UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS

Diverse Intrusion-tolerant Systems

"Documento Provisório"

Doutoramento em Informática
Especialidade em Ciência da Computação

Miguel Garcia Tavares Henriques

Tese orientada por:
Prof. Doutor Alysson Neves Bessani
e pelo Prof. Doutor Nuno Fuentecilla Maia Ferreira Neves

Documento especialmente elaborado para a obtenção do grau de doutor

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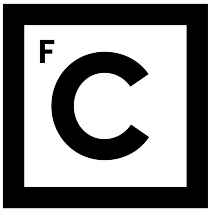

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Abstract

Over the past 20 years, there have been indisputable advances on the development of Byzantine Fault-Tolerant (BFT) replicated systems. These systems keep operational safety as long as at most f out of n replicas fail simultaneously. Therefore, in order to maintain correctness it is assumed that replicas do not suffer from common mode failures, or in other words that replicas fail independently. In an adversarial setting, this requires that replicas do not include similar vulnerabilities, or otherwise a single exploit could be employed to compromise a significant part of the system. The thesis investigates how this assumption can be substantiated in practice by exploring diversity when managing the configurations of replicas.

The thesis begins with an analysis of a large dataset of vulnerability information to get evidence that diversity can contribute to failure independence. In particular, we used the data from a vulnerability database to devise strategies for building groups of n replicas with different Operating Systems (OS). Our results demonstrate that it is possible to create dependable configurations of OSes, which do not share vulnerabilities over reasonable periods of time (i.e., a few years).

Then, the thesis proposes a new design for a firewall-like service that protects and regulates the access to critical systems, and that could benefit from our diversity management approach. The solution provides fault and intrusion tolerance by implementing an architecture based on two filtering layers, enabling efficient removal of invalid messages at early stages in order to decrease the costs associated with BFT replication in the later stages.

The thesis also presents a novel solution for managing diverse replicas. It collects and processes data from several data sources to continuously compute a risk metric. Once the risk increases, the solution replaces a potentially vulnerable replica by another one, trying to maximize the failure independence of the replicated service. Then, the replaced replica is put on quarantine and updated with the available patches, to be prepared for later re-use. We devised various experiments that show the dependability gains and performance impact of our prototype, including key benchmarks and three BFT applications (a key-value store, our firewall-like service, and a blockchain).

Keywords: Diversity, Vulnerabilities, Operating Systems, Intrusion Tolerance, Rejuvenations.

Resumo

Ao longo dos últimos 20 anos, temos assistido a avanços incontestáveis no desenvolvimento de sistemas replicados tolerantes a faltas Bizantinas (BFT). Estes sistemas mantêm uma operação correcta enquanto apenas f de um total de n réplicas falharem simultaneamente. Por isso, para garantir a correcção do sistema é assumido que as réplicas não sofrem de falhas comuns, por outras palavras que as replicas falham de forma independente. Em situações adversariais, esta assumpção implica que as réplicas não contêm vulnerabilidades semelhantes, caso contrário um único ataque pode ser usado para comprometer uma parte significativa do sistema. Esta tese investiga a forma de substanciar esta assumpção na prática explorando diversidade nas configurações das réplicas.

A tese começa com uma análise de um considerável conjunto de dados sobre vulnerabilidades para obter evidências de que a diversidade pode garantir independência nas falhas. Em particular, utilizámos dados de uma base de dados de vulnerabilidades para desenhar estratégias que constroem grupos de n réplicas com Sistemas Operativos (SO) diferentes. Os resultados demonstram que é possível criar configurações confiáveis de SOs que não partilhem vulnerabilidades num período razoável de tempo (i.e., alguns anos).

A tese propõe a um desenho de um serviço tipo antepara (do inglês *firewall*) que protege e controla o acesso a sistemas críticos e que pode beneficiar da nossa gestão de diversidade. A solução garante tolerância a faltas e intrusões através da implementação de uma arquitectura com filtros em duas camadas, permitindo descartar mensagens inválidas o quanto antes evitando os custos associados com a replicação BFT destas mensagens.

A tese também apresenta uma solução nova para gestão da diversidade de réplicas. A solução recolhe e processa dados de várias fontes de dados para calcular continuamente uma métrica de risco. Uma vez que o risco aumente, réplicas potencialmente vulneráveis são substituídas por outras réplicas (diferentes) para tentar maximizar a independência das falhas no serviço replicado. Depois, as réplicas removidas são colocadas em quarentena e actualizadas com as correcções disponíveis para mais tarde serem reutilizadas. Realizámos várias experiências que mostram os ganhos de confiabilidade e o impacto de desempenho do nosso protótipo, incluindo testes padrão (do inglês *benchmark*) e três aplicações BFT (uma aplicação de armazenamento chave-valor, o nosso serviço tipo antepara e uma blockchain).

Palavras-chave: Diversidade, Vulnerabilidades, Sistemas Operativos, Tolerância a Intrusões, Rejuvenescimento.

Resumo Alargado

A Tolerância a Faltas Bizantinas (BFT) é uma área de investigação bem estabelecida ao longo de vários anos. BFT tem como principal objectivo garantir a segurança de sistemas replicados mesmo na presença de faltas nos nós que os compõem. Resumidamente, os protocolos BFT garantem que as réplicas do sistema processam os pedidos dos clientes de maneira semelhante, comportando-se como uma máquina de estados replicada. Tipicamente, nestes sistemas a segurança é assegurada mesmo que um subconjunto das réplicas (normalmente, f em n réplicas) seja incorrecta. Ainda que não seja explícito, esta assumpção é verdadeira apenas se as réplicas falharem de forma independente. Caso contrário, comprometer f réplicas é virtualmente o mesmo que comprometer $f+1$ réplicas.

A primeira publicação de BFT é de 1980 [143] e foram sendo publicados mais trabalhos uns anos mais tarde [100, 154]. No entanto, só em 1999 é que BFT despertou a curiosidade da comunidade cientifica com o trabalho de Castro e Liskov [31]. Nos últimos vinte anos de investigação, foram feitos vários avanços no desempenho (ex., [10, 17, 108]), uso dos recursos (ex., [18, 118, 185, 192, 199]), e robustez (ex., [6, 22, 40]) destes sistemas. No entanto, BFT no geral e estes trabalhos em particular assumem, explicitamente ou implicitamente, que as réplicas falham de forma independente. Está implícito que é mais difícil comprometer todo o sistema (i.e., $f+1$ réplicas) se as réplicas não partilharem vulnerabilidades. Alguns trabalhos apresentam mecanismos ortogonais (ex., [11, 160]) para gerar diversidade e impedir vulnerabilidades comuns. Além destes, apenas alguns trabalhos implementam mecanismos de diversidade ainda que de forma muito limitada (ex., [6, 33, 160]).

Actualmente ainda não existe uma forma sistematizada para construir sistemas BFT confiáveis usando diversidade. Ademais, considerar um conjunto inicial de n réplicas diferentes, não é suficiente para sistemas que precisem de executar serviços durante muito tempo. Algures no tempo o sistema terá f réplicas comprometidas e precisará de as limpar e recuperar dos efeitos de possíveis falhas ou intrusões. Já existem vários trabalhos que implementam soluções de recuperação proactiva em sistemas BFT (ex., [32, 50, 144, 160, 171]). Estes reiniciam periodicamente as réplicas de forma a limpar o estado comprometido ou impedir ataques silenciosos em curso. No entanto, estes trabalhos (i) assumem que as réplicas falham de forma independente, (ii) não apresentam critérios para as escolhas de diversidade, ou (iii) apresentam soluções mais limitadas, por exemplo ofuscação de memória [26, 167]. Por estas razões e sem algum cuidado na escolha da diversidade das réplicas, estas podem manter as mesmas vulnerabilidades após as recuperações.

Finalmente, ao contrário das soluções BFT que já apresentam bastante maturidade, poucos investigaram como aplicar diversidade de forma confiável e quando é que as réplicas devem ser recuperadas. Esta tese tem como principal objectivo dar uma resposta teórica e prática para este problema.

Primeiramente, estendemos os resultados encorajadores do trabalho de mestrado do autor desta tese sobre diversidade de Sistemas Operativos (SO) [65]. Esse trabalho foi um dos primeiros passos para construir sistemas BFT confiáveis avaliando se existia realmente razão para assumir (explícita ou implicitamente) as vantagens da diversidade (ex., [1, 20, 32, 33, 39, 43, 98, 108, 130, 199]). Em particular, neste trabalho aumentámos o número de anos da análise, desenvolvemos três estratégias manuais para seleccionar SOs diversos de forma a minimizar a ocorrência de vulnerabilidades comuns. Além disso, observámos que mesmo utilizando versões diferentes do mesmo SO é possível construir configurações com poucas ou nenhumas vulnerabilidades partilhadas.

Nem todos os sistemas necessitam de técnicas avançadas como a tolerância a intrusões. Técnicas que permitam a adopção de diversidade nas réplicas são especialmente relevantes em sistemas críticos. Estes, devido à sua natureza, justificam um custo adicional para garantir a sua confiabilidade e segurança. Um bom exemplo deste tipo de aplicações são as anteparas (do inglês *firewalls*). Estas são usadas tipicamente como a primeira barreira de protecção contra ataques externos. As anteparas são responsáveis por gerir o tráfego que entra e sai de uma rede de acordo com determinadas regras ou comportamentos. As soluções mais genéricas sofrem de algumas limitações: como qualquer outro programa também contêm vulnerabilidades, normalmente são pontos únicos de falhas, levando a protecção seja comprometida caso uma vulnerabilidade seja explorada. É por isso importante garantir o funcionamento correcto deste tipo de sistemas.

Propomos, para resolver as limitações existentes, uma antepara aplicacional BFT chamada SIEVEQ. Esta integra o conceito de antepara com o de fila de mensagens. A solução apresenta uma arquitectura com vários níveis de filtragem, como uma peneira (do inglês *sieve*). Estes níveis permitem descartar mensagens que de outra forma seriam encaminhadas para todas as réplicas da antepara. Validámos este sistema em vários cenários de faltas, por exemplo com ataques de negação de serviço. Os resultados mostram uma melhoria no desempenho em comparação com sistemas semelhantes. Além disso, utilizámos uma amostra do tráfego dos Jogos Olímpicos de Verão de 2012 e verificámos que a nossa antepara tem capacidade para processar uma quantidade de dados realista.

