Figure 10.13 shows the results that build on Figure 10.12 where the IP randomization technique is additionally enabled. In this case, we configured four controllers to be part

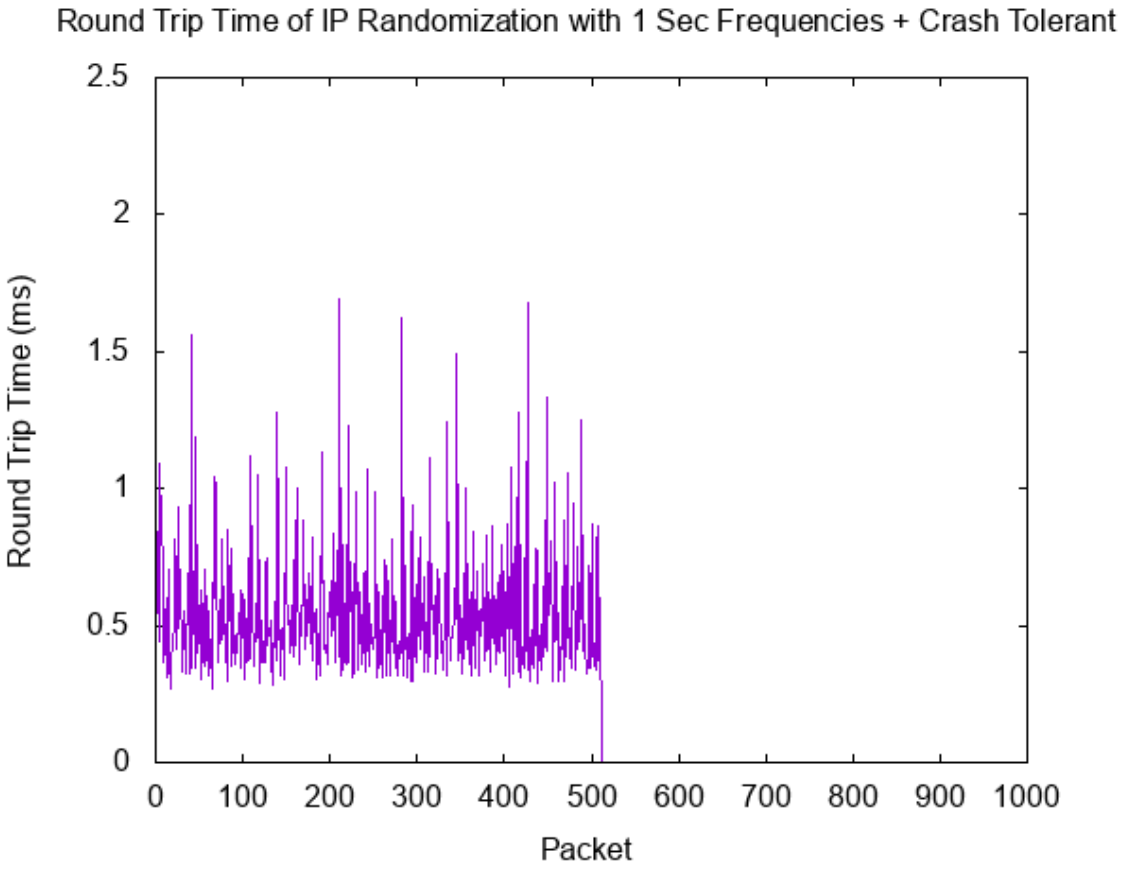


Figure 10.13: Latency metrics captured within the VPP environment over a 1,000 second interval of time. The results show the effects of applying the SDN framework combined with the IP randomization MTD technique and the Paxos crash tolerant algorithm.

of the cluster of failover controllers to handle the event of crash related faults. The experiment was setup so that every 250 seconds, one of the controllers from the cluster would crash and no longer be responsive. The crash is meant to simulate an adversary exploiting a controller one at a time and to measure the performance impacts during those time periods when a failover occurs. As shown in Figure 10.13, connectivity is lost 500 seconds into the experiment. This is caused due to the fact that at least half of the systems, 2 in this case, in the cluster of 4 had crashed at that time (since the experiment was designed for controllers to crash every 250 seconds). The Paxos crash tolerant algorithms require a majority of the cluster to be responsive in order to have a consensus agreement which is not possible when half of the controllers fail. The average latency measured when a

consensus agreement could be successfully reached was 0.542 ms, which is comparable to the IP randomization algorithms running independently without the fault tolerant algorithms enabled.

We then captured latency measurements when the Byzantine fault tolerant algorithms were enabled. In this set of experiments, an individual flow residing on one of the controllers was maliciously modified to route traffic to the adversary instead of to the original destination endpoint. The Byzantine fault tolerant algorithms implemented could handle f failures when there are $3f+1$ controllers. In this scenario, 1 failure can be tolerated since there are 4 controllers configured within the cluster. Figure 10.14 shows the round trip time measurements associated with the Byzantine fault tolerant algorithms and the IP randomization enabled. The results are similar to those of the crash tolerant algorithms in that communications discontinued after 500 seconds. After 2 failures, a consensus agreement on the flows installed could no longer be achieved. The increased latency, as shown in Figure 10.14, is attributed to the compromised controllers attempting to communicate the malicious flow to the other controllers in the cluster and the other controllers waiting for a consensus agreement amongst the cluster. However, since the other controllers are also participating in the Byzantine fault tolerant algorithms, they detect the differences in the malicious flows being communicated to them and reject those differences until a consensus agreement can be achieved between the cluster. The spikes in latency after every 250th packet show the additional communications taking place when the malicious flows are sent. The average latency when we enabled all of the SDN framework, the IP randomization, and the Byzantine fault tolerant algorithms was measured to be 0.587 ms, which is also comparable to the VPP baseline.

We also captured throughput measurements when the crash tolerant and Byzantine fault tolerant algorithms were enabled. A baseline measurement of throughput was captured over a 1,000 second interval with a 10 Mbits/sec link configured. As shown in Figure 10.15, the baseline measurements in the VPP environment, the link is capable of full uti-

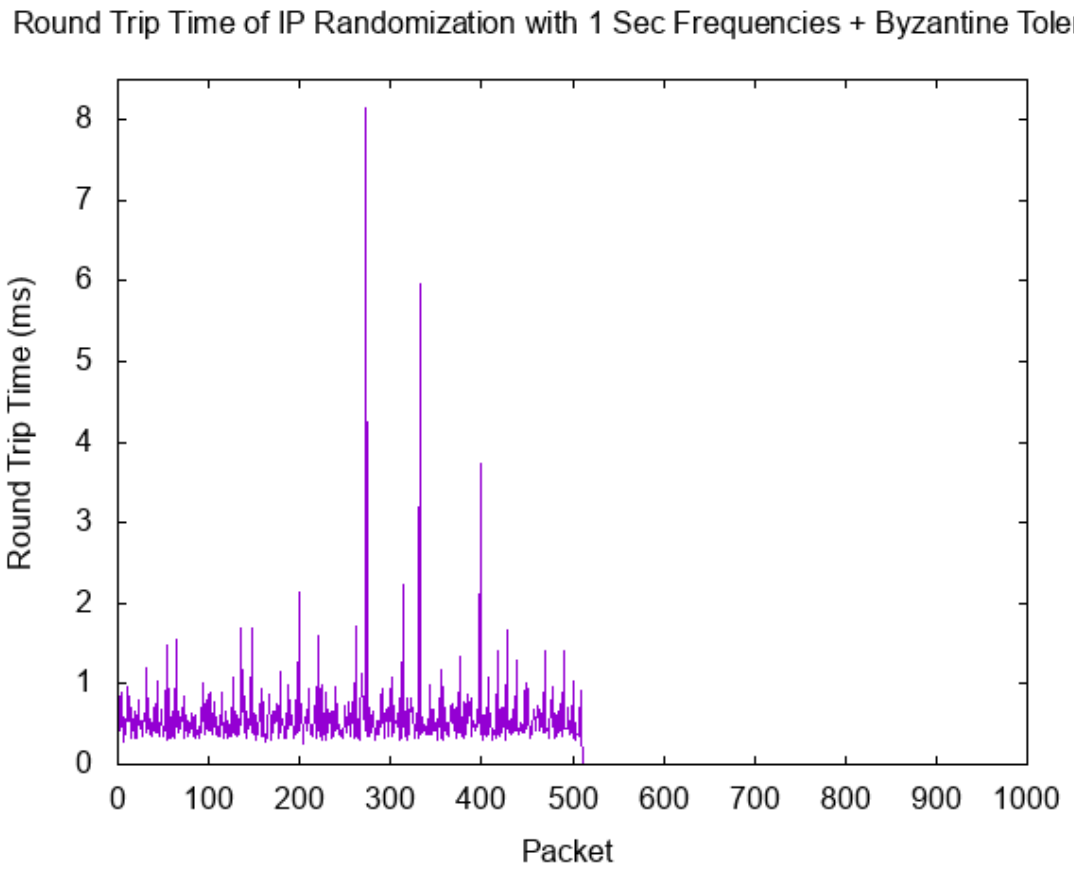


Figure 10.14: Latency metrics captured within the VPP environment over a 1,000 second interval of time. The results show the effects of applying the SDN framework combined with both the IP randomization MTD technique and the Byzantine fault tolerant algorithms.

lization at 10 Mbits/sec when configured without any of the SDN framework, the MTD techniques or the fault tolerant algorithms enabled.

Figure 10.16 shows the results that we collected over a 1,000 second interval when the VPP is configured to operate in an SDN configuration. The throughput was unaffected when SDN was enabled and when the `iperf3` tool was configured to maintain a continuous throughput rate of 10 Mbit/sec across the network. In this experiment, we configured two Open vSwitch instances with two end hosts communicating to one another through the Open vSwitches. We installed flow rules on each of the Open vSwitch instances to appropriately forward traffic between the two switches. In the flow rules, the source or