Apesar dos primeiros resultados sobre diversidade serem encorajadores, encontrámos algumas limitações que podem comprometer a adopção desta técnica para garantir independência das faltas. Estas limitações afectam todos os trabalhos (ex., [4, 27, 63, 73, 76, 164]) que utilizam o *National Vulnerability Database* (NVD). É possível encontrar vulnerabilidades no NVD que não foram reportadas para todos os SOs que na prática são afectados. Encontrámos esta informação disponível noutras fontes, por exemplo, nos sites dos próprios produtores de programas. Além disso, o NVD carece de alguns dados relevantes sobre ataques e correcções (do inglês *patch*) que são relevantes

quando consideramos o ciclo de vida das vulnerabilidades. Identificámos outro problema nas soluções existentes, relacionado com uso de condições temporais para activar as recuperações das réplicas. Está implícito que as réplicas necessitam do mesmo esforço até serem comprometidas. Isto é particularmente relevante quando falamos de sistemas com diversidade [135], pois não é realista assumir que réplicas diferentes tenham as mesmas vulnerabilidades. É necessário construir soluções que adaptem o sistema de acordo com a avaliação do risco deste ser comprometido, ou seja de $f + 1$ réplicas terem a mesma vulnerabilidade e terem a sua segurança quebrada com um só ataque.

Desenvolvemos uma solução que mostra as vantagens de utilizar e gerir a diversidade de forma confiável. Esta solução elimina as limitações do NVD utilizando outras fontes de dados para enriquecer a nossa base de conhecimento sobre possíveis vulnerabilidades, ataques e correcções; Além disso, utilizamos técnicas de agrupamento de dados (do inglês *clustering*) que permitem agrupar informação não estruturada em grupos organizados por semelhança. A nossa solução recolhe informação online para monitorizar o risco do sistema contínua e automaticamente. Quando o risco aumenta, o sistema substitui as réplicas potencialmente vulneráveis por uma réplica que maximize a diversidade do conjunto. Esta solução foi implementada num protótipo, chamado LAZARUS, que é o primeiro sistema a modificar a superfície de ataque de sistemas BFT de forma confiável. O protótipo concretiza a gestão das réplicas com recurso à virtualização de máquinas e técnicas de aprovisionamento. Actualmente o LAZARUS suporta a gestão de 17 versões de SOs.

Validámos esta solução em dois conjuntos de experiências. A primeira demonstra que a gestão de risco do LAZARUS consegue reduzir significativamente o número de vulnerabilidades partilhadas num sistema replicado. A segunda avalia o impacto que a virtualização e a diversidade podem ter no desempenho. Em particular, estudámos o comportamento do LAZARUS com três aplicações diferentes: (1) uma solução de armazenamento chave-valor (KVS); (2) uma antepara de nível aplicacional (SIEVEQ); e (3) um sistema de ordenação de mensagens para uma plataforma de *blockchain*. Os resultados mostram que alguns conjuntos de SOs conseguem ter um desempenho aproximado a uma solução sem diversidade e em máquinas físicas. No entanto, algumas decisões de implementação ainda permitem algum espaço para melhorar, uma vez que tiveram um custo considerável no desempenho do sistema.

Palavras-chave: Diversidade, Vulnerabilidades, Sistemas Operativos, Tolerância a Intrusões, Rejuvenescimento.

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Acronyms

ARFF Attribute-Relation File Format. 104, 105

ASLR Address Space Layout Randomization. 18

BFT Byzantine Fault Tolerance. 1–4, 6–9, 12–16, 21, 22, 27, 30, 31, 49, 53–55, 57, 58, 67, 83–85, 87, 92, 95, 97, 99, 107, 108, 110, 112, 113, 115–117

BM Bare Metal. 107, 110

COTS Components Off-the-Shelf. 18, 21, 27, 28

CPE Common Platform Enumeration. 31–33, 97

CVC Common Vulnerability Count. 41

CVCst Common Vulnerability Count Strategy. 39, 40, 43, 44

CVE Common Vulnerabilities and Exposures. 25, 26, 31, 32, 86, 98, 104

CVI Common Vulnerability Indicator. 36–39, 42–45

CVIst Common Vulnerability Indicator Strategy. 39, 43, 51

CVSS Common Vulnerability Scoring System. 24–26, 29, 32, 87, 88, 93, 98, 116

DBMS Databases Management Systems. 84

DNS Domain Name System. 1, 35

DoS Denial-of-Service. 4, 5, 29, 35, 54–56, 59, 60, 63, 68, 70, 72, 74, 76–78, 81, 116

FPGA Field-Programmable Gate Array. 75

GPU Graphics Processing Unit. 75

HMAC Hash-based Message Authentication Code. 71

ICS Industrial Control Systems. 81

IDS Intrusion Detection System. 4, 20, 21, 53, 75, 117

IP Internet Protocol. 117

IRT Inter-Reporting Times. xxi, 45–47

IRTst Inter-Reporting Times Strategy. 39, 46

JVM Java Virtual Machine. 74, 84, 107

KVS Key-Value Store. 110, 113

LTU Logical Trusted Unit. 83, 84, 100, 101, 117

MAC Message Authentication Code. 14, 55, 61–64, 66, 68, 71

MTD Moving Target Defense. 29

NFS Network File System. 22

NIST National Institute of Standards and Technology. 31

NVD National Vulnerability Database. 3–5, 19, 23, 25–27, 29, 31–35, 39, 40, 47, 50, 51, 53, 84, 86, 89, 97, 98, 115, 116

OS Operating System. 2, 3, 5–7, 10, 19, 20, 22, 23, 26, 28–43, 45–51, 53, 58, 59, 84–86, 92, 95, 97, 99, 106–113, 115–117

OSI Open Systems Interconnection. 53

OSINT Open Source Intelligence. 6, 22, 83, 84, 87, 89, 97, 98, 101, 102, 116

OSVDB Open Sourced Vulnerability Database. 23–26

OTS Off-the-Shelf. 3, 11, 16, 18–22, 30, 31, 34, 85

PO Proactive Obfuscation. 22

POA Potential for Attack. 23

PPZDA Potential Pseudo Zero-Day Attack. 23

PRRW Proactive-Reactive Recovery Wormhole. 15, 16

PZDA Pseudo Zero-Day Attack. 23

RSA Rivest–Shamir–Adleman. 71

SCADA Supervisory Control and Data Acquisition. 6, 53, 101

SCIT Self-Cleaning Intrusion Tolerance. 28

SHA Secure Hash Algorithm. 71

SIEM Security Information and Event Management. 5, 72, 78, 79, 81

SMR State Machine Replication. 11, 12, 14, 15, 71, 76, 101, 102

SQL Structured Query Language. 19, 32

SVM Support Vector Machines. 25, 26

TLS Transport Layer Security. 99

TOM Total Ordered Multicast. 58, 63, 66, 68, 69, 71

VM Virtual Machine. 6, 15, 22, 29, 58, 73, 83, 97, 99, 101, 103, 106, 107, 109, 110, 117

VMM Virtual Machine Manager. 15

VPN Virtual Private Network. 27

WINE World Wide Intelligence Network Environment. 24

XML Extensible Markup Language. 31, 32

XSS Cross-site scripting. 86

YCSB Yahoo! Cloud Serving Benchmark. 110–112

ZDA Zero-Day Attack. 23

1 Introduction

1.1 Context and Motivation

Intrusion Tolerance. Byzantine Fault Tolerance (BFT)[1] is a well-established area of research that aims to guarantee the safety of replicated systems even in the presence of some faulty nodes that arbitrarily deviate from their specification. In a nutshell, BFT protocols guarantee that replicas agree on the order of the message execution, ensuring that replicas work as a state machine. The BFT safety holds as long as no more than f out of a group of n replicas are faulty. Although not explicit, this assumption leverages on the strict condition that nodes (must) fail independently. Otherwise, compromising f replicas is virtually the same as compromising $f+1$ because the same vulnerabilities would exist in all nodes.

BFT was first proposed in 1980 by Pease *et al.* [143], and in the following years a few other works continued to investigate on this subject [100, 154]. However, only much later, with the work by Castro and Liskov [31] did the distributed system community start to actively research on this area. In the last twenty years, BFT systems have benefit from great advances on the performance (e.g., [10, 17, 108]), use of resources (e.g., [18, 118, 185, 192, 199]), and robustness (e.g., [6, 22, 40]). However, BFT in general and these works in particular, assume, either implicitly or explicitly, that replicas fail independently. This assumption implies that it should take more time to compromise a system if its nodes do not share weaknesses. A few works suggest some form of diversity mechanism (e.g., [11, 160]) to avoid these common weaknesses or rule out the possibility of malicious failures from their system models. However, only a few works have implemented and experimented with such diversity mechanisms (e.g., [6, 33, 160]) but in a very limited way.

In other contexts, dependable applications take advantage of diversity mechanisms. In these cases, diversity is applied *intuitively*. For example, in avionics engineering, a few aircraft solutions embrace the diversity of components to avoid accidental failures [198]. More specifically, in 2014, the U.S. Navy developed the Resilient Hull, Mechanical, and Electrical Security (RHIMES), which introduce diversity through a "*slightly different implementation*" for each programmable logic controller [61]. Another example of a critical system that naturally adopted diversity are the Domain Name System (DNS) root servers. According to L. Liman (chair of the Root Server System Advisory Committee)

[1] In this thesis we interchange Byzantine fault tolerance (*noun*) with Byzantine fault-tolerant (*adjective*) using the BFT acronym for both.

each operator employs its own configurations as "*it allows for great operational diversity*" [111]. The goal is to avoid that a single software bug would bring down all servers. A more recent example is Blockchain technology, that in some cases, implements a BFT network in a large and decentralized way. Therefore, it shares the same limitations of the enumerated BFT works, i.e., the network nodes may have common weaknesses. Recent evidence already demonstrated that Bitcoin [91] can suffer from this problem with potential nefarious consequences. Moreover, Ethereum stats show that a few Operating Systems (OSes) are deployed in the various nodes [54, 55] to deter attacks from exploiting common mode failures.

Despite the adoption of (naive) diversity solutions in practical systems, other variables must be considered to make systems dependable and secure. For example, even considering an initial set of n diverse replicas, long-running services need to be constantly monitored to remove possible failures and intrusions. A few works on the proactive recovery of BFT systems [32, 50, 144, 160, 171] propose periodically replicas restarts to clean up undetected faulty states introduced by a stealth attacker. However, these works (i) assume failure independence of the nodes, and (ii) do not provide a well-thought justification to support their diversity decisions or (iii) use limited solutions (e.g., memory randomization) [26, 167]. Therefore, replicas may keep the same weaknesses unless careful diversity choices are introduced on recoveries.

Finally, contrary to the already established maturity of BFT solutions, there is a lack of research work debating how to apply diversity in a dependable way (e.g., choosing software configurations that are more dependable) and when these configurations should be changed (e.g., which is the most appropriate moment for recovering replicas with different software).

Vulnerabilities. The reason why BFT solutions have to make stronger assumptions on the replicas failure independence is due to the existence of vulnerabilities in their code.[2] These weaknesses can be exploited by a malicious entity to compromise a security property (i.e., integrity, confidentiality, and availability). If a vulnerability is found by a vendor or by a third-party software analyst, the vendor releases a patch that can be applied in the system to remove the weakness. On the contrary, if a vulnerability is found by malicious hackers, it is especially critical as their disclosure occurs only after the detection of its exploitation. This particular type of weakness is called zero-day vulnerability. Such vulnerabilities are a critical element present in many notable attacks (e.g., Stuxnet [57]) and are traded on the black market at high prices [3, 177]. Moreover, big companies and organizations are promoting bug bounty programs as an attempt to find zero-day vulnerabilities before these are found by malicious hackers (e.g., Google Vulnerability Reward Program [71], Facebook Bug Bounty Program [56], Microsoft Bounty [123], and DARPA Cyber Grand Challenge (2016) [47]).

[2] In this document, a vulnerability is a special kind of software weakness (or bug or flaw) that can be exploited to break some security property.

In a BFT context, an attacker can compromise a replica once a piece of code is developed to exploit a vulnerability in a software component of the node. If the replicas have the same code and configuration, they share the same vulnerabilities. Therefore, as soon as the attacker discovers a zero-day vulnerability, he or she will eventually be able to compromise $f + 1$ replicas. The rationale behind diversity on BFT is that different replicas do not share the same vulnerabilities. Therefore, it becomes more difficult to discover and exploit vulnerabilities in $f + 1$ replicas than to compromise just f replicas.

1.2 Objectives and Contributions

In the past, several researchers developed and improved techniques that made intrusion tolerance a cornerstone of security and dependability. Nevertheless, a few problems were left open and still lack effective answers. This thesis aims to push forward intrusion tolerance to a more effective and practical ground. The main contributions of this thesis are summarized into the following sections, along with the related publications.

1.2.1 Evidence for Implementing Diversity

The results achieved during the author's MSc thesis encouraged us to extend the work on the diversity of Off-the-Shelf (OTS) OSes [65]. This is a first step towards the design and development of dependable BFT systems, and it aims to assess how accurate were the implicit or explicit assumptions on diversity (e.g., [1, 20, 32, 33, 39, 43, 98, 108, 130, 199]). We studied the information about vulnerabilities from the National Vulnerability Database (NVD) [133] to answer the question: *What are the dependability gains from using diverse OSes on a replicated intrusion-tolerant system?* Some of the extensions to the original work, that are presented in this thesis are: (i) we expanded the dataset from NVD to further years, to extend previous observations; (ii) we devised three manual strategies for selecting diverse software components, to minimize the incidence of common vulnerabilities in replicated systems; and (iii) we found out that employing different OS releases of the same OS is enough to warrant its adoption as a more straightforward and manageable configuration for replicated systems. The described contributions (together with the ones published during the MSc [65]) are reported in the following publication:

1. **Analysis of Operating System Diversity for Intrusion Tolerance**, Miguel Garcia, Alysson Bessani, Ilir Gashi, Nuno Neves, and Rafael Obelheiro, in *Software: Practice and Experience, 44(6), June 2014*.

1.2.2 BFT Multi-layer Resiliency

Firewalls are used as the primary protection against external threats, controlling the traffic that flows in and out of a network. Typically, they decide if a packet should go through (or be dropped) based on the analysis of its contents. Most generic firewall solutions suffer from two inherent problems: First, they have vulnerabilities as any other system, and as a consequence, they can also be the target of attacks. For example, NVD shows that many security issues have been observed in commonly used firewalls. The following numbers of security issues are reported by NVD for the interval 2010 and 2018:[3] 205 for the Cisco Adaptive Security Appliance; 123 in Juniper Networks solutions; and 50 related to iptables/netfilter. Moreovoer, common protection solutions often have been the target of malicious actions as part of a wider scale attack (e.g., anti-virus software [34], Intrusion Detection System (IDS) [7] or firewalls [37, 38, 97, 175]). Second, firewalls are typically a single point of failure, which means that when they crash, the ability of the protected system to communicate may be compromised, at least momentarily. Therefore, ensuring the correct operation of the firewall under a wide range of failure scenarios becomes imperative. In the last decade, several significant advances occurred in the development of intrusion-tolerant systems. However, to the best of our knowledge, very few works proposed intrusion-tolerant protection devices, such as firewalls. Performance reasons might explain this gap, as BFT replication protocols are usually associated with significant overheads and limited scalability. Additionally, achieving complete transparency to the rest of the system can be challenging to reconcile with the objective of having fast message filtering under attack.

We address these problems with a new protection system, called SIEVEQ, that mixes the firewall paradigm with a message queue service. In SIEVEQ, we explore a different design for replicated protection devices, where we trade some transparency on senders and receivers for a more efficient and resilient firewall solution. In particular, we propose an architecture in which critical services and devices can only be accessed through a message queue where application-level filtering is implemented. It is assumed that these services have a limited number of senders, which can be appropriately configured to ensure that only they are authorized to communicate through SIEVEQ. The solution is based on a fault- and intrusion-tolerant architecture that applies filtering operations in two stages, acting like a sieve. The first stage, called *pre-filtering*, performs lightweight checks, making it efficient to detect and discard malicious messages from external adversaries. In particular, messages are only allowed to go through if they come from a pre-defined set of authenticated senders. Denial-of-Service (DoS) traffic from external sources is immediately dropped, preventing those messages from overloading the next stage. The second stage, named *filtering*, enforces more refined application level policies, which can require the inspection of some message fields or need the enforcement of specific ordering rules.

[3] To the date of Jul 12^{th} 2018.

SIEVEQ was evaluated in different scenarios and the results show that it is much more resilient to DoS attacks and various kinds of intrusions than existing replicated-firewall approaches. We also evaluated SIEVEQ considering the protection of a Security Information and Event Management (SIEM) system. The test environment emulated the setup of the 2012 Summer Olympic Games, where the same sort of security events was generated and transmitted across the network. The experiments demonstrate that SIEVEQ can handle a workload up to sixteen times higher than the observed load in the 2012 Summer Olympic Games, without noticeable degradation in performance.

The contributions of this work resulted in the following publications:

2. **An Intrusion-Tolerant Firewall Design for Protecting SIEM Systems**, Miguel Garcia, Nuno Neves, and Alysson Bessani, in the *Workshop on Systems Resilience together with the IEEE/IFIP International Conference on Dependable Systems and Networks, Budapest, June 2013*.

3. **SIEVEQ: A Layered BFT Protection System for Critical Services**, Miguel Garcia, Nuno Neves, and Alysson Bessani, in *IEEE Transactions on Dependable and Secure Computing, 15(3), May 2018*.

1.2.3 Applying Diversity on BFT Systems

Our initial attempt to validate diversity gave substantial evidence to the claim that employing different OSes ensures failure independence to some extent. However, this preliminary analysis suffers from the limitation of being based on a single dataset, which might have imprecisions (e.g., [4, 27, 63, 73, 76, 164]). For example, it is possible to find vulnerabilities in the NVD feeds that are only reported for a subset of the OSes that are affected by them. We have found this missing information on other sources (e.g., the vendors' security advisories). Therefore, NVD-based studies may provide optimistic conclusions about the benefits of selecting different software components based on common vulnerabilities. Moreover, NVD lacks data concerning exploits and patches that is relevant when considering the vulnerabilities life-cycle.

Systems that implement time-triggered recoveries consider that it takes the same time/effort to compromise each replica, by assuming that vulnerabilities are similarly easy to find and exploit. This assumption is unrealistic, especially when diversity is considered [135]. Therefore, tailored methods are required to evaluate the risk of a replicated system becoming vulnerable (i.e., $f+1$ replicas suffer from the same weaknesses).

In this thesis, we address these problems from both a theoretical and practical perspective, with the objective of *finding evidence that demonstrates the gains of utilizing diversity*, *managing diversity in*

a dependable way, and *implementing diversity with practical mechanisms*. First, we suppress the aforementioned limitations of NVD by using clustering techniques that group similar vulnerabilities, which potentially can be attacked by (variations of) the same exploit. Moreover, we employ additional Open Source Intelligence (OSINT) data sources to build a more complete knowledge base about the possible vulnerabilities, exploits, and patches related to the systems of interest. Then, the clusters and the collected data are used to calculate a metric that is employed to assess the risk of a BFT system becoming compromised by the existence of common vulnerabilities. Once the risk increases, the system replaces the potentially vulnerable replica by another one, to maximize the failure independence of the replicated service. The solution continuously collects data from the online sources and monitors the risk of the BFT in such a way that removes the human from the loop. These mechanisms were implemented, in a prototype named LAZARUS, to be fully automated and transparent to BFT systems. Moreover, the current implementation of LAZARUS manages 17 OS versions, supporting the BFT replication of a set of representative applications. The replicas run in Virtual Machines (VMs), allowing provisioning mechanisms to configure them.

We conducted two sets of experiments: The first one demonstrates that LAZARUS risk management can prevent a group of replicas from sharing vulnerabilities over time; The second one, reveals the potential negative impact that virtualization and diversity can have on performance. In this experiment, we evaluated LAZARUS with three BFT applications: (1) a Key-Value Store, (2) the SIEVEQ firewall (presented in the previous section), and (3) a BFT ordering service for the Hyperledger Fabric blockchain platform. The overall results show that if naive configurations are avoided, BFT applications in virtualized diverse configurations can perform close to a homogeneous bare metal setup.

The contributions of this work resulted in the following publications:

4. **DIVERSYS: DIVErse Rejuvenation SYStem**, Miguel Garcia, Nuno Neves, and Alysson Bessani, in the *Simpósio Nacional de Informática (INFORUM), Caparica, September 2012*.

5. **Towards an Execution Environment for Intrusion-Tolerant Systems**, Miguel Garcia, Alysson Bessani, and Nuno Neves, Poster session in the *European Conference on Computer Systems (EuroSys), London, June 2016*.

6. **LAZARUS: Automatic Management of Diversity in BFT Systems**, Miguel Garcia, Alysson Bessani, and Nuno Neves – *Submitted for publication in 2019*.

Additional contributions. A collaboration with a colleague resulted in a work on the design and implementation of a Supervisory Control and Data Acquisition (SCADA) system enhanced with BFT techniques. We documented the challenges of building such a system from a "traditional" non-BFT solution. This effort resulted in a prototype, implemented by the colleague, that integrates the Eclipse

NeoSCADA [53] and the BFT-SMaRt [22] open-source projects. Although this contribution is out of the scope of the thesis, it is easy to envision the integration of this prototype with Lazarus.

7. **On the Challenges of Building a BFT SCADA**, André Nogueira, Miguel Garcia, Alysson Bessani, and Nuno Neves, in *Proceedings of the IEEE/IFIP International Conference on Dependable Systems and Networks, Luxembourg, June 2018.*

1.2.4 Thesis Statement

We summarize our findings in the following thesis statement:

> *It is possible to build dependable BFT replicated systems by minimizing the number of shared vulnerabilities in the nodes through software diversity. Additionally, it is possible to manage these systems by continuously monitoring OSINT data and deciding when replicas should be rejuvenated with diverse software, aiming at the deployment of a more dependable configuration.*

1.3 Thesis Overview

Chapter 2: Background and Related Work. Provides a background overview of intrusion tolerance. It also presents the most relevant related works on the different areas of intrusion tolerance. In particular, it is focused on BFT protocols, replica rejuvenations, and diversity. It also identifies several works that implement diversity guided by *intuition*, then it covers the works that analyze vulnerabilities. Finally, it describes some solutions to manage intrusion-tolerant systems.