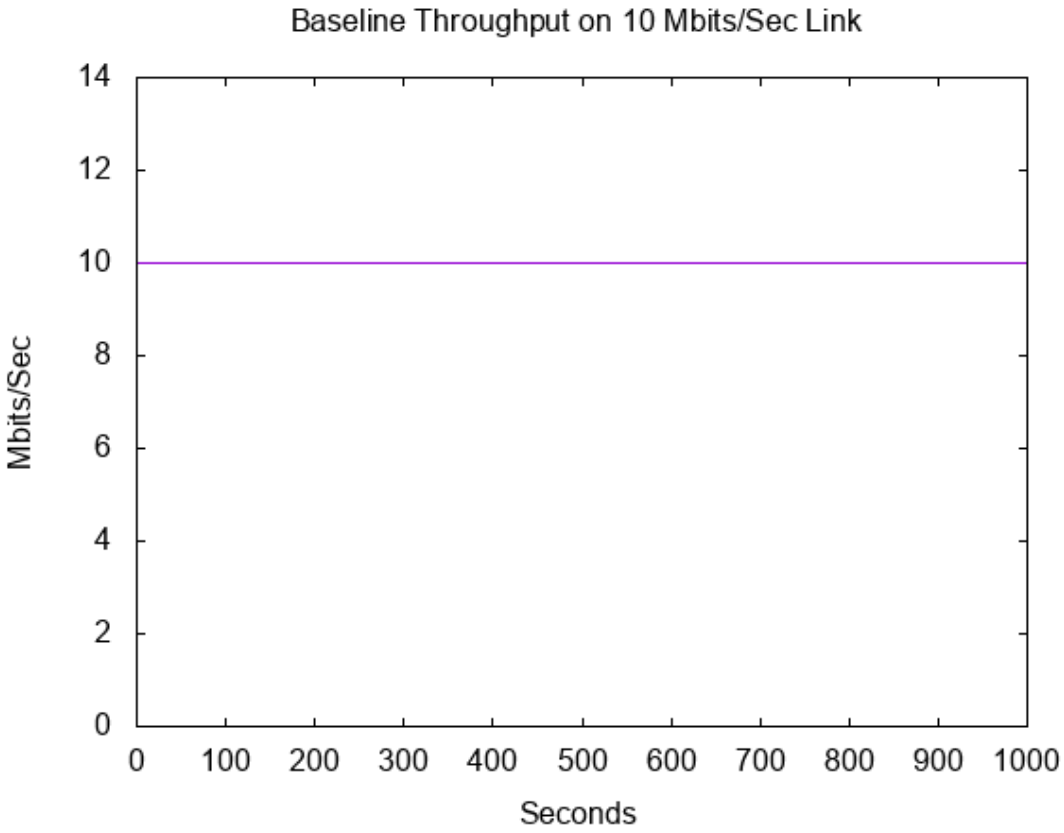


Figure 10.15: Throughput measurements using traditional switches with 10 Mbit/sec links configured through the `iperf3` tool over a 1,000 second period.

destination IP addresses were not rewritten. The flow rules only matched packets based on the incoming physical port and the source and destination IP addresses before forwarding out the appropriate output port.

Figure 10.17 shows the throughput results captured in the VPP environment when IP randomization is enabled. We obtained similar results from the baseline indicating that the IP randomization and SDN framework do not have a noticeable impact on the throughput observed within the VPP environment. These results are consistent with those discussed previously on the latency impacts of enabling both the SDN framework and the IP randomization technique. Throughput is not typically a strong requirement for ICS environments since only small amounts of data are usually sent, except for potentially in the case

where synchrophasor data is continuously being communicated across the network which can require high amounts of bandwidth.

Figures 10.18 - 10.21 show the throughput measurements when the crash tolerant algorithms are enabled within the VPP environment. The performance metrics were captured over the same 1,000 second interval of time with a 10 Mbits/sec link configured across the network. In each of these experiments, an SDN controller was manually brought down to simulate an adversary causing a crash in one of the controller every 250 seconds. It was also assumed that the controllers would remain in a crashed state and could not recover. The number of controllers in the cluster varied between 2 controllers and 5 controllers.

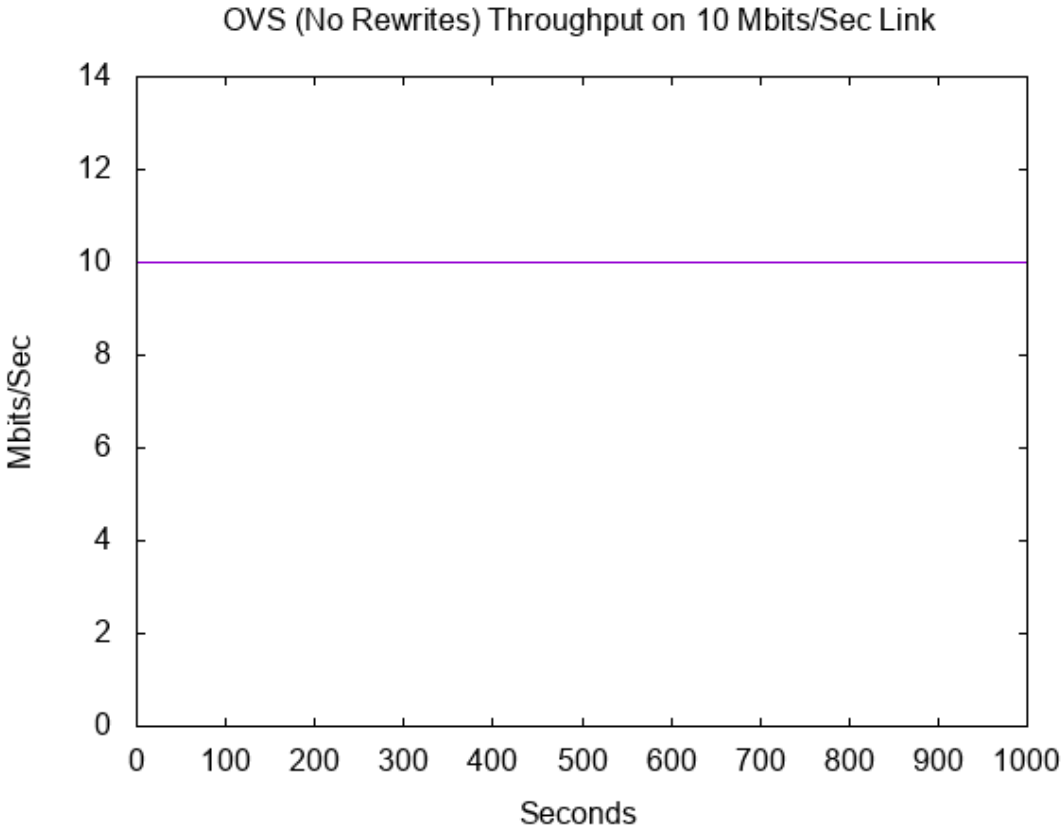


Figure 10.16: Throughput measurements using Open vSwitch instances that only forward traffic based on incoming physical ports, with 10 Mbit/sec links configured through the `iperf3` tool over a 1,000 second period.

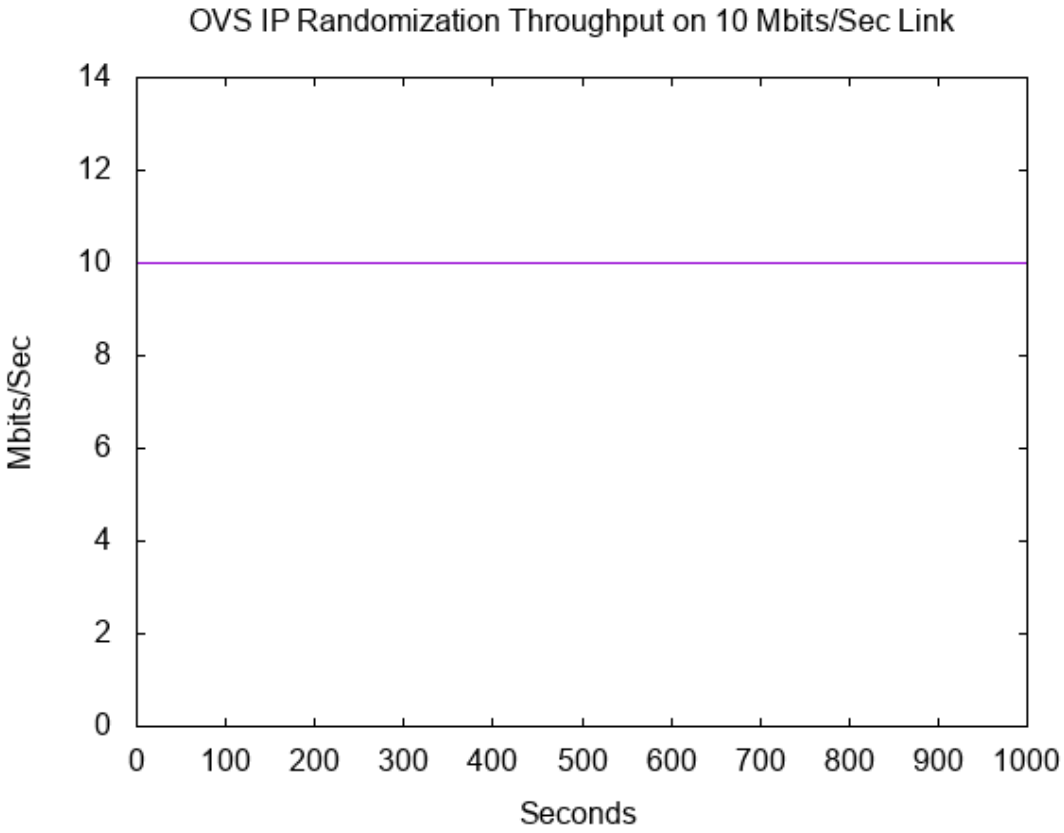


Figure 10.17: Throughput measurements using Open vSwitches that randomize source and destination IP addresses before forwarding traffic. Network links were configured to operate at 10 Mbits/sec through the `iperf3` tool over a 1,000 second period.

Figure 10.18 shows the results obtained when 2 SDN controllers form the cluster. The throughput initially maintains a 10 Mbit/sec connection, until the first controller crashes at the 250 second time mark. After the first controller fails at 250 seconds, throughput drops to 0 Mbits/sec. The decrease in throughput is attributed to the requirement that a majority of the cluster systems to be up and running. As soon as a single controller in the cluster crashes, there can no longer be a majority consensus agreement since there are only 2 controllers configured as part of the original cluster.

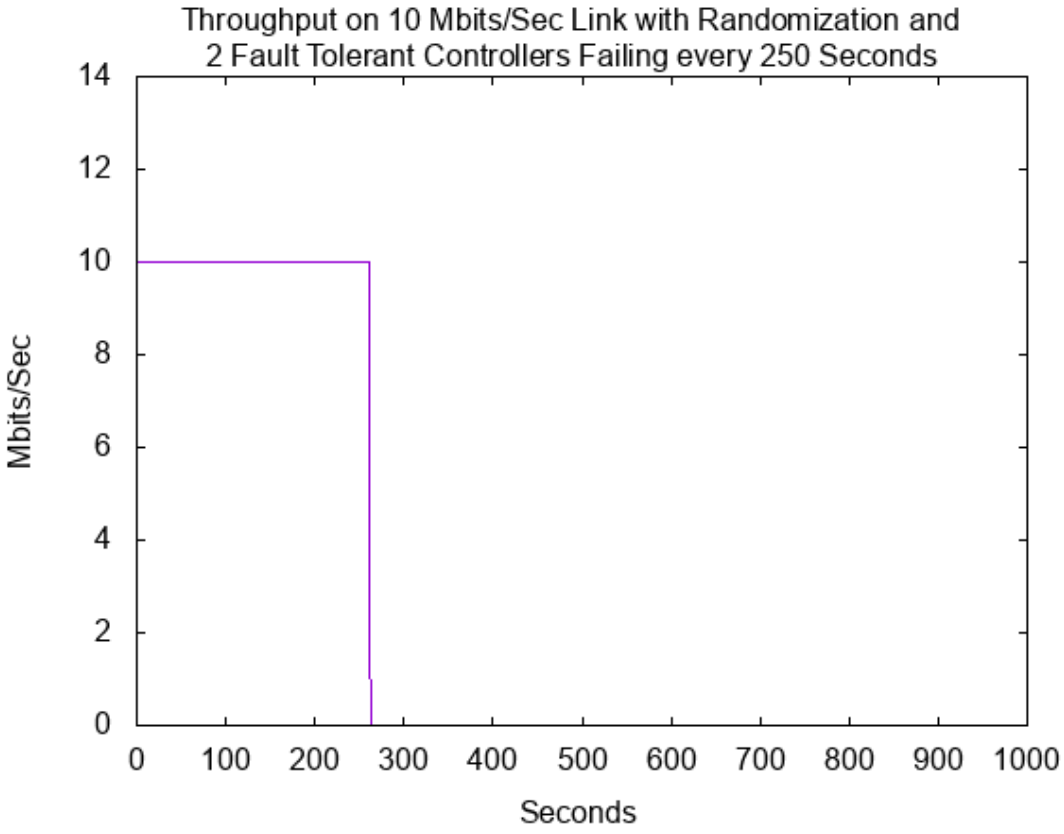


Figure 10.18: Throughput measurements using Open vSwitch instances that randomize source and destination IP addresses were collected before forwarding traffic with 10 Mbit/sec links configured through the `iperf3` tool over a 1,000 second period. A cluster of two controllers is configured with the Raft consensus algorithm [1] where the leader controller fails every 250 seconds.

Figure 10.19 shows the results obtained when 3 controllers form the cluster. The throughput is maintained at 10 Mbit/sec, until 2 of the controllers crash at the 500 second time mark. After the first controller failure occurs at 250 seconds, throughput is maintained at 10 Mbits/sec because a majority of the controllers, 2 in this case, are still up and running. As soon as the second controller crashes, the throughput drops to 0 Mbits/sec. The drop in throughput is attributed to the requirement that a majority of the cluster systems be up and running. As soon as 2 out of 3 controllers in the cluster crash, there can no longer be a majority consensus agreement.

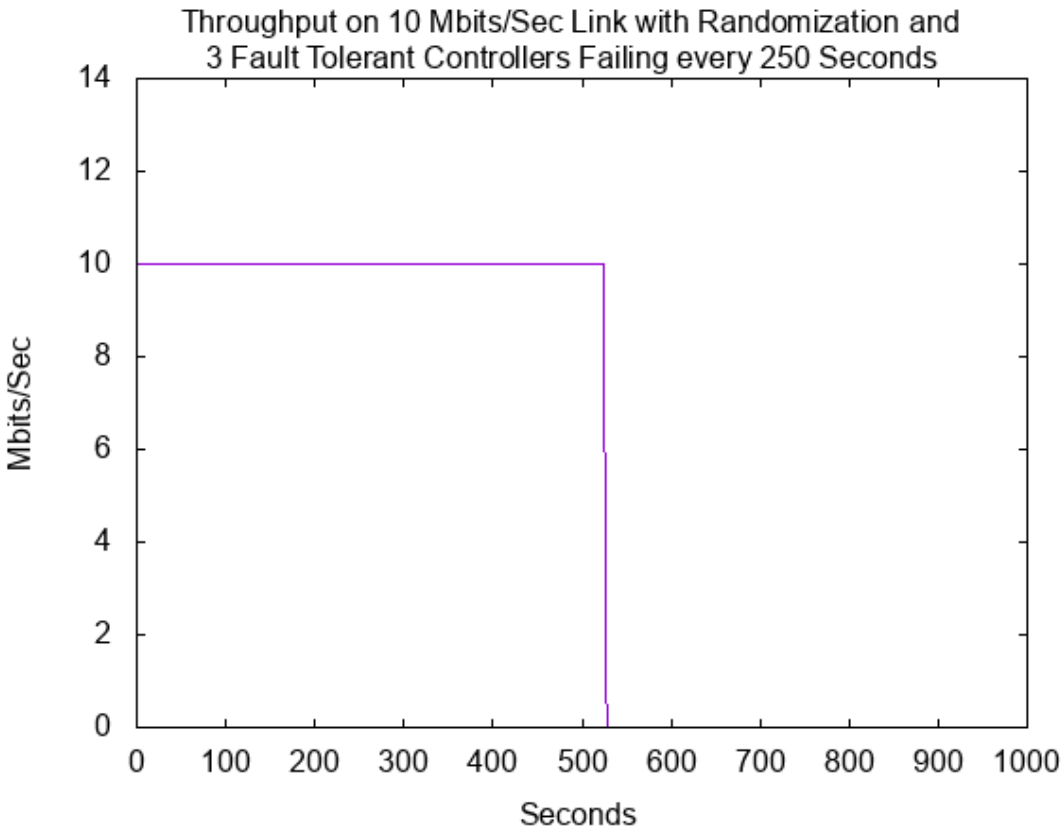


Figure 10.19: Throughput measurements using Open vSwitch instances that randomize source and destination IP addresses before forwarding traffic, with 10 Mbit/sec links configured through the `iperf3` tool over a 1,000 second period. A cluster of three controllers is configured with the Raft consensus algorithm where the leader controller fails every 250 seconds.

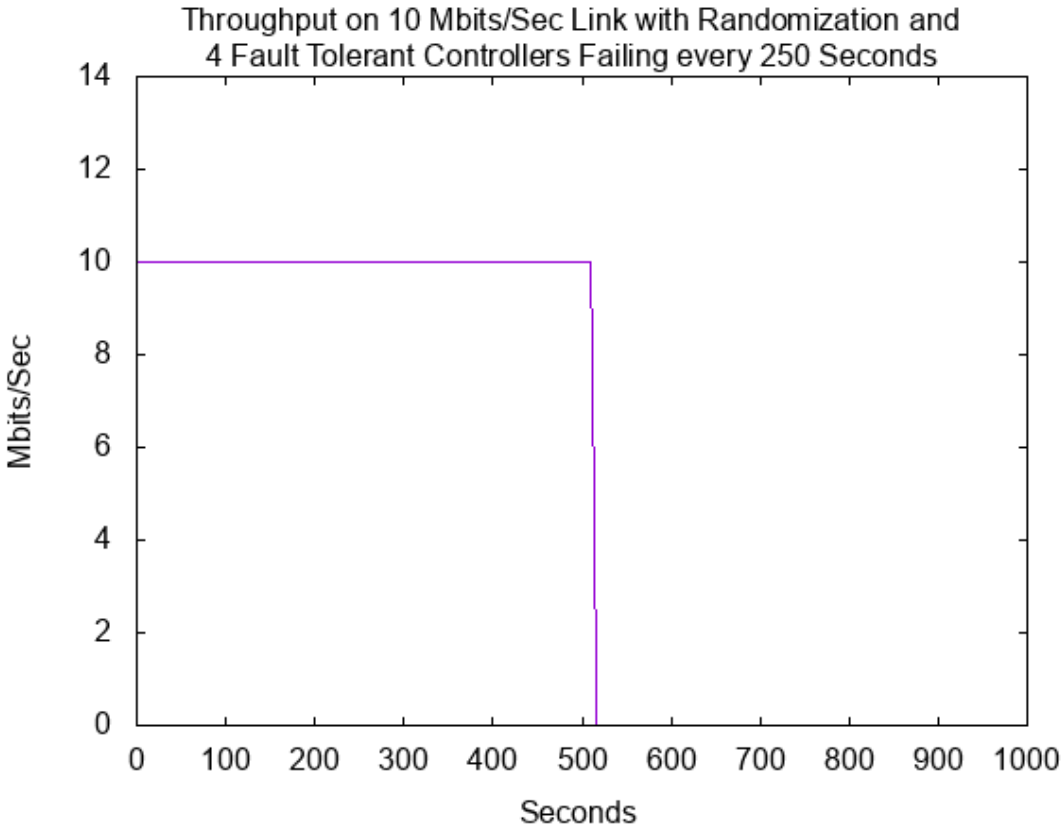


Figure 10.20: Throughput measurements using Open vSwitch instances that randomize source and destination IP addresses before forwarding traffic, with 10 Mbit/sec links configured through the `iperf3` tool over a 1,000 second period. A four controller cluster is configured with the Raft consensus algorithm where the leader controller fails every 250 seconds.

Figure 10.20 shows the results obtained when 4 controllers form the cluster. The throughput is maintained at 10 Mbit/sec, until 2 of the controllers crash at the 500 second time mark. After the first controller failure occurs at 250 seconds, throughput is maintained at 10 Mbits/sec because a majority of the controllers, 3 in this case, are still up and running. As soon as the second controller crashes, the throughput drops to 0 Mbits/sec. The drop in throughput is attributed to the requirement that a majority of the cluster systems be up and running. As soon as half of the four controllers in the cluster crash, there can no longer be a majority consensus agreement.

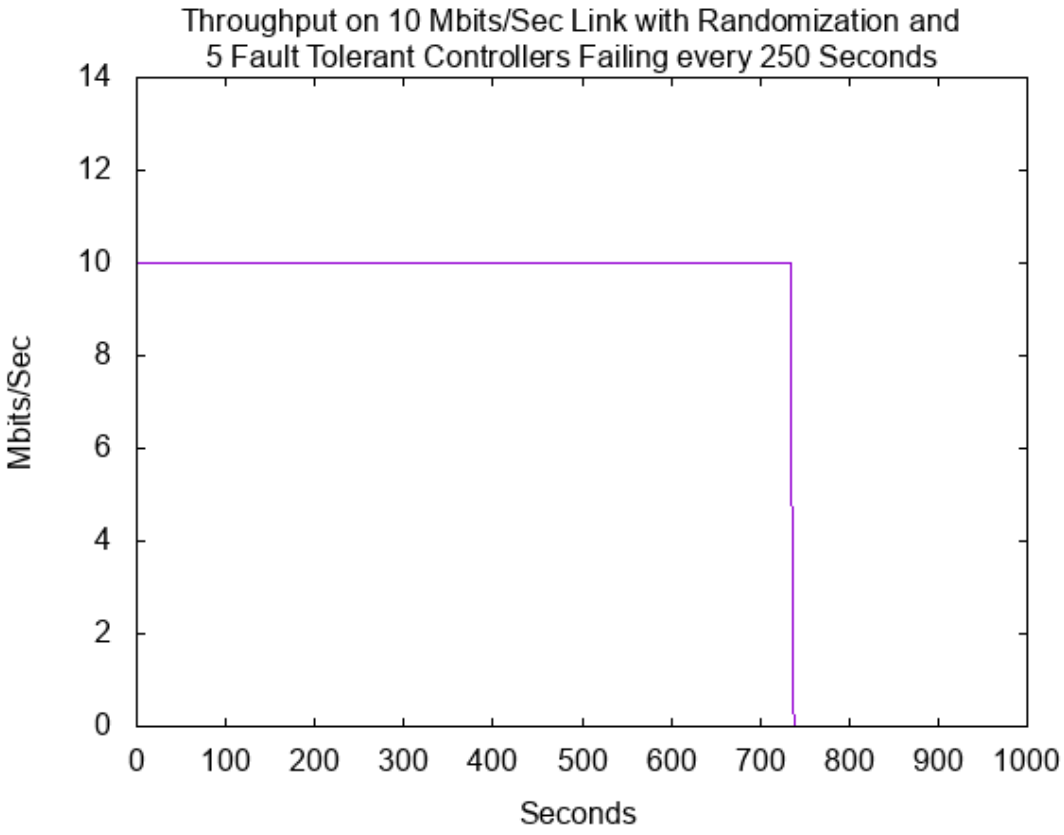


Figure 10.21: Throughput measurements using Open vSwitch instances that randomize source and destination IP addresses before forwarding traffic, with 10 Mbit/sec links configured through the `iperf3` tool over a 1,000 second period. A five controller cluster is configured with the Raft consensus algorithm where the leader controller fails every 250 seconds.