Chapter 3: A Study on Common OS Vulnerabilities. Gives evidence that diversity may improve systems' dependability. It shows that with carefully made choices one can build dependable systems using different OSes. Although some solutions are (now recognized by us as) naive, they were a significant contribution to push us towards building dependable systems with diversity.

Chapter 4: SieveQ: A BFT Firewall. Presents SieveQ that implements a firewall-like application. The SieveQ architecture provides additional resilient mechanisms when compared with state-of-the-art solutions, such as resorting to several levels of filtering and alternative mechanisms for replication. To conclude the chapter, we present an evaluation showing the performance and resilience of SieveQ under attack.

Chapter 5: Diversity Management for BFT Systems. Describes our proposal for solving a few of the existing open problems with intrusion tolerance. In particular, we show how to solve data

source limitations that affected several works in the past. Moreover, we present a new metric that is used to minimize the risk of BFT replicas becoming vulnerable by common mode failures. Finally, we evaluate the efficacy of our approach by executing the algorithm against different configuration strategies that have been used in related works.

Chapter 6: LAZARUS Implementation. Presents the LAZARUS implementation and describes the decisions made on its several components. For example, how LAZARUS collects the data from the different sources and uses it to build clusters; how we setup and deploy the different nodes using provision and virtualization tools. Moreover, we present an extensive performance evaluation of LAZARUS-managed systems. In particular, we evaluate the performance of three real BFT applications, one of which is SIEVEQ.

Chapter 7: Conclusion and Future Research Directions. Summarizes the results that were achieved with this thesis and identify possible directions for future research.

2 Background and Related Work

This chapter explains why intrusion tolerance is useful, and then it describes the most relevant related works within this topic. It covers mainly the state-of-the-art of BFT replication protocols, the techniques to rejuvenate replicas, and the benefits of using software diversity on distributed and replicated systems. It also presents a few practical attempts to build systems that explore these techniques. Finally, it describes some of the works on vulnerability analysis and how such analysis can improve classical intrusion-tolerant systems.

2.1 The Need for Intrusion Tolerance

A realistic way to provide security is to build mechanisms that protect potentially vulnerable systems from attackers. This is particularly important when considering critical systems that attract highly motivated attackers. Here, the focus is on designing mechanisms that make the systems safer despite their number of vulnerabilities and the attacker's power. In the following, we make an overview of the various approaches that can be combined to deal with the challenge of providing security and dependability [13] for critical systems.

2.1.1 Vulnerability Prevention

One of the primary techniques to reduce the attackers' success is to avoid the introduction of vulnerabilities throughout the development phases until the software is deployed in production. One way to do that is to detect and remove vulnerabilities during the development and testing stages. Here, we distinguish seven different approaches that attempt to prevent software weaknesses.

The most basic approach is manual analysis. Typically, developers (named testers) resort to automatic tools to perform a set of tests that validate program inputs and outputs. Often, in this type of analysis, the tester needs to check the results manually. The accuracy of the solution depends on how well the inputs cover all the behavior of the software and if the tester understands well the causes for the output violations (a description of this process is presented in [188]).

Model checking is another approach, which abstracts the software code and formally verifies the program invariants. However, the most common techniques typically over-simplify the protocols to

make them formally verifiable or just verify one or a few versions [35, 104, 136]. Moreover, this process is time-consuming, and prohibitively expensive for most companies, which makes it difficult to scale to complex systems [69]. For example, an OS microkernel was formally verified [104], but contrary to the Linux kernel that has more than 20 million lines of code [120], this only had 10 thousand lines of code.

One way to find pieces of code that could harm the correctness of the software is to run static vulnerability analyzers. Depending on the tool capabilities, this type of analysis can be limited as it looks for small parts of the code that alone may not cause major alarm. On the other hand, it is exhaustive but may require the availability of the source code. In the software's reliability area, there are significant advances in automatic and efficient error detection [195]. A particular technique used in security that tackles both coverage and code complexity is taint analysis [126, 139, 197]. In this technique, any program variable that can be modified by a user is seen as a vulnerability trigger. Then, when it is accessed, and copied to other variables, the taint propagates to other parts of the program. The main limitation of taint analysis is that it can make mistakes while deciding on the propagation of values, leaving bugs undetected or producing many false alarms.

Another conventional solution to explore software bugs is fuzzing. This is a dynamic technique, as it runs against executing software, and its success in finding vulnerabilities results from a good set of input test cases. These can be built manually and tuned for a particular application, or randomly generated. For the latter they are likely to fail on triggering more complex vulnerabilities due to complex guard conditions [64].

Symbolic execution is a technique that (statically) analyzes software code to generate path constraints and then creates test inputs to (symbolically) run the program [29]. However, this approach has some limitations that makes it difficult to scale, due to multiple path analysis.

A few works combine the best characteristics of some of the approaches described before to overpass some of their limitations. For example, solutions that combine symbolic execution and fuzzing [70, 101, 174] or symbolic execution with taint analysis [75].

Finally, some works proposed workarounds that intended to minimize the window of vulnerability between the vulnerability disclosure and the patch release [74, 88]. Typically, these solutions have two phases: first, the detection phase where they look for vulnerabilities in the source code, and a second one, where they instrument the code with a vulnerability workaround. Although they may have good coverage of the vulnerabilities, there are a few caveats on applying such solutions. For example, workarounds may crash the application upon the vulnerability activation, or they may disable the relevant functions that clients use in the software [88] compromising the availability.

Although these techniques are steps towards more robust software, they all have limitations on coverage, as either they fail to test the whole code, or they miss some more complex vulnerabilities. In any case, these techniques are very useful to employ before the vulnerable system is in production.

2.1.2 Fault Detection and Removal

Most of the previously described techniques work offline and are not complete. Therefore, unknown vulnerabilities may arise when the application is already online, allowing the system to be compromised. Therefore, we need more complementary approaches to cope with the vulnerabilities that are left in the programs and that can be successfully exploited. A possible solution is to detect intrusions at runtime and then trigger recovery mechanisms to clear their effects.

Since some attacks exploit a combination of different vulnerabilities (e.g., [57]), which isolated would be harmless, it is hard to detect them when the system is in production. Three potential problems with fault detection and removal are: First, perfect intrusion detectors are dependent on the application semantics [52], and therefore, OTS detectors will necessarily be inaccurate; Moreover, typically forms of detection are based on attack signatures [168] and consequently they will miss previously unknown attacks and the signatures databases can become outdated. Second, the application can experience some periods of unavailability while it is recovering [190], thus preventing the users from benefiting from the offered service; Finally, recovering a system might clean its faults, but the software remains vulnerable. Therefore, it might be easy for an attacker to repeat the same procedure to compromise the system every time it recovers.

2.1.3 Fault Tolerance and Masking

Previous approaches assume that vulnerability removal can be achieved or that it is possible to detect all the attacks against the system. However, these assumptions are unrealistic, and it is not advisable to trust the security and dependability to a sole approach, as it creates a single point-of-failure [184]. Thus, once the system becomes compromised the whole infrastructure becomes exposed to more attacks.

One way to build a system with tolerance and masking capabilities is to utilize a group of application replicas that execute equal commands in the same order. Primary-backup replication (i.e., $1+1$ replicas) would suffice if only crash faults are considered. If one of the replicas stops executing, the other can replace it and still deliver the service correctly. However, if arbitrary faults may occur, this form of replication is insufficient because compromised replicas could return arbitrary results to the users, impeding the correct answer to be delivered.

State Machine Replication (SMR) [112] is an approach that has been employed to ensure fault tolerance [162] of fundamental services in modern internet-scale infrastructures (e.g., [30, 42, 89]). SMR is achieved in distributed systems that run an agreement protocol that guarantees that all the replica nodes (i) start from the same state, (ii) process an equal sequence of messages, and (iii) execute the same state transitions. These properties guarantee that a service runs in a similar manner in all replicas, and therefore, they all produce the same outputs. However, to address malicious (or sometimes called Byzantine) faults one needs to complement SMR with intrusion tolerance techniques [184].

Intrusion tolerance was first proposed by Fraga and Powell [59] as a way to build secure systems capable of maintaining its correctness despite the existence of faults. More formally, we adopt the following definition:

Definition 1. *"An intrusion-tolerant system is a replicated system in which a malicious adversary needs to compromise more than f out-of n components in less than T time units to make it fail."* [19]

BFT SMR allows a system to operate correctly even in the presence of compromised replicas. Since no single replica can be trusted completely, the system's correctness comes from the Byzantine majority of correct nodes. For example, to tolerate a single fault (i.e., $f = 1$) the system must have four replicas (where $n \geq 3f + 1$) [32]. Although BFT protocols provide safety for a bounded number of faulty nodes, with sufficient time (i.e., greater than T) an adversary can compromise $f + 1$ nodes. To address this issue, additional mechanisms are needed to clean the replicas' state. For instance, one may employ periodic recoveries [32, 50, 144, 160, 171].

If a recovered node remains vulnerable to the same attack, the time to compromise $f + 1$ replicas becomes smaller as the attacker already knows how to exploit the existing weaknesses. For this reason, several authors have built their systems assuming that some mechanism is used to provide failure independence even when recoveries occur [20, 32, 171, 185]. Hence, to avoid reintroducing nodes with the same flaws in the system, the recovery should change the replica's code somehow.

In the following sections, we present and describe several works on specific areas of intrusion tolerance, covering the various issues that we have just mentioned.

2.2 Byzantine Fault Tolerance

Castro and Liskov's PBFT [31] was the first approach for building a practical BFT replicated system. It was initially proposed as a solution to handle faults of both accidental and malicious nature. The correctness of a BFT service comes from a quorum of correct nodes capable of reaching consensus on the total order of messages to be processed by the replicas. PBFT implements a SMR protocol

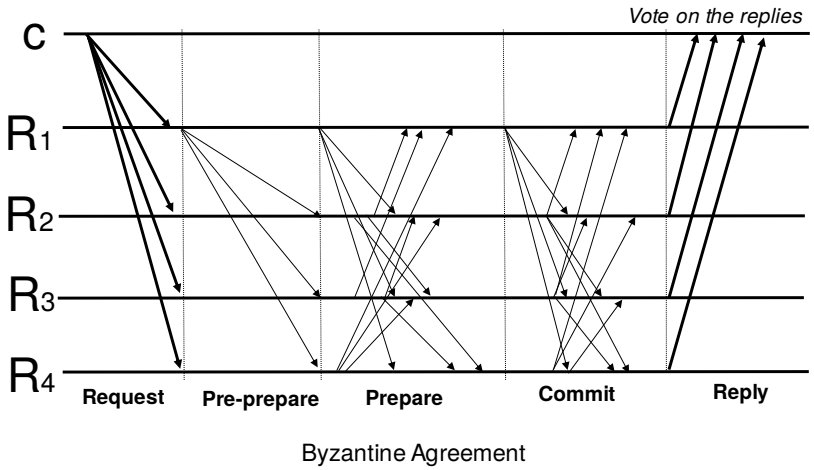


Figure 2.1 – PBFT protocol overview, where *C* represents a client of a service implemented by replicas *Ri*.

that guarantees safety even with up to $\lfloor \frac{n-1}{3} \rfloor$ faulty replicas out of a total of n. To tolerate a single replica failure, this sort of solution typically requires four replicas.

PBFT guarantees that each correct replica executes the same commands in the same order and then produces equal outputs. Figure 2.1 illustrates an execution of the PBFT protocol and it can be summarized as follows. A client *(C)* sends a *request* to all the replicas *(R1-R4)* to execute an operation of the service. Then, the leader replica assigns a sequence number to the request and multicasts a *pre-prepare* message to the other replicas. If the replicas agree with the leader, they multicast a *prepare* message to each other. At this phase of the protocol, every correct replica agrees on the ordering of the message. Next, every replica multicasts a *commit* message. After correct replicas receive the *commit* messages from a quorum, they execute the request deterministically. In the end, they *reply* to the client with result of the operation. The client waits for $f + 1$ equal responses to guarantee that the correct result is delivered.

PBFT good performance encouraged the development of other to improve BFT in different ways. Table 2.1 gives an overview of a few of them.

Relationship with this thesis. In this thesis, we propose a control plane for BFT systems. The goal is to ensure that a service executes correctly while tolerating malicious failures in a subset of the replicas. The implementation of a BFT protocol is a complex task, namely if it supports mechanisms for state transfer and reconfiguration while ensuring good performance. Therefore, we will rely on existent libraries instead of building a new one. [1]

[1] Nevertheless, for some of our contributions (see Chapter 4) we had to perform some modifications on the chosen library.

ZYZZYVA [108]	Introduced speculation to avoid the expensive three-phase commit before processing the requests. Since this may introduce some inconsistencies in the state of the replicas when speculation fails, it needs the help from the client to fix the problem.
AARDVARK [40]	Introduced a new design that improves the performance under faulty scenarios trading some performance on the normal case. The decision was to design a system that prefers robustness over performance on gracious executions. Some counter-intuitive decisions on the architecture favored the overall execution on both gracious and faulty scenarios.
RITAS [130]	It allows an alternative SMR implementation based on randomized protocols. More precisely, it uses a local coin toss algorithm to reach agreement among the nodes. This work demonstrated that the *claimed inefficiency* of randomized protocols is not verified in practice.
PRIME [6]	It introduced a new *correctness criterion* that derives from bounded delays during a normal execution. Uses a mechanism to detect malicious leaders that delay the execution to the limit of the (defined) time out. The protocol ensures that the (correct) non-leader replicas can bound the *delay* of the leader based on messages they receive from the clients.
MINBFT [185]	Reduced the number n from $3f+1$ to $2f+1$ by leveraging on trusted components. These components are deemed trusted because they are based on simple hardware that can be verified. Additionally, this solution decreases one communication step when compared to other BFT protocols.
BFT-SMART [22]	It was developed to be a modular and multicore-aware. It supports replica reconfiguration, as it allows nodes to leave and join the replica group. It is one of the few BFT systems with a robust implementation available and being maintained.
COP [17]	It is the fastest BFT implementations, having reached 2.4 million operations per second. This was achieved mostly due to BFT architecture changes, like the creation of *consensus instances* which are assigned to a client or a group of clients. These (separated) *consensus instances* are executed in parallel increasing the throughput of the system.
ABSTRACT [10]	It subsumes some of the works described before in a platform that works as a modular composite of BFT solutions. The main idea is to make use of the several optimizations made by each solution, for example, it uses ZYZZYVA protocol in best-case scenarios.

Table 2.1 – Brief overview of some relevant BFT works.

2.3 Replica Rejuvenation

Software rejuvenation was proposed in the 90's [86, 87] as a proactive approach to prevent component performance degradation and failures due to software aging. This solution was implemented using three components: a watchdog process (`watchd`), a checkpoint library (`libft`) and a replication mechanism (`REPL`). A primary component executes the application and also runs the `watchd` to monitor the application crashes and hangs. The backup component keeps its application inactive and observes the primary node in order to be able to substitute it. Additionally, there is a routine (provided by `libft`) that periodically makes checkpoints and logs messages. These checkpoints are replicated with `REPL` in the backup node. When the primary node crashes or hangs, it is restarted, and if needed the backup takes his place on the execution.

Some years later, proactive recovery was also adopted on BFT systems by Castro and Liskov [32]. In order to support long-running services, the aim is to rejuvenate replicas periodically to eliminate the effects that an attacker could have caused on a faulty node. This mechanism allows that the system remains correct as long as the adversary controls up to f replicas before a recovery. Moreover, PBFT introduced additional mechanisms to guarantee that SMR properties are maintained even

with recoveries. In particular, a state transfer protocol, which allows that recovered replicas fetch a correct and up to date state from the other (correct) replicas. Additional assumptions were needed to guarantee the PBFT liveness and safety during the recoveries: (i) each replica contains a trusted chip to save its private key, which can sign and decrypt messages without revealing this key; (ii) the replicas' public keys are stored in a read-only memory; and (iii) a watchdog timer is used to avoid human interaction to restart replicas. The watchdog hands the execution to a recovery monitor that cannot be interrupted.

An alternative way to implement BFT systems is to resort to quorum systems. Zhou *et al.* [204] presented COCA, a fault-tolerant online certification authority to be deployed both in a local area network and on the internet. Proactive recovery is also employed to rejuvenate replicas' state including the capacity to refresh the private keys of the nodes. The adoption of quorum systems does not require timing assumptions and, contrary to PBFT, COCA did not rely on trusted components. However, these options may compromise the safety (i.e., f faulty nodes in-between recoveries) of asynchronous systems as shown by Sousa *et al.* [173]. More precisely, Sousa *et al.* demonstrated the need for hybrid-systems that require some level of synchrony to guarantee safety and liveness of proactive recovery systems.

Virtualization was later identified, by Reiser and Kapitza [153] and Distler *et al.* [51], as a useful mechanism to implement proactive recovery. They proposed an architecture, named VM-FIT, that was divided into two parts: an untrusted domain and a trusted domain. The intrusion-tolerant replicated system executes in the untrusted domain where replicas run in a separate VM. VM-FIT executes in a trusted domain, i.e., in the Virtual Machine Manager (VMM). Virtualization provides isolation between the untrusted and the trusted domains. Therefore, the trusted domain can trigger recoveries in a synchronous manner. Moreover, virtualization reduces the service's downtime during recoveries and makes the state transfer between replicas more efficient. The authors implemented this system using the Xen Hypervisor. The trusted domain is placed in the hypervisor (`Dom0`), and the replicas run in the untrusted VMs (`DomUs`).

Sousa *et al.* [171] dealt with the presence of silent faults in the nodes and introduced the Proactive-Reactive Recovery Wormhole (PRRW). It forced the recovery of faulty replicas when they exhibit malicious behavior without sacrificing periodic rejuvenations. This type of technique can only be implemented with synchrony assumptions as the rejuvenations are time triggered [172]. To address this need, the authors proposed a hybrid system model: the payload was an any-synchrony subsystem where the replicas execute, and the wormhole was a synchronous subsystem. The authors implemented this approach using the Xen Hypervisor as the wormhole. Zhao *et al.* [203] improved PRRW with an algorithm to schedule the rejuvenations triggered by monitoring the network and CPU/memory usage.

Relationship with this thesis. BFT replication with proactive recovery represents one of the cornerstones of intrusion tolerance. Proactive recovery allows the system to reduce the replicas' vulnerability window by cleaning the faulty states, preventing the attacker to be successful at compromising more than f replicas simultaneously. Nevertheless, BFT replication with proactive recovery only guarantees that the system is correct while nodes recover before $f+1$ replicas become faulty. All works on *safe* proactive recovery require the use of a trusted local component on each replica to trigger the periodic recoveries [32, 50, 144, 160, 171]. Some of these works employed hardware timers while others resorted to virtualization to separate the execution domains. In our proposal, we adopt an architecture inspired on [51] and [171]. More importantly, most of these solutions just assumed that replicas fail independently without addressing that issue, which is a topic central to our research. The following section reviews diversity as a way to get failure independence.

2.4 Diversity

The correctness of a BFT system is ensured under the assumption that replicas fail independently. Therefore, it is expected implicitly (or explicitly) that there is some mechanism that creates replicas with different vulnerabilities, which would increase substantially the effort to exploit each node. One practical way to achieve this is to build diverse replicas.

Diversity can be implemented in different manners [49, 113], which may differ in the mean and on the amount of diversity generated, but the goal is always the same: to create different attack surfaces (details in the survey [16]). In particular, it decreases the chances of someone finding a bug that compromises $f+1$ replicas at the same time [32]. In other words, diversity would contribute to avoid common weaknesses among replicas. We present three different approaches to attain diversity: (i) N-version programming consists in designing and/or implementing distinct versions of the same specification; (ii) Automatic diversity covers various memory organization schemes and compiling distinct binary executables (from the same source); and (iii) OTS diversity comprises the use of different products with similar functionality, to take advantage of the many implementations that are already available.

2.4.1 N-version Programming

The first work on diversity was published in 1975 by Randell *et al.* [150]. They introduced the concept of using different software designs and implementations as a way to increase reliability. The idea was to deploy additional spare replicas along the primary replica, and once there is a mismatch result among the nodes, a spare would substitute the current.

Chen and Avizienis [12, 36] defined the notion of N-version programming with the goal of improving software reliability in redundant systems. The principle was to resort to *N* teams that would develop *N* versions of the same software specification, which would be semantically equivalent. Then, the N-version programs would execute and compare the outputs. If the outputs are equivalent then the result is accepted.

Later on, Knight and Leveson [105] made an empirical study that concluded that N-version must be employed with some care, as it may not provide increased reliability guarantees in certain scenarios.

2.4.2 Automatic Diversity

The idea of having *N* different teams to develop *N* software versions is not attractive from several perspectives (including the cost) and soon appeared automatic approaches for introducing diversity. Forrest *et al.* [58] suggested randomized program transformations to generate application diversity. They made modifications to the `gcc` compiler to force random padding to be inserted into each stack frame. Therefore, the diverse versions are generated during the source code compilation and the aim is to make the intruder's work more difficult when exploiting buffer overflow bugs. More recently, a few other works propose the usage of diversity-based compilers to build different executables [107, 144, 160, 191].