Figure 10.21 shows the results obtained when 5 controllers form the cluster. The throughput is maintained at 10 Mbit/sec, until 3 of the controllers crash at the 750 second time mark. After the first controller failure occurs at 250 seconds, throughput is maintained at 10 Mbits/sec because a majority of the controllers, 4 in this case, are still up and running. When the second controller crashes at the 500 second mark, the cluster can still reach a consensus agreement since a majority 3 out of 5 controllers are still up and running. As soon as the third controller crashes, the throughput drops to 0 Mbits/sec. The drop in throughput is attributed to the requirement that a majority of the cluster systems be up and running. As soon as 3 or more of the 5 controllers in the cluster crash, there can no longer be a majority consensus agreement.

The next set of metrics we captured are collected from the end devices that serve as the SDN controllers. CPU and memory utilization measurements were captured to understand the impacts to the SDN controllers themselves, which are responsible for installing the appropriate flows on each of the SDN switches to correctly route traffic. We initially performed the measurements to capture a baseline of the VPP environment, then also when enabling the IP randomization techniques, then when also enabling the crash tolerant algorithms, and finally when enabling the Byzantine fault tolerant algorithms. The specifications of the SDN controller systems are as follows:

- 2.60 GHz Intel® Xeon® CPU ES-2670 processor
- 1 GB RAM
- 20 GB SATA Disk Drive
- Gigabit Ethernet card
- Ubuntu 16.04 64-bit

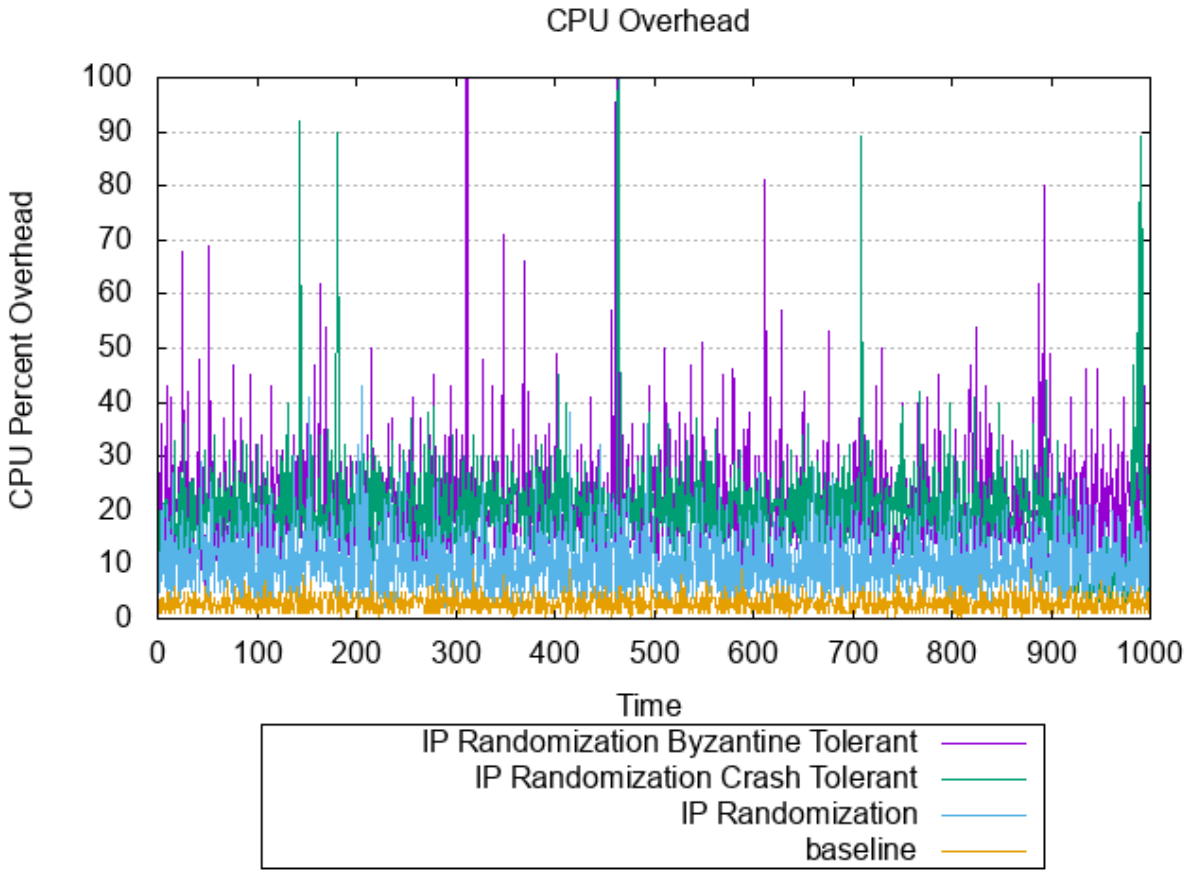


Figure 10.22: CPU impacts on the SDN controller when deploying Byzantine fault tolerant algorithms with IP randomization enabled, crash tolerant algorithms with IP randomization enabled, no fault tolerant algorithms with IP randomization enabled, and a baseline with no fault tolerant algorithms and IP randomization disabled.

Figure 10.22 shows the CPU utilization impacts on the controllers over a 1,000 second interval of time. All scenarios are plotted on the same graph to compare different measurements easily. The lowest CPU impact came from the baseline CPU measurements when the VPP was configured to run without any of the SDN, IP randomization, or fault tolerant algorithms enabled. The average CPU utilization in that scenario was measured to be ∼2.7% of CPU overhead. When IP randomization is enabled, the average CPU utilization increases to ∼10.3% of CPU overhead. When the crash tolerant and IP randomization algorithms are enabled, the average CPU utilization becomes ∼20.4% of CPU overhead. Finally, when the Byzantine and IP randomization algorithms are enabled, the average CPU utilization is measured to be ∼20.7% of CPU overhead.

The largest increase measured when we incrementally enabled new features was after the fault tolerant algorithms were enabled. An additional ∼7.6% (on average) of CPU usage was needed when enabling the IP randomization algorithms from the baseline measurements. After enabling the fault tolerant algorithms, an additional (on average) ∼17.7% of CPU usage was required for the crash tolerant algorithms and ∼17.9% of CPU usage was needed for the Byzantine fault tolerant algorithms. The fault tolerant algorithms were implemented in Java and the Java Virtual Machine environment required 512 megabytes to be initialized. Although the endpoint controllers did experience a higher level of load on the CPU, there were not significant degradations in latency and throughput as shown in Figures 10.11 - 10.14 and Figures 10.17 - 10.21. Within an ICS environment, the fault tolerant algorithms do not provide a significant amount of overhead and would be appropriate to apply, provided that the controllers have similar specifications as described previously. Outside of an ICS environment, the feasibility of applying the fault tolerant algorithms will depend on the requirements of those environments as well as the other processes that would also be running on the SDN controller. Isolating and separating the controller onto its own standalone system may be an appropriate option if there are a significant number of processes and applications hosted on the same system.

The memory overhead was also captured on each of the controllers within the cluster. The metrics we captured were for a baseline configuration, when IP randomization was enabled, when IP randomization combined with the Paxos crash tolerant algorithms were enabled, and when IP randomization combined with the Byzantine fault tolerant algorithms were enabled. The baseline memory consumption within the VPP environment running without any of the security protections over a 1,000 second interval was measured at ∼28.8% utilized on average. When enabling IP randomization, the crash tolerant algorithms, and the Byzantine fault tolerant algorithms, the average memory usage increased to 91.4%, 92.2%, and 92.6%, respectively. These results are reflected in Figure 10.23. The reason for the large increase is due to the memory required to initialize the Java Virtual

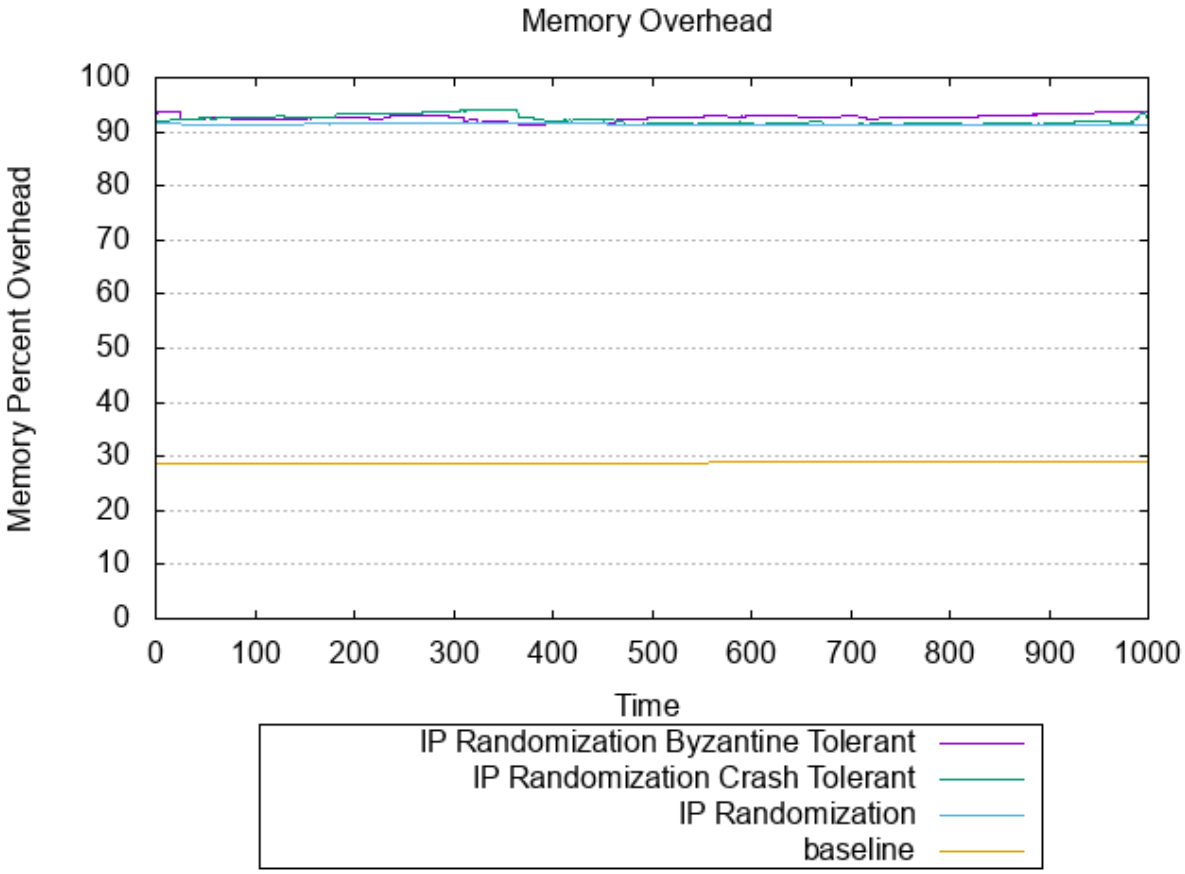


Figure 10.23: Memory impacts on the SDN controller when deploying Byzantine fault tolerant algorithms with IP randomization enabled, crash tolerant algorithms with IP randomization enabled, no fault tolerant algorithms with IP randomization enabled, and a baseline with no fault tolerant algorithms and IP randomization disabled.

Machine that is needed to start the OpenDaylight controller. The amount of memory used within OpenDaylight was configured to be 512 megabytes, or half of a gigabyte, which was the major contributor to the increase in memory usage. The large memory requirements combined with the fact that the controllers each only had 1 gigabyte of memory is the reason for the greater than 50% increases in memory usage. In an operational setting, the memory requirements of the OpenDaylight controller should be factored into the decision about the specifications chosen for that system. With the small amount of memory available on the controller systems used in this set of experiments, the memory was nearly at a maximum. This could cause delays in communicating new flows to each of the SDN switches in the network which would then potentially cascade into latency increases.

10.2.5 IPv6

An evaluation of the IP randomization MTD technique using IPv6 addresses was performed within the VPP environment. IPv6 was chosen to validate the simulated results of the adversarial workload increases described in Chapter 9 for IPv4 and also to evaluate the feasibility and effectiveness of IPv6 within an ICS setting. IPv6 is currently not widely deployed within ICS environments but researchers have been considering it for inclusion for several years [138]. IPv6 is the successor of IPv4 and was designed to expand on the limited amount of IPv4 addresses available [139]. IPv4 addresses consist of 32 bit addresses whereas IPv6 addresses consist of 128 bit addresses. The larger address space provides additional entropy for the IP randomization scheme. As shown previously in Chapter 9, an adversary can brute force a pair of CIDR class C IP addresses in under 0.03 seconds, which is a minimal delay for an adversary. Using IPv6 addresses allows the defender to expand the entropy beyond the typical 8 bits of entropy that would be customary in an IPv4 deployment. IPv6 addresses would typically have on the order of 64 bits available in many deployments [140] or $100 \times (2^{56} - 1)$ percent more entropy. This added entropy makes brute force techniques infeasible for an individual adversary.

We have captured metrics on the effectiveness of IPv6 randomization to evaluate the impacts on the increased amount of workload placed on the adversary. We have also analyzed individual adversaries and distributed adversaries for their effectiveness in learning the randomized IPv6 mappings. Our experiments within the VPP environment captured the number of probes that an adversary must attempt before successfully reverse engineering the randomized IPv6 addresses. The IPv6 addresses chosen contained 10 bits of entropy on both the source and destination addresses. In our tests, we repeated each experiment with 10,000 trials to verify that the results obtained from the IPv4 addresses scaled similarly when expanding the IP address space.

10.2.6 Individual Adversaries

Figures 10.24 - 10.27 show the experimental results obtained within the VPP environment when an individual adversary attacks the IPv6 randomization schemes using the

four adversarial strategies described in Section 10.1.3 to reverse engineer the randomized IPv6 addresses. The first strategy is to spoof randomly-chosen source and destination IPv6 addresses continuously until a successful spoofed packet is injected into the network. This process may potentially repeat previously failed attempts. The second strategy performs the same strategy except a table is maintained to avoid repeating previously failed attempts. The last two strategies scan IPv6 addresses sequentially, with the first of the two starting with the first available IPv6 address and the second strategy starting at a random IPv6 address. The four strategies we used were taken from RFC 6056 [100].

The top most curves for each of the four strategies are shown in Figures 10.24 - 10.27 for an individual adversary attacking the system. The random with repetition strategy, again, followed the binomial distribution. Since previous attempts may be repeated, the probability from one probe to the next is constant and does not improve as more probes are made. Figure 10.24 shows the constant curve and the expectation of $2^{10+10} = 2^{20}$ probes required until the first success that was experimentally encountered within the VPP environment. The source and destination IPv6 addresses both had 10 bits of entropy built in for a total of 20 bits of entropy combined.

The same analysis was performed when the adversary strategy was modified to randomly probe the network with spoofed IPv6 addresses that did not repeat. The difference in this strategy is that the adversaries' probability will improve with each attempt since previous attempts are not repeated. We varied the randomization frequencies in these experiments and the intervals are shown along the x-axis of Figure 10.25. As the randomization frequencies increase in time going to the right on the curve, the success rate of the adversary improves. This is attributed to the environment remaining statically configured for longer periods of time which allows the adversary to probe the network over longer periods of time before the IP address configuration changes. Once the randomization intervals increase beyond 256 seconds, the adversary success rates begin to improve more significantly. However, when there is any amount of randomization fre-

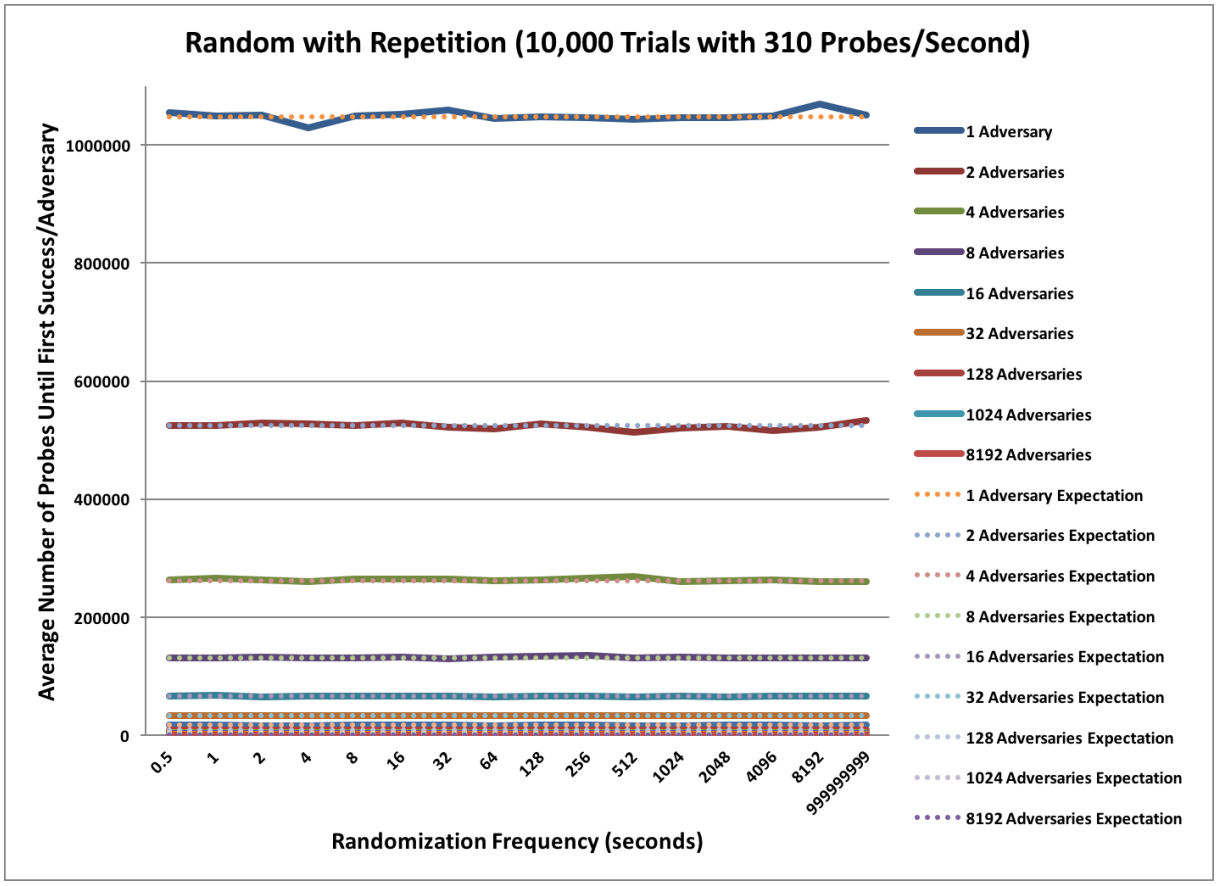


Figure 10.24: The solid lines represent the number of attempted spoofed packets that need to be injected into the network with varying randomization frequencies. As the randomization frequencies increase in time, the number of spoofed packets attempted by the adversary decreases. The dashed lines represent the theoretical expectation curve of the binomial distribution, which match the experimented data closely. Each of the curves represent the total number of adversaries, varying from 1 adversary to 8,192 adversaries. The frequency intervals varied from 0.5 seconds to not randomizing at all (a static configuration). We performed 10,000 trials in the VPP environment with an adversary that was capable of submitting 310 injected packets per second.