Hosek and Cadar [84] described VARAN, a N-version execution framework. VARAN is composed of a leader replica and a few followers that share a memory ring. These components are launched by a coordinator that orchestrates and setups the execution environment. Each follower runs a binary that has system calls rewritten in a different manner. This optimization plays a significant performance improvement when compared with other solutions that rewrite the whole program. Another major improvement is achieved with the shared memory ring as it allows concurrent accesses by multiple producers and consumers. Nevertheless, the results show that VARAN introduces overheads in some system calls (e.g., of 36% for `close` and 240% for `open`) when compared with a native setup. The experiments also scale out the number of followers, which, as expected, increases the overhead as more nodes are added. Although VARAN aims for reliability, a few principles could be adopted in the security domain after solving some challenges, namely the use of the same address space that allows return-oriented programming attacks [26, 167].

BUNSHIN by Xu *et al.* [194] works as classic N-version systems, where the N variants receive the input, execute it, and then a voter checks for divergences in the output. However, BUNSHIN does not create *N* real versions and in fact it splits the program into parts where each part (of each variant) executes some security checks. In this way, it is possible to reduce the overheads of typical N-variant solutions as the code is practically the same while creating different checks that should capture

faulty behavior. Most of the overhead introduced is due to the variants synchronization before the output voting. Nevertheless, the security of the systems holds on the assumption that an attacker cannot easily overpass the sanity checks.

A different approach based on memory address obfuscation (i.e., Address Space Layout Randomization (ASLR)) was proposed by Bhatkar *et al.* [23]. Their solution transformed object files and executables at the link- and load-time, without kernel or compiler modifications. The goal is to ensure that an attack that compromises one target will not succeed on the other targets. Each time the program is executed, its virtual addresses and data are randomized, and therefore the attacker needs to find new ways to exploit memory errors like buffer overflows. However, recent works have shown that solutions like ASLR are still vulnerable to attacks [26, 93, 167, 183].

As it was observed in a survey by Larsen *et al.* [113], it is quite difficult to measure the efficacy of automatic techniques. For example, entropy analysis may consider two versions of a binary as high entropy but, they could be equally vulnerable to a specific attack. Another way to evaluate these solutions is to test them against real attacks, but this would raise coverage issues.

2.4.3 Off-the-shelf Diversity

The previous approaches generate diversity before the software's distribution. OTS diversity, by the other hand, relies on the existence of different software components that are ready to be used. There are plenty of products that provide the same functionality and that were developed by distinct vendors. In other words, OTS diversity is like an opportunistic N-version programming.

2.4.3.1 Studies

There are a few works that study the diversity of Components Off-the-Shelf (COTS) as a way to achieve failure independence. Han *et al.* [76] made a systematic analysis of the effectiveness of using OTS diversity to improve the system's security. First, the authors tried to find if there were software substitutes to provide the same functionality. Then, they determined if the OTS software shared the same vulnerabilities and if so, if the same vulnerability could be exploited with the same attack. In this study, they analyzed more than 6k vulnerabilities from NVD. The results showed that 98.5% of the vulnerable software had substitutes. Moreover, the majority of them did not have the same vulnerabilities or could not be compromised with the same exploit code. It is not expected that a single exploit works in different OSes because each one has a different memory scheme and file system. Even between releases from the same OS, the low-level functions sometimes change across the versions. The study also concluded that 22.5% of the vulnerabilities were present in multiple

software components. However, only 7.1% from those vulnerabilities were present in software that offers the same service.

Gashi *et al.* [68] made an experimental evaluation of the benefits of adopting different Structured Query Language (SQL) databases. The authors analyzed bug reports of four database servers (PostgreSQL, Interbase, Oracle, and Microsoft SQL Server) and determined which products were affected by each bug reported. They have found few cases of a single bug compromising more than one server. In fact, there were no coincident failures in more than two of the servers. The conclusion was that OTS database servers' diversity is an effective mean to improve the system's reliability. However, the authors recognize the need for SQL translators to increase the interoperability between servers in the replicated scenario.

In the same line, Garcia *et al.* [65] studied the vulnerabilities shared among OTS OSes. This study was carried out taking as input the vulnerability feeds from NVD, for a period comprised of 11-years. The goal was to find to what extent different OSes had common vulnerabilities. To do that, 2270 vulnerabilities entries were analyzed manually and classified into different categories. Then, three types of servers were defined: (i) a server that contained most the packages/applications available (Fat server); (ii) a server that did not contain unnecessary applications for a particular service (Thin server); and (iii) a thin server but with physically controlled access (Isolated thin server). It was assumed that the third setting was the most advisable for critical systems because additional care is taken to install and setup software. For each configuration it was found the number of vulnerabilities in pairs of OSes. As expected, in the Isolated thin server, the number of common vulnerabilities was considerably less than in the other configurations. There was only one vulnerability that was shared among six OSes, two that were found in five OSes, and 130 that were included in two OSes. The study also looked for common vulnerabilities in different versions of the same OS. It was observed that even if few OSes were employed, it is possible to achieve vulnerability independence just with different versions of the same OS. The authors found evidence that suggests that using OS diversity in a replicated system can improve its dependability.

2.4.3.2 Network diversity

Diversity assignment was also used as a solution to increase the network's resiliency (in particular in terms of connectivity). Newell *et al.* [138] presented their solution as a diversity assignment problem that although it is NP-hard to solve, it was showed that for medium-sized random network graphs, it was feasible to find solutions within an acceptable time. They used mixed-integer programming for medium-sized networks and for larger networks they proposed a fast greedy approach. For the first one, it was possible to achieve optimality, and for the latter an approximation of the optimal. One of the results showed that random diversity assignment is far worse than a criteria assignment (as the one they proposed). Their results showed improvements of diversity on the connectivity. However,

the models did not use realistic data, as it was assumed that the expectancy values for the probability of node compromise were known and independent for each replica.

In the same line, Zhang *et al.* [202] proposed a metric to evaluate the resilience of private networks. The idea was to define what is the least attacking effort to compromise some critical assets of the network (i.e., the work is focused on distributed yet not replicated systems). The authors proposed three metrics which were evaluated in a simulated environment. None of these metrics used vulnerability data to correlate the existence of common weaknesses, but employed data about the topology, services installed, etc. In the end, the authors made a simulated evaluation of generated graph networks and evaluated their metrics against these graphs. The results show that increasing the diversity on the nodes reduced the propagation of worms through the network.

Relationship with this thesis. We presented three different techniques that support diversity as a fault tolerance mechanism. N-version programming is the most costly since it needs different developers or software to validate the code versions if these are automatically generated. On the contrary, employing OTS and automatic diversity approaches (like randomization) is almost for free. The first can be obtained from components that are ready to be used. The second relies on some form of program modification and is supported at some level by most OSes. Most studies give evidence that diversity can improve a system's dependability. However, diversity still has some gaps that must be addressed to make it a useful building block of intrusion tolerance. For example, how does one measure diversity as a contribution to increasing failure independence?

2.5 Practical Systems with Diversity

2.5.1 Diversity on Fault/Intrusion Detection

A few works implemented diversity in their systems without employing evidence about vulnerability data to support their decisions. Totel *et al.* [181] proposed an IDS based on design diversity. The authors described an architecture that uses a set of replicated COTS servers, a proxy, and an IDS. The proxy is responsible for forwarding the requests from the client to every COTS server. When the servers reply, the proxy sends the responses to the IDS to be analyzed. The IDS compares the responses from the COTS servers, and if it detects some differences, an alarm is raised. Next, the proxy votes the responses and replies to the clients. The authors developed an algorithm to detect intrusions and tested their solutions against Snort [166] and WebStat [187]. The results showed that using a diverse-COTS service (e.g., HTTP) allows the IDS to deliver fewer alarms without missing the intrusions.

Bairavasundaram and Sundararaman [15] implemented ENVYFS, an N-version file systems that improves the reliability of stored data. Their solution is able to tolerate file system mistakes (e.g., crash and integrity errors). To keep the system simple, the authors used a virtual layer that abstract the specific file systems underneath, therefore some challenges arise from the different implementation details. Another challenge was to avoid the need for multiple storages as it uses *N* variants of file systems. They solved this issue by resorting to only one storage layer and the different file systems in between. Each file system executes the operations, and then a voter collects the majority of outputs to the storage layer. The results showed that ENVYFS is able to improve the reliability by leveraging on multiple file systems. However, ENVYFS pays a performance penalty due to waiting for a majority of file systems responses. In most of the times, it took the sum of the time of the three file systems used.

Diversity has also been employed for malware detector. Xu and Kim [193] introduced PLATPAL to analyze the behavioral discrepancies of malicious document files on different platforms (e.g.,Windows or Macintosh). PLATPAL loads a file in both systems and monitors the execution traces or crashes. In the end, both systems compare the outputs, and an attack is signaled if divergences are observed. The authors focused on a particular application, the pdf Adobe Acrobat Reader. Therefore, besides the internal discrepancies, the correct executions should be very similar. There are some limitations, namely, it failed to detect attacks that needed some human interaction. Although PLATPAL was proposed to detect malicious payloads on files, it vouched (indirectly) for diversity as it showed that an attacker needed to deploy multiple payloads to compromise a system with the same attack (for the majority of the malware samples used).

Very recently, diversity has been applied to detect malicious web scrapping activities on the internet [121]. The authors used a large data set, provided by a multi-national in the global travel industry, with traffic labeled as malicious and benign to investigate how diverse two tools perform. One of these tools is an in-house tool called Arcaned and the other is a commercial tool (anonymized) referred to as CommTool. The results indicate that employing diverse tools may help to counteract to malicious scrapping.

2.5.2 Diversity on BFT

A few BFT works already adopted practical diversity mechanisms. One of the first proposals was BASE [33], an extension of PBFT [31] that explored opportunistic OTS diversity in BFT replication. The system provided an abstraction layer for running diverse service codebases on top of the PBFT library. The key issue addressed by BASE was how to deal with different representations of the replica's state, allowing a replica that recovers from a failure to rebuild its state from other replicas. BASE was evaluated considering four different OSes and their native Network File System (NFS) implementations: Linux, OpenBSD, Solaris, and FreeBSD. The results showed that performance

varied significantly when diversity was considered. Nevertheless, BASE did not address the problem of selecting replicas nor the reconfiguration of the replica group.

Roeder and Schneider [160] proposed a solution that combined automatic diversity with rejuvenations, calling it Proactive Obfuscation (PO). The idea was to change the application and library code periodically, while preserving the original semantics by employing program transformations, i.e., system call obfuscation reordering, memory randomization, and functions return checks (through an IBM `gcc` patch that inserts and checks a random value after the functions return). Each replica generated its own obfuscated executable from a read-only device containing the "master code" based on time-triggered epochs that a controller initiates in a secure way through a trusted component. All obfuscation mechanisms were implemented and evaluated on OpenBSD 4.0, and their results showed that PO adds little extra overhead to the non-PO execution.