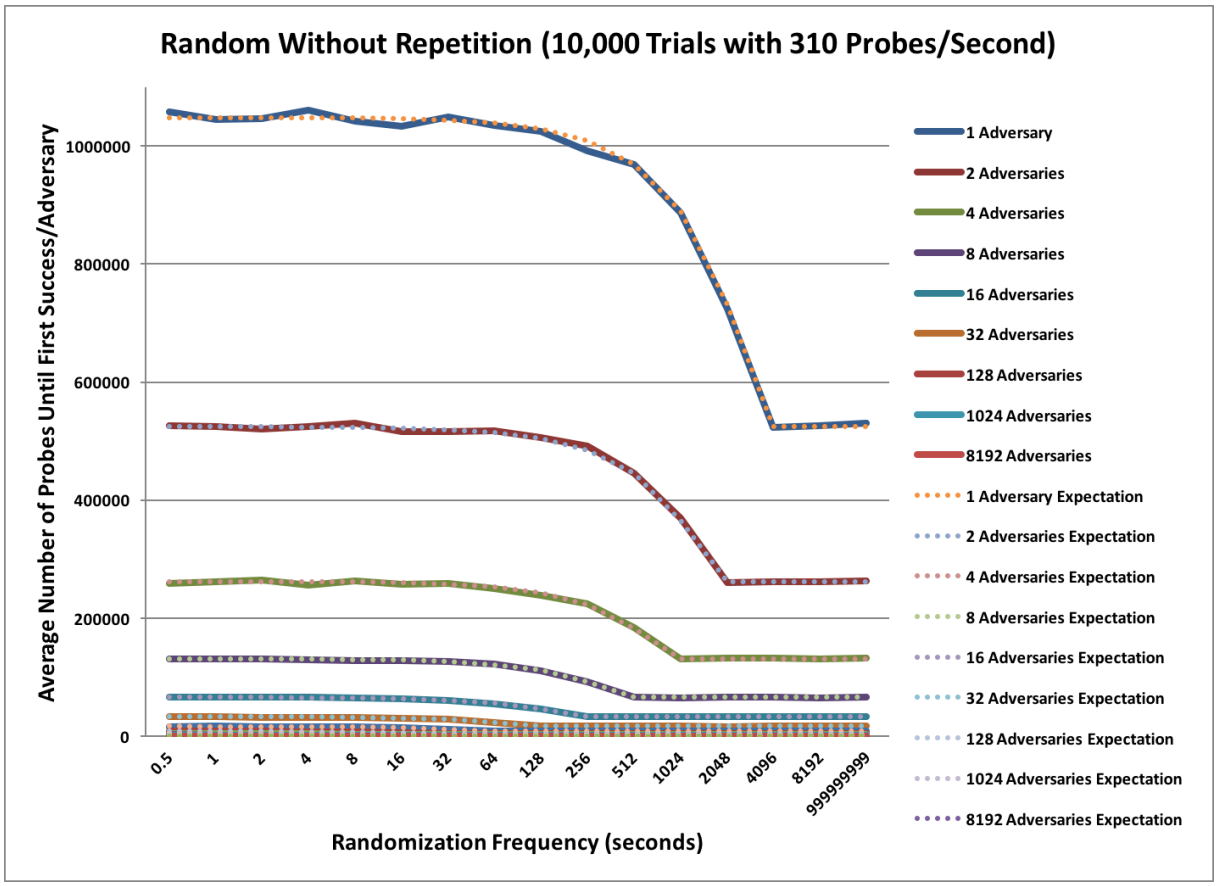


Figure 10.25: The hypergeometric distribution is followed when the strategy of the adversary is to randomly spoof the source and destination IPv6 addresses until a success is observed without ever repeating previous failed attempts. The results captured experimentally match those of the expectation curve (dashed lines) when the number of adversaries and the frequencies at which the defender re-randomizes the IPv6 addresses are varied.

quency beyond 4,096 seconds, the adversaries' success rates become constant. The reason for the constant rate of success beyond 4,096 seconds of randomization is because with 20 bits of entropy, the entire attack space can be exhausted when the adversary is capable of injecting 310 probes per second (310*4,096 $\approx 2^8 * 2^{12} = 2^{20}$). The 310 probes per second includes the time to craft, spoof random addresses, and inject the packet into the network. This strategy follows the hypergeometric distribution which is overlayed onto the experimental results collected and closely matches those results.

The serial guessing strategies shown in Figures 10.26 - 10.27 have similar results as the random without repetition strategy shown in Figure 10.25. The results of this strategy also follow the hypergeometric distribution and the experimental results are strongly correlated with that distribution.

10.2.7 Distributed Adversaries

The next set of experiments show the results when the adversary divides the work between several adversaries to reduce the overall amount of time until success. The number of distributed adversaries was varied between 2 adversaries and 8,192 adversaries. The adversaries we evaluated were those that fit the formula 2^n where $0 \leq n \leq 13$. This experiment setup was developed to evaluate the success rates of a DDoS attack on the IPv6 randomization scheme within the VPP environment. Each of the curves below the top curve in Figures 10.25 - 10.27 show the experimental results obtained from a varying number of adversaries beyond a single adversary.

As the number of adversaries increases, the number of attempts by each adversary decreases since the work is divided evenly between them. Similar to the IPv4 results from the DETERLab experiments shown in Figure 10.5, the y-axis shows the number of probes required until the first successful spoofed packet is injected into the network by any of the individual adversaries. The number of probes until a success occurs when two adversaries are launching a DDoS varies between $2^{18} - 2^{19}$ probes. This is a large number of probes that should easily be noticed by a defender. As the number of adversaries increases, the

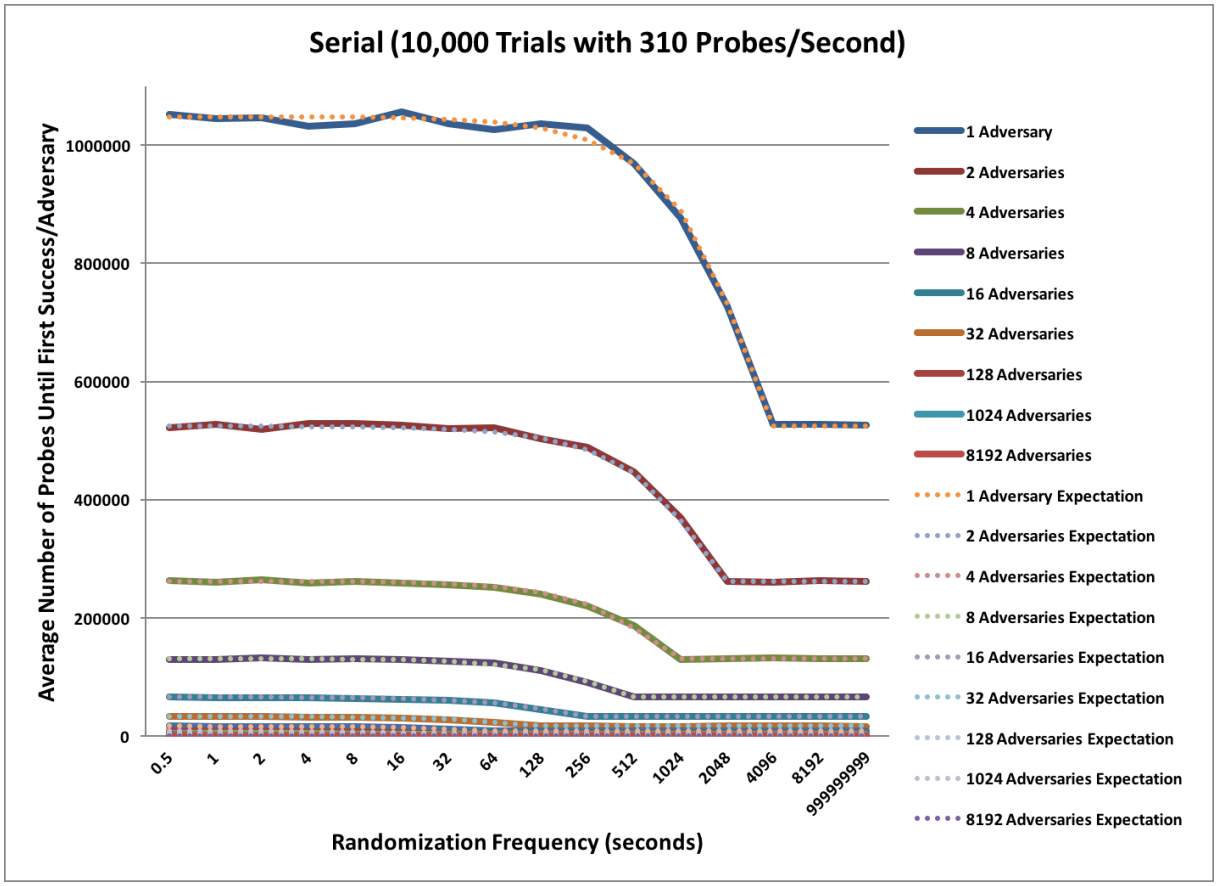


Figure 10.26: The hypergeometric distribution is followed when the strategy of the adversary is to serially spoof the source and destination IPv6 addresses (starting at IPv6 addresses A.B.C.D.E.F.G.0000-T.U.V.W.X.Y.Z.FFFF, where A, B, C, D, E, F, G, T, U, V, W, X, Y, and Z are 16 bit values of an IPv6 address) until success. The results captured experimentally match those of the expectation curve (dashed lines) when varying the number of adversaries and the frequencies at which the defender re-randomizes the IPv6 addresses.

number of overall probes stays the same amongst all adversaries combined but the time needed until a success occurs is reduced. This reduction in time highlights the need for the defender to monitor the number of probes observed in the network. As the number of total probes observed approaches 800,000, at a minimum, the defender should begin to take action on the noisy activity produced by the adversary. The defender may choose to block the adversaries by activating firewall rules or should at least begin to investigate the anomalous behavior.

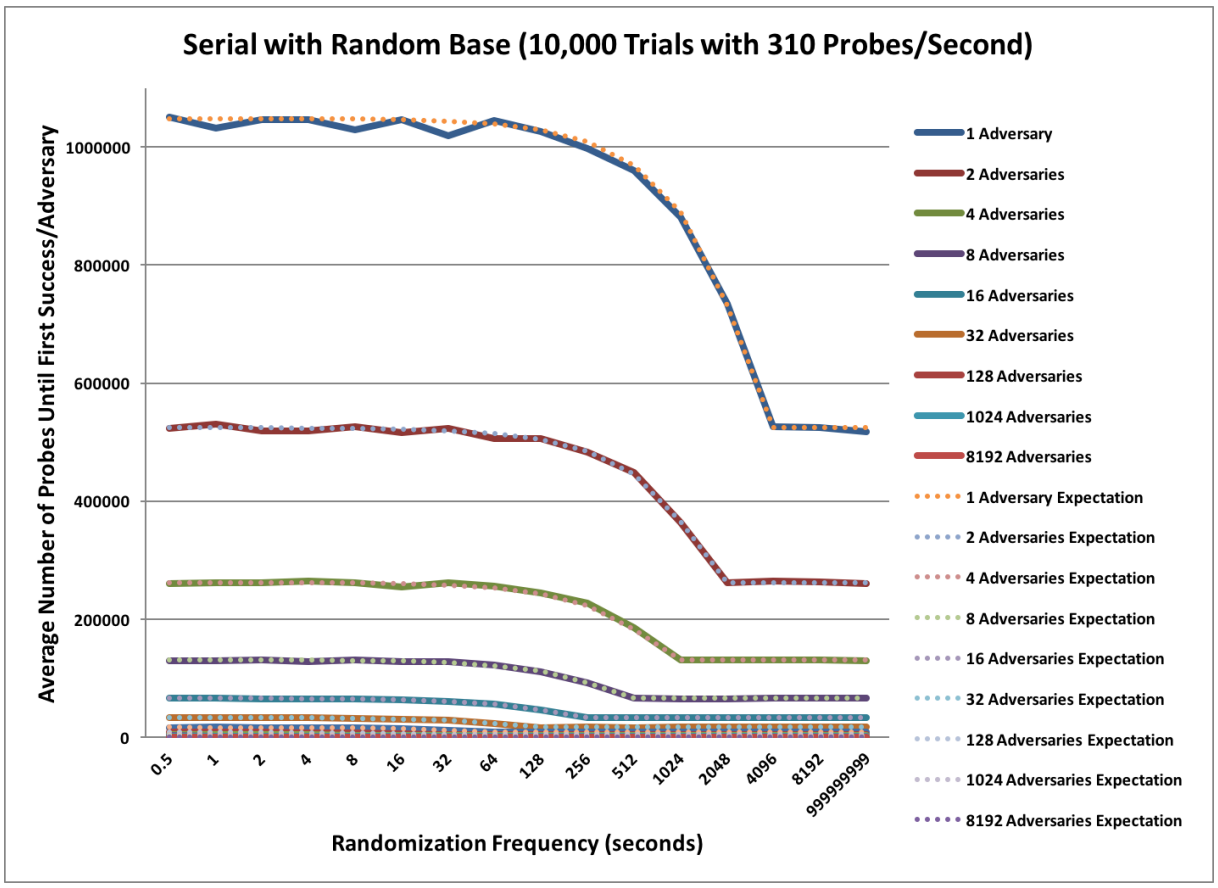


Figure 10.27: The hypergeometric distribution is similarly followed when the adversary follows the strategy of serially spoofing source and destination IPv6 addresses (starting at IPv6 addresses A.B.C.D.E.F.G.R-T.U.V.W.X.Y.Z.Q, where A, B, C, D, E, F, G, R, T, U, V, W, X, Y, Q, and Z are 16 bit values of an IPv6 address) until success. R is a random 16-bit value and Q is R-1. The results captured experimentally match those of the expectation curve (dashed lines) when varying the number of adversaries and the frequencies at which the defender re-randomizes the network IPv6 addresses.

Both of the remaining two strategies (serial probing strategy starting at the first available IPv6 address and incrementally probing until the maximum IPv6 address is reached and the serial probing starting at a random IPv6 address) followed the same pattern as the random without repetition strategy previously discussed. These two strategies also follow the hypergeometric distribution and we have experimentally shown that they exhibit similar behavior as the address space scales to IPv6 addresses. The amount of entropy to be expected in an IPv6 address could be 64 bits in a typical IPv6 deployments. 64 bits would significantly increase the time and number of adversaries needed to carry out a successful attack. In fact, to achieve the same results as the 20-bit case described in our research, the adversary would require 2^{44} adversaries when launching a DDoS to achieve the same success rates. IPv6 yields a higher level of protection, in terms of the amount of entropy available to a defender, when protecting ICS environments from attack.

10.2.8 Side Channel Attacks

An adversary can also make use of side-channel information to attack the MTD techniques deployed. For the IP randomization schemes, the adversary may be aware that the IP randomization defense has been deployed and may wish to understand how much time is available until the next randomization period occurs. If the adversary is passively observing round trip times in the network, the randomization frequencies can be determined. Figure 10.28 and Figure 10.29 show our round trip time latency measurements that were captured over a 100 second interval with two hosts communicating over an SDN network with IP randomization enabled.

Figure 10.28 shows the round trip times when 2 second randomization frequencies are configured. In the plot, there are fluctuations that occur every $\sim$2 seconds. The increases are attributed to the new flow updates being installed on each of the switches and the additional time required to make a match with the new flow rules installed. The Open vSwitch takes time to install the new flow rules, remove old flow rules that have expired, and also match incoming and outgoing packets against the additional flow rules installed. From this information gathered, the adversary can then learn that they must launch their

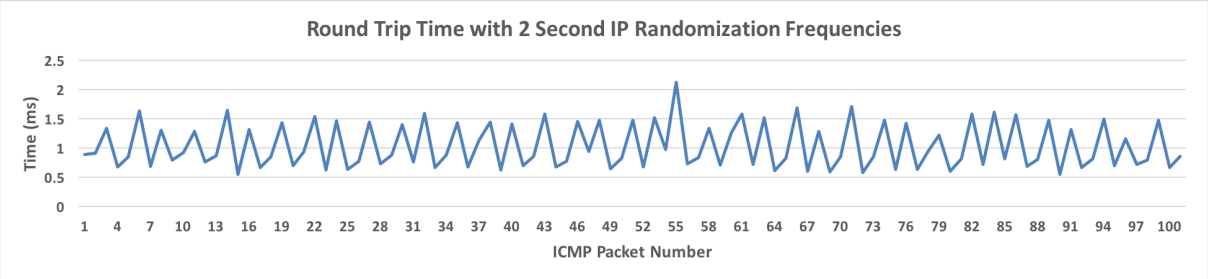


Figure 10.28: The RTT times over a 100 second interval have spikes in latency every ∼2 seconds since these are the periods of time where IP randomization occurs. The adversary can then understand the amount of time available to setup an exploit until the next randomized interval occurs.

attack within a ∼2 second window of time. This knowledge can help an adversary work on an exploit offline so that it meets this criteria.

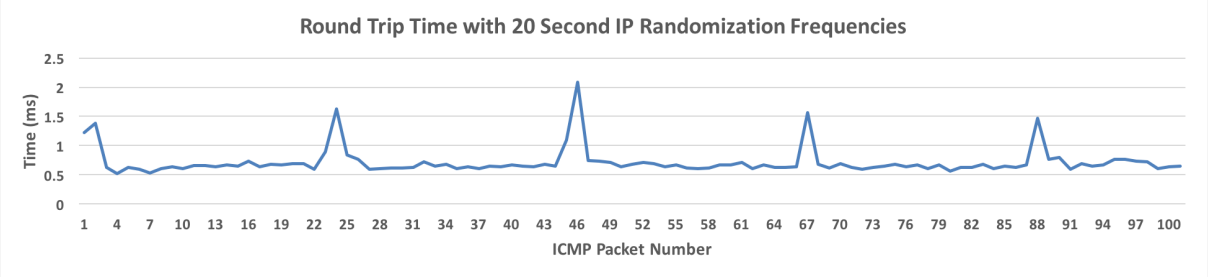


Figure 10.29: The RTT times over a 100 second interval have spikes in latency every ∼20 seconds since these are the periods of time where IP randomization occurs. The adversary can then understand the amount of time available to setup an exploit until the next randomized interval occurs.

Similarly, Figure 10.29 shows the round trip times when 20 second randomization frequencies are configured. In the plot, there are fluctuations that occur every ∼20 seconds. The increases are attributed to the new flow updates being installed on each of the switches and the additional time required to make a match with the new flow rules installed. The Open vSwitch takes time to install the new flow rules every 20 seconds, remove old flow rules that are expired, and also match incoming and outgoing packets against the additional flow rules installed. The adversary can then learn that they must launch their attack within a ∼20 second window of time in this scenario. Comparing Figure 10.28 and Figure 10.29 can easily allow the adversary to differentiate the randomization frequen-

cies of re-randomizing the IPv6 addresses every 2 seconds and every 20 seconds. This knowledge can help an adversary work on an exploit offline so that their exploits meet this criteria.

One possible mitigation for this side channel attack is to configure the randomization frequency intervals to occur at random frequencies. The random frequencies can be bounded by user configurable lower and upper bound limits to ensure that the randomization frequencies are occurring often enough to be effective so that the network does not keep the same configuration for too long. Keeping the same configuration for too long would provide the adversary with more time to launch their attacks against a fixed target. The algorithms to install random flows would also have to be slightly modified for this approach to work so that each randomized flow remains active until the next flow with a different randomly-chosen expiration time is installed. Given that the flows will expire at random times, the algorithms will have to ensure that the next flow is installed before the previous randomized flow expires. This will require the randomization algorithms to track the previous randomization expiration times and to ensure that the next flows are installed before the current flow expires.

Alternatively, the randomization techniques can be activated only at the points in time where a suspected attack is detected. This approach pushes the burden out to the detection agent to trigger the IP randomization scheme and reduces the amount of overhead introduced onto the network. One potential risk of this approach would be if the detection agent did not detect the exploit until it was too late. In this scenario, this particular side channel attack would be eliminated and the adversary would not be able to determine the randomization intervals, but the adversary would accomplish their goal of evading the detection agent and ultimately exploiting the system. This tradeoff should be considered when determining the frequency of the randomization intervals.

This is just one example of a side channel attack that an adversary can leverage to their advantage. Other possible side-channel attacks can include performing power analysis [141] on the Open vSwitch instances to learn the randomization intervals, observing the flow processing time to learn the forwarding table of the Open vSwitch being used [142], recovering keys [143] of crypto algorithms if a secure communication channel is used between the controller and the SDN switches, or by attacking the pseudo random number generators that is used to produce and generate the random mappings [144] of the MTD technique. Side channel attacks should be considered when deploying each of the MTD protections described.

Chapter 11

Conclusions

The MTD approaches we developed have been shown to be effective within an ICS environment. We performed several experiments with a variety of configurations for each MTD technique. The techniques presented here, although effective individually, are meant to be a piece of the larger computer security puzzle. The MTD techniques presented here can be thought of as additional layers of defense to help protect a system from an adversary attempting to gain an understanding of a system in the early stages of an attack. Additional defenses can be deployed alongside the MTD techniques to create an even more secure system. This chapter is meant to highlight the limitations, lessons learned, opportunities for future research, and to summarize our research.

11.1 Limitations and Lessons Learned

We applied MTD techniques and fault tolerant algorithms to ICS environments with successful experimental results. However, there are several lessons learned along the way and limitations of each approach that we observed. The lessons learned and limitations apply to both the techniques themselves as well as the experimental processes used to capture the results. Our intent in this section is to convey that the solutions presented here are additional layers of defense available to a defender. Deploying an individual MTD technique or a suite of MTD techniques alongside other computer security protections will depend on the application. Combining the MTD and fault tolerant techniques with additional security protections is often a requirement in order to meet security guarantees that are

not necessarily provided by the MTD techniques by themselves. For example, the MTD techniques may provide a mitigation to a "hitlist" type of attack [145], but the MTD techniques themselves do not provide the ability to detect the hitlist attack. Intrusion detection systems (IDSs), firewalls, security information and event management systems, and virus scanners, for example, should all be included as part of the overall security protection. The MTD strategies by themselves are not meant to be a comprehensive security solution that protects against all threats, but rather should be applied as an additional layer of defense in general.

One of the lessons learned in our research was that if there are commercially available products that are under consideration for integration as part of any security solution, they should be fully evaluated to ensure that they will meet all of the requirements of the targeted use case. If there is a mismatch in performance or functionality, early identification is important. We evaluated several switches that are SDN capable and their implementations varied significantly. The variations in implementation resulted in drastically different results. The differences did not impact the feasibility of applying the MTD approaches to an ICS environment in this case, but could make a difference in environments outside of ICS. Comparing performance in the software implementation to the hardware implementation required several experiments to identify and narrow down the observed slow down in latency to be attributed to the software based implementation.

The next lesson we learned in our research was that a full analysis of several software options that are candidates for integration into a system should be performed. We leveraged several open source software packages to support the MTD techniques developed. Open source software can be an extremely valuable and cost effective solution, but these solutions are not necessarily always stable production-ready solutions. The Open Daylight controller is a large code base written in the Java programming language with numerous contributors and a large amount of features available. The complexity of Open Daylight makes it difficult to troubleshoot and correct any errors encountered. Care should be

taken when selecting open source software as bugs that are discovered along the way may become problematic to correct or fit within the timeline of the project. We encountered a few OpenDaylight bugs, but we developed workarounds for those bugs. One problem we observed was when submitting a bulk amount of flows to be installed that was contained within a single transaction using a module named "bulk-o-matic." When the Open Daylight controller received the bulk flow inquiries, the bulk-o-matic module would throw several null pointer exceptions frequently but not every time, even when resubmitting the same query. The uncertainty of knowing if a flow would successfully install or fail is not an option within ICS environments. The workaround was to continuously submit queries until the bulk-o-matic module eventually accepted the bulk flow query. This solution was not ideal, but it did work after a few attempted queries so it was not a major focus of concern. This could be a major concern in a production environment because of the uncertainty about knowing when the bulk-o-matic module would actually accept and install the bulk flow.