A similar approach by Platania *et al.* [144] adopted a compiler-based diversity for the PRIME BFT library [6] using the MultiCompiler tool [82]. This compiler was used to create diverse binaries from the same source code through randomization and padding techniques. The authors also proposed a theoretical rejuvenation model that received as input: the probability of a replica being correct over a year (c); the number of rejuvenations per day across the whole system (r); the number of replicas (n); and the system's lifetime. Although operators can control only r and n, the authors suggested (but did not show how) that c would be estimated using OSINT from the internet (e.g., CERT alerts, bug reports, and other historical data). The authors implemented their solution in two settings, including a virtualized environment provided by the Xen Hypervisor. In this setting, each replica executed in a Linux VM, the recovery watchdog runs in a trusted domain of the same machine, and the proactive-recovery controller runs in another physical machine.

Relationship with this thesis. Diversity is one of the building blocks of intrusion tolerance, alongside with BFT and rejuvenations. We presented a few works that already used in some manner diversity in intrusion-tolerant systems. Although we do not discard the possibility of employing other diversity techniques, such as randomization, we are more interested in OTS diversity. This type of diversity allows us to use data that is freely available to estimate a risk value that measures how vulnerable is each component.

Previous works are still limited in terms of how to create diversity to avoid common failures. They implement diversity assuming (unrealistically) complete fault independence. For example, different OTS OSes can share the same weaknesses due to some shared libraries or kernel code. There is a need to understand how diversity can be efficiently employed in a replicated system to make fault independence sound. Moreover, further work is still necessary to create automatic mechanisms that abstract diversity management for the administrators.

2.6 Vulnerability Analysis

In another line of research, a few works analyzed the life-cycle and evolution of vulnerabilities. These studies looked for data sources that provide information about weaknesses, exploits, and patches. In the following, we present the main works on the usage of vulnerability data to measure and manage the security of computer systems.

2.6.1 Vulnerability Life-cycle

The different stages of vulnerability life-cycle were described by Jumratjaroenvanit and Teng-Amnuay [94]. The authors' goal was to understand how the various life-cycle dates can be useful to estimate the probability of an attack. The methodology was to collect and analyze data from public data sources on the discovery-, disclosure-, exploit-date and exploit-, and patch-availability. Moreover, they considered five life-cycle types: (i) Zero-Day Attack (ZDA), which typically is done by a black-hat and is characterized by equal dates of disclosure and exploit; (ii) Pseudo Zero-Day Attack (PZDA), which is a ZDA but with a patch already available, but not applied; (iii) Potential Pseudo Zero-Day Attack (PPZDA) is a PZDA but does not matter if the patch is available or not; (iv) Potential for Attack (POA) is a zero-day vulnerability. One of the results showed that the language safety level was the less influential factor on the number of accounted vulnerabilities. Thus, safety languages do not seem to impact so much on the number of vulnerabilities as expected. The study also demonstrated that two weeks of work were enough to have a 50% chance of finding a zero-day vulnerability. In some cases, 53 hours were sufficient to locate one vulnerability with more than 95% of probability.

Frei *et al.* [63] made a quantitative analysis of 27k vulnerabilities disclosed in the last decade. The authors proposed a model that explains the key factors in a vulnerability life-cycle. All the dates associated with the life-cycle were described in detail before the analysis. A few public vulnerability databases (e.g., NVD and Open Sourced Vulnerability Database (OSVDB)) were used to collect the various related attributes. The results showed that the number of patches increased after the vulnerability's disclosure. One interesting result was the *gap of insecurity* measurement, where the patch availability was compared against the exploit availability. The data showed that exploits are always ahead of patches. In some cases, after 30 days of the disclosure, the exploits outnumbered the number of patches by 90%.

A study conducted by Shahzad *et al.* [164] analyzed vulnerability data between 1988 to 2011 from three sources: NVD, OSVDB, and the dataset from Frei and colleagues [62]. They collected vulnerabilities that affected popular applications like Internet Explorer, Firefox, and Chrome, and popular OSes such as Windows, Mac OS X, Solaris, and several Linux distributions. From their dataset, 2.8% of the vulnerabilities have an exploit released before their public disclosure. More

dramatic is the percentage of exploits that are released on the day of the vulnerability disclosure, which was in the order of 88.2%. It was observed that 9.7% of the vulnerabilities had exploits released after their disclosure. Microsoft and Apple had more exploits before the vulnerability disclosure than the other software providers. This may primarily be because hackers find it more rewarding to exploit these products due to their broader market capitalization. To what concerns patching, the authors argue that 10% of the vulnerabilities had a patch before their disclosure, and 62% had a patch on its disclosure day. There was a considerable number of vulnerabilities (28%) that were disclosed only after a patch was made available. Another conclusion was that it is easier to exploit open-source code vulnerabilities than in closed-source – this conclusion may seem obvious, but no one had shown it previously with statistical tests.

Zero-day vulnerabilities that appeared in 2008 to 2011 were part of a systematic study by Bilge and Dumitras [24]. The main dataset comes from the World Wide Intelligence Network Environment (WINE) developed by Symantec, which samples and aggregates data from several hosts running its products (e.g., Norton Antivirus). The WINE data was correlated with OSVDB and Symantec's Threat Explorer for attack/exploit information, allowing the measurement of the duration of zero-day attacks. It was observed that a typical attack can last ten months. Moreover, they found that the vulnerabilities exploited in Stuxnet were used in a different attack two years before. One of the main conclusions was that the disclosure of zero-day vulnerabilities increases the risk up to five orders of magnitude of users being attacked.

Holm [81] made an analysis of malware alarms to determine if there is a statistical distribution to model the number of intrusions or the time to compromise a computer system. The author collected information from different software configurations of an IT company from 2009 to 2012. Each computer was equipped with anti-malware software that stored logging data in a central database about malware detection events. The results showed that the Pareto distribution is the best to model the time of the first compromise. Another result was that the more the system is intruded, the more vulnerable it becomes. The author presented a few hypotheses to justify this, for example, once a system was compromised it can no longer be trusted. Another more plausible hypothesis is that security awareness only was increased temporarily as a result of the intrusion, and then it was again neglected. Automatic attacks caused most of the malware considered in this study. This probably happened due to the type of company as conclusions may change if malware arrives due to a targeted attack as it requires a different strategy to penetrate the system.

2.6.2 Metrics and Risk Management

Poolsappasit *et al.* [145] described a security risk assessment method that incorporated the cause-effect relationships of the network states and the likelihood of exploiting such relationships. To do that, they measured the organizations' security risk using the Common Vulnerability Scoring System

(CVSS) metric. The authors generated a map of the network as an attack graph and collected its vulnerabilities and exposures. This information helps the administrators to have an overview of the network weaknesses and the associate cost of the assets. Then, the administrator is able to build the countermeasures that can be taken to avoid such weaknesses, which will be linked as attributes to the model. Next, the administrator assigns the damage costs to every attribute. Finally, a genetic algorithm evolves the network for states where the cost of losing assets is minimal. Their empirical results show that the costs of being compromised can be minimized by assessing the security of the system and applying the most cost-efficient countermeasures. Nevertheless, and besides the manual setup that the system administrator needs to perform, it is missing an evaluation on the time for the system to react to the detected attacks.

The patch deployment process of ten popular client applications was analyzed over a five-year period by Nappa *et al.* [132]. The authors have found that there was a strong correlation between the bug disclosure and the beginning of the patching process among vendors. It occurred within seven days for 77% of the studied vulnerabilities. A *survival analysis* (inspired in studies that measure the mortality rates associated with diseases) was performed to measure the probability that a host remains vulnerable beyond a specific time. The experimental results showed that real-world WINE exploits still compromised 50% of the hosts with weaknesses (after vulnerabilities disclosure). The median percentage of hosts that have been patched before the exploit was released was at most 14%. Together with the number of shared vulnerable code with different patching delays, these values motivate attackers to re-use already known exploits or to create patch-based exploits [28]. The authors also showed evidence to support the natural intuition that silent or automatic updates reduce the survivability of vulnerabilities.

Machine learning techniques were employed by Bozorgi *et al.* [27] to classify vulnerabilities and predict future exploits. The results showed that their trained classifiers outperform current measures like CVSS exploitability subscore. They have built a dataset based on two public databases, the Mitre' Common Vulnerabilities and Exposures (CVE) (which is a part of NVD) and the OSVDB. The bag-of-words machine learning technique was utilized to extract the textual attributes that were more relevant to analyze. They also resorted to Support Vector Machines (SVM) to train the model and conduct offline and online experiments. In the offline setting, which they trained and evaluated data in a static fashion, they achieved an accuracy of 90% of correct predictions. In the online setting, where they emulated a live execution with past data, the results showed that after a small period the model stabilized showing a false negative rate of 9% and a false positive rate of 5%. Here, they were able to make predictions of up to two days before the exploit was released with an accuracy of 75-80%. The main result, of interest to this thesis, was the comparison between their model and CVSS as an indicator of how much a vulnerability was likely to be exploited. It was observed that the CVSS assigned high scores to weaknesses that were not exploited.

An in-depth analysis using NVD, Exploit-DB, SYM, and EKITS *breaks down* the CVSS metric on its several attributes [4]. From this analysis the authors concluded that the CVSS exploitability subscore *resembled more a constant than a variable*, thus not having a real impact on the CVSS overall score. The study determined how CVSS influences the *risk factor* of the use cases and assessed the effectiveness of treatment over a randomized sample of subjects. It was observed that from the security relevance standpoint correcting vulnerabilities based on their CVSS was statistically equivalent to picking a random vulnerability to fix. The authors suggest that it is more critical to eliminate bugs that appear in the black markets of vulnerabilities (this was re-evaluated in a recent study by the same authors [3]). In particular, it was indicated that the inclusion of black market information as a *risk factor* could increase the risk reduction by up to 80%. However, the authors also pointed out that using the EKITS data source may be a threat to the validity of the study, as it is unstructured and therefore it requires manual analysis.

Using an alternative data source, Sabottke *et al.* [161] presented a study with Twitter data (e.g., specific words, the number of retweets, and information about the users posting these messages) to find information about exploits. A Twitter-based exploit detector was developed to provide an adequate response in a short time frame. This allows the security community to foresee the exploit activity before the information reaches the *de facto* disclosure data sources, like NVD and ExploitDB. However, to complement and strengthen the results, the paper also used sources like NVD, OSVDB, Exploit-DB, Microsoft Security Advisories, and Symantec WINE. Real-world exploits were distinguished from the proof-of-concept exploits, as the latter are by-products of the disclosure process. The real-world exploits are typically not known until a critical zero-day attack occurs. The results showed that their proposal offered a reasonable level of confidence about the predictions. For example, a SVM classifier set to a precision of 25% could detect the Heartbleed exploits within 10 minutes of their first appearance on Twitter. They also showed that organizations like NVD overestimate the severity of some vulnerabilities (with CVSS) that never become in fact exploited.