Another lesson learned came from the experimentation process itself where we repeatedly performed experiments, each within a higher fidelity environment. Our research took the approach of running experiments in a simulated environment, then in a virtualized environment, and finally in a representative environment. The reason for this was that the simulated environment provided a means to collect results quickly to evaluate the feasibility of each MTD approach. The virtualized results provided a higher fidelity model that could be used to collect metrics of each MTD approach with network latency built in. Finally, the representative environment provided a platform to obtain results that did not potentially overlook pieces of the system that could not be anticipated in a simulated or virtualized environment. The sequence of tests provided insights into the effectiveness of each approach and allowed for cross-validation of each environment. The approach also allowed for easier troubleshooting early in the process before reaching the representative environment. Not all research projects will have access to a representative testbed, but in either case it is important to perform experimentation and simulations beforehand to en-

sure that the technology is feasible for the target environment before investing a significant amount of time and money into an approach that has not been fully tested and evaluated.

A limitation of the approaches we have presented are that they each depend on IP routable communications to operate. The concepts can be applied towards communications at layer 2 and below but have not been adapted towards those use cases at this point. The ability to introduce SDN into ICS environments may also not be an option as the environments may already be fully developed so it may be difficult to integrate new technologies. In this scenario, it may be difficult to convince decision makers to upgrade hardware or introduce software to support the SDN capabilities when everything in the network has been working fine as is for several years. This could also be a difficult proposition since standards and requirements must be met before introducing any technology into an ICS setting. There is also a long testing process that must be satisfied before any technology can make it to a field deployment, particularly in an ICS setting.

11.2 Future Work

Future areas of research can focus on expanding our research beyond ICS environments. Additional environments for potential research include cloud computing, Internet of Things (IoT), and mobile environments, each of which has their own unique sets of constraints and requirements. The tradeoffs between security and usability can similarly be analyzed and evaluated in each of those respective environments. Cloud computing has a large capacity, in terms of resources, however complete control of the physical infrastructure is lost. The loss of physical control may make some MTD defenses more difficult to deploy such as the MTD defenses that depend on specific hardware that must be installed. IoT environments may be difficult to scale path randomization since the enumeration of all possible paths in the network grows exponentially as the size of the network grows. Mobile environments may make IP randomization more challenging in recognizing the large number of devices that are dynamically entering and leaving the network constantly.

Furthermore, including the ability to perform forensic analysis as the MTD techniques are operating is another area of future research. If the IDSs are alarming on packets and logging randomized IP addresses, that information by itself is of little value to a forensic analyst. The forensic analysis has to be tied into and aware of the MTD techniques deployed to be effective which needs further investigation. Forensic capabilities built into the MTD techniques will be important for analysis in the event of a system compromise or also when actively observing the current state of the network. For better situational awareness, the MTD techniques should be available for security operations personnel to understand the current state of the network.

Autonomous systems are another area of future research for each of the MTD techniques discussed. If the SDN controller fails or one of the SDN capable switches fail, instabilities within the network will occur. To address this problem, building autonomy into the design is an interesting area of future research. With autonomy built-in, the SDN controllers and SDN switches can continue to operate and self-heal after a failure occurs. Currently, fault tolerant algorithms are developed to protect the SDN controller from failures. However, if all controllers fail, an interesting area of research is whether or not the switches can detect the controller failures and continue to operate on their own and take over the role of the controller. Similarly, if any of the SDN switches fail, an additional area of research would be to detect such failures and automate the reconfiguration of the network parameters to continue to operate as expected.

Another area for future research is to investigate the MTD techniques being applied and retrofitted into environments where SDN is not prevalent. In the case of traditional networks, an end point solution may be an appropriate area to apply the MTD techniques. As an endpoint solution, however, the MTD techniques should be designed so that network connections are not broken as network configurations are randomized. For IP randomization, modifications to the kernel would be necessary to maintain established connections within the TCP/IP stack during reconfiguration periods. Another solution

outside of the endpoint solution would be to introduce the MTD as a gateway device. This was the approach taken as part of our research. A related potential area for future research is to borrow techniques from metamorphic code generation typically used by an adversary, but instead apply those strategies as a computer defense. Continuously modifying software so that it is functionally equivalent but continuously changing implementations in time would increase the difficulty for an adversary to exploit software vulnerabilities.

Another area of research is to develop the SDN switches so that they are individually fault tolerant. Designing in crash tolerant and Byzantine fault tolerant algorithms would introduce resiliency into the SDN switches. These algorithms would require a cluster configuration for each of the SDN switches which may not be practical in all cases. However, in high fidelity environments, this would create resiliency for both the controller and the SDN switches. The ability to tolerate faults, crash or Byzantine faults, is an important area of research when designing and deploying any security system. An evaluation of the tradeoffs to the impact on the operational network and the adversary should also be performed in future areas of research to measure and quantify the effectiveness of the MTD techniques.

An additional area of future research is to introduce diversity into the SDN controllers as well as the SDN capable switches deployed. Diversity amongst implementations provided by several vendors would increase the difficulty for an adversary to successfully attack a large number of systems with a single exploit. The system as a whole would also be more resilient to attacks launched by adversaries. The adversary would be required to develop several versions of an exploit that would have to be tailored to each implementation in order to be successful. Furthermore, certain implementations may not be vulnerable to exploits which would result in a more robust solution when combined with the crash tolerant and Byzantine fault tolerant algorithms. An evaluation of the operational performance impacts of the diverse deployments would be another area of future research that

would help determine if the solution is still feasible of meeting the real-time constraints of an ICS environment.

11.3 Summary

We have developed several MTD approaches with the goal of introducing additional security protections to ICS environments. ICS networks are typically statically configured and have predictable communication patterns that do not change over extended periods of time. We have developed IPv4 randomization, IPv6 randomization, application port number randomization, and network communication path randomization to serve as MTD strategies for ICS networks. We evaluated all of the strategies for their effectiveness within an ICS environment. We implemented the MTD solutions as an SDN based solution and as an endpoint based solution. The SDN solution had the benefit of being a scalable solution that was transparent to the end devices, whereas the end point solution had the benefit of building the security protections directly into the end devices. Additionally, we developed the SDN controller systems to be fault tolerant to system crashes and Byzantine faults.

Each of the MTD strategies proved to be feasible within an ICS setting, all of which increased latency by less than 50 ms and in most cases under 20 ms. The environments evaluated as part of our research included a simulated environment, a virtualized environment and two representative environments. The simulated environment was a standalone system using local processes to simulate an adversary and a defender. The virtualized environment consisted of virtual machines to model an ICS system with the same ICS protocols enabled that would typically be seen in a field deployment. The representative environments included physical systems that harnessed the defender systems and the adversary systems.

The path randomization technique was the only technique that incurred more than 20 ms because of the possibility to take much longer paths than the fastest optimal path of

communication. All other approaches were well under the 20 ms requirement of most ICS environments. The operational measurements captured included bandwidth, throughput, CPU and memory utilization. Although bandwidth and throughput are typically not critical in most ICS environments due to the low bandwidth communications, the evaluation was performed in the event of synchrophasor measurements being a part of the network communications, which can consume bandwidth rates of 150 Mbits/sec[146]. We configured the network links to 10 Mbits/sec in the experiments performed and there were no significant performance impacts observed Our results showed a $\sim$1.8% decrease of bandwidth and throughput on average.

We also captured CPU utilization, memory utilization, and latency metrics when introducing the fault tolerant algorithms. The fault tolerant algorithms included crash tolerant algorithms and Byzantine fault tolerant algorithms for the SDN controller. The SDN controller was distributed into a cluster of SDN controllers and was shown to withstand crashes and malicious modifications of network flows. The CPU overhead of the crash tolerant algorithms averaged to be 17.7% more utilization than the baseline. The Byzantine fault tolerant algorithms consumed 17.9% more of the CPU to operate than the baseline measurements. These metrics may or may not be acceptable depending on the load placed on the SDN controller which would vary in each deployment. The memory requirements on the controller were quite a bit higher, mainly attributed to the open source SDN controller operating in a Java Virtual Machine that required 512 MB to run. An additional 92.2% and 92.6% of memory usage was utilized when enabling the Paxos crash tolerant algorithms and the Byzantine fault tolerant algorithms, respectably. The latency improved when enabling the SDN network because packets match criteria was minimal and ARP requests were not needed. The baseline round-trip time was observed to be 0.612 ms, while the crash tolerant and Byzantine tolerant algorithms showed a round-trip time of 0.546 ms and 0.542 ms, respectively. The fault tolerant algorithms impact observed in the set of experiments performed as part of our research was not a factor.

We evaluated several SDN capable switches, including two hardware switches and one software switch. The two hardware switches varied in their functionality. The first switch performed the match criteria and the action for the flows within software. The second switch performed these same operations in hardware. The latency was drastically reduced in the hardware implementation compared to the software implementation. The delays of the hardware switch were on the order of microseconds, while the software flow implementation gave results that were delayed on the order of milliseconds. The open source software switch evaluated also gave results that were in the milliseconds of increased delay. All SDN capable switches were well within the constraints of a typical ICS environment, but the hardware switch had the best performance results observed.

MTD is an active and promising area of research for ICS environments. We have shown that MTD techniques can be beneficial and effective in such a setting. The approaches were researched and analyzed against a number of adversaries either performing a DoS or DDoS attack. We performed experiments that showed that the amount of entropy available to the defender directly affected the adversaries' success rates. As the entropy increased, the success rates of the adversary decreased. We also considered adversaries performing side channel attacks and we discussed strategies to prevent such attacks against the MTD techniques, one of which was to vary the randomization frequencies to random intervals of time instead of fixed intervals of time. We then evaluated the operational costs and adversarial costs against one another to determine a balance between security and usability.

The MTD approaches presented here are meant to provide an additional layer of defense to an ICS system. The MTD approaches are not intended to be deployed by themselves, but rather integrated into a system of security tools to achieve an elevated overall level of security. A number of open problems that can build upon our research include evaluating these approaches in environments outside of ICS, exploring possible options of developing the same techniques for systems that have not adopted SDN, integrating the

MTD approaches within existing security monitoring systems, developing the MTD solutions so that they can run autonomously if needed, introducing fault tolerant algorithms to the SDN switches, adding in self-healing techniques to recover from attacks that are successful, and finally introducing diversity into the SDN controllers and SDN switches deployed. Each of the future areas of research can improve and enhance the existing concepts to create more resilient solutions that complement and build upon our research. We have shown that MTD techniques can be successful in an ICS setting and they have the potential of being applied more broadly towards other general computing environments.

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