Gorbenko *et al.* [73] resorted to the CVE and NVD databases to study vulnerability life-cycles of different OSes. The authors made an effort to analyze the relationship between vulnerability discovery and fix, to estimate the time vendors take to patch the software. Moreover, they also studied common weaknesses among different OSes. The results show that between 2012 and 2016 most of OSes were patched for every vulnerability that was disclosed in that period. Another interesting result was related to *forever-day vulnerability* (i.e., vulnerabilities that are publicly disclosed but not yet patched). They showed that, for the analyzed period, Ubuntu never had a single day free from vulnerabilities, and Windows and Red Hat had only 12 and 10 days, respectively. However, the most important results were the implications of CVSS on the *days-of-gray-risk* (i.e., the number of days it takes for a vendor to release a patch). It was observed that there was no obvious relation between the level of CVSS severity and the time it took for a vendor to develop a patch.

Other works, studied malware prediction. In particular, RISKTELLER [25], predicts the risk of a system becoming infected by some malware. A total of 600k machines belonging to 18 organizations was used in the analysis. They collected the log data from all machines together with external data (e.g., from NVD). A dataset with 89 features was defined, including patching behavior, temporal patterns, application categories, and past threat history. RISKTELLER employed machine learning models to learn and classify the software of each machine. The results showed that it can make predictions on the risk of a system being attacked with an accuracy of 96%.

Relationship with this thesis. We presented several works that carried out risk management in a way to prevent exploits or to take action upon vulnerability detection. There is a lot of relevant information freely available to address the security and dependability of software. In a replicated context this information is even more relevant. First, to react upon vulnerability/exploit disclosures, and second to select what configurations are less vulnerable to common weaknesses. We want to explore the free available data to improve the dependability and security of intrusion-tolerant systems by ensuring the assumption of failure independence. More precisely, our focus is on assuring that no more than f replicas become compromised within time T.

2.7 Management of Vulnerable Systems

In the previous sections, we presented a few approaches that provide support for recovery and diversity of nodes, several of which for BFT replicated systems. In this section, we focus on some works that already combine, even if in a limited way, the idea of diversity and rejuvenations. We review a few mechanisms that explore the idea of risk management (see [200] for a survey).

Reynolds *et al.* [159] presented the HACQIT architecture. It was build to assure fault tolerance by resorting to backup replicas on separate LANs and allowing only authorized clients through a Virtual Private Network (VPN). Moreover, HACQIT employed redundancy and diversity to detect and mask errors in the system components. The approach ensures that the same input is sent to the replicas for execution, and if their outputs are different, then a particular node is considered faulty. It also used a forensic agent to analyze the logs of failed nodes to prevent bad requests in the future. Finally, it implemented a recovery mechanism that was triggered by the native security auditing of Windows NT/2000. Unfortunately, no experimental evaluation was presented.

Wang *et al.* [189] described an architecture named SITAR that aims for supporting intrusion-tolerant systems with diversity and dynamic reconfigurations. SITAR defends a set of potentially vulnerable COTS servers. The system was protected by an intrusion-tolerant multilayer architecture that used redundancy and security protocols to guarantee that all nodes agree on the decisions. It was composed of three main components: the proxy servers, the acceptor monitors, and the ballot monitors. The proxies receive the requests and audit them based on the current threat level, before propagating the

messages to the COTS servers. On the way back, the acceptance monitors validate the responses and run an agreement protocol to select a final output from the COTS servers. There was also an adaptive reconfiguration module that monitors the other components by receiving heartbeats and intrusion triggers. It takes action by removing modules that are perceived as compromised and starting new ones. It is noteworthy that no results considering diversity were shown.

The same kind of solution was also applied to cluster deployments. Arsenault *et al.* [9] presented the Self-Cleaning Intrusion Tolerance (SCIT), a centralized architecture in which the goal was to recover the elements of a cluster without harming the availability of the overall service. Recovering the cluster's nodes allows for resetting the state and avoiding huge windows of vulnerability. Nevertheless, the SCIT service itself can be harmed. Therefore, the authors leveraged on trusted hardware to offer additional guarantees to the system, namely predictable and continuous operation regardless of the presence of attacks.

Junqueira *et al.* [96] proposed *informed replication* as an approach to design distributed systems that can survive catastrophes. It focused on the diversity of the components to avoid common pathogens that could compromise the entire system. A new system model was adopted to map different attributes of a node. These attributes represented characteristics that should be distinct on each node to avoid common failures. While modeling the system, some biases were introduced. For instance, the authors considered that two different services that used the same port were affected by the same vulnerability, or that the same service running with two distinct ports was not vulnerable. A heuristic was proposed to build configurations in linear time. The goal was to distribute the OSes and applications in various configurations to minimize the number of common attributes that could be compromised. Two metrics were utilized to choose OSes and applications: selecting randomly and based on their popularity. The results showed that their solution mitigated the number of pathogens that could compromise an entire configuration as its attributes were selected in order to maximize their difference. The heuristic guaranteed 99% chances of data survival on an attack of single- and double-exploit pathogens, while needing only three and five copies respectively.

More focused on reliability, Zhai *et al.* [201] presented a system that looks for failure independence on cloud nodes. The system collected audit data from the nodes to evaluate their independence by identifying potential correlated failures. Then, the different configuration dependencies were analyzed and ranked in risk groups as a way to see how the different dependencies made the system fail. The main limitation of this work was that it depended on the will of cloud providers to share private data to be analyzed by external agents. The authors evaluated the efficacy of their solution to find the minimal risk groups (with fewer dependencies) on sampling data to make faster decisions while losing some accuracy. Since the main focus of the work was the reliability of cloud systems, no evaluation was done on the vulnerabilities of such systems.

Seondong *et al.* [80] described a system that used data from NVD to select the best configuration of diverse OSes and web servers. The algorithm minimized the CVSS of shared vulnerabilities among the various software components. Although their experiments explored different configurations of software stacks, the decisions were based on the CVSS. All the experiments were done in a simulator (i.e., CSIM 20) which made it difficult to understand the performance of the solution in the real world. Moreover, the resilience of the system was evaluated against DoS attacks that affect particular vulnerabilities in the software. Depending on the type of the DoS, it can cause a performance degradation without exploiting any particular vulnerability. This, however, does not shed light on the ability of the system to prevent $f + 1$ replicas from being compromised. In any case, this is the work that most resembles one of the main contributions of this thesis.

An emerging area, called Moving Target Defense (MTD), re-defines some of the already existing solutions with the goal of achieving a continuous change of the attack surface. MTD employs techniques like VM migration, different types of diversity, etc. Some authors have made an effort to formalize this sub-area of intrusion tolerance [205].

Okhravi *et al.* [140] presented TALENT, a framework for live migration of critical infrastructures across heterogeneous platforms. The idea was to create a moving target that would make advanced targeted attacks harder to succeed. TALENT implemented OS-level virtualization with containers, which allowed the system to migrate the OS between machines periodically or upon detection of malicious activity. The virtualization was implemented with `OpenVZ` and `LXC` for Linux, `Virtuozzo` for Windows, and `Jail` for FreeBSD. The network was also virtualized, more precisely, a second layer of virtualization was used to migrate the IP address from one container to another. Additionally, the state of the application also had to be migrated by employing a checkpointing technique. When all the programs were checkpointed, the state was saved and then was migrated by mirroring the file system. TALENT also had a sort of risk assessment, called operation assessment, which monitored and adjusted the diverse components using vulnerability information. However, there were almost no details on how the risk was measured and on how to adapt to the threats efficiently.

Hong and Kim [83] classified MTD into three categories, shuffle, diversity and redundancy. The three categories were integrated in HARM and it was assessed how each technique could improve the security of distributed systems. The solution was built on top of VMs, with each one hosting two or three OSes in it. The three techniques were evaluated separately, and only two OSes were considered in the diversity evaluation. The results show that deploying random diversity did not improve the risk level of the system. In an ideal scenario each host would have at least one VM with a diverse OS. On the other hand, having diverse OSes across hosts decreased the connectivity, in case of some OS became compromised. However, these results were not surprising as only two OSes were considered. On the contrary, with more OSes the system would maintain the level of connectivity while assuring the dependability of the hosts.

Relationship with this thesis. We presented a few control systems that manage diverse nodes that are potentially vulnerable and exploitable. Some of the works described in other sections already combined a few of these mechanisms (e.g., Sousa *et al.* [171] introduce reactive recovery upon detection of faulty behavior). However, only a few have implemented or discussed the real implications of using diversity (with the exceptions like BASE [33] that implemented OTS diversity and assessed its performance overhead). Our thesis studies diversity in two domains: *(i)* how it can improve the dependability of BFT systems and *(ii)* what are the real overheads of implementing diversity on BFT systems.

2.8 Final Remarks

This chapter summarizes the most relevant works that are related to this thesis. We have made a background revision of the intrusion tolerance area, and then we described the different topics that support intrusion-tolerant systems. Our main contributions are to the management of BFT systems, in particular, on how to create diverse replicas that effectively are independent and on deciding when the replicas need to be recovered. Although we could adopt solutions from artificial diversity, we are more interested in employing OTS diversity. The selection of such approach allow us to use data to make decisions on which diverse options work better together.

3 A Study on Common OS Vulnerabilities

This chapter presents a data analysis that gives evidence to support our thesis. In particular, we describe three strategies to select different OSes to be part of a BFT replicated system. These strategies leverage on the vulnerability database developed in a previous work. Contrary to automatic diversity, OTS diversity can be supported by data evidence to understand the correlation between vulnerabilities and products. Therefore, we focus on the diversity of OSes (not only the kernel but the whole product) for three fundamental reasons: (1) by far, most of the replica's code is the OS; (2) such size and importance, make OSes a valuable target, with new vulnerabilities and exploits being discovered every day; and (3) there are many options of OSes that can be used. The promising results confirm the intuition that applying OS diversity implies vulnerability independence to some extent.

3.1 Methodology

We describe the adopted methodology in this section, in particular, we focus on how the dataset was selected, processed, and analyzed.

3.1.1 Data Source

We have analyzed OS vulnerability data from the NVD database [133]. According to National Institute of Standards and Technology (NIST) a vulnerability is defined as follows:

Definition 2. *"[...] A vulnerability is a weakness in an information system, system security procedures, internal controls, or implementation that could be exploited by a threat source."* [134]

NIST's NVD is the authoritative data source for disclosure of vulnerabilities and associated information. NVD aggregates vulnerability reports from more than 70 security companies, advisory groups, and organizations, thus being the most extensive vulnerability database on the web. All data is made available as Extensible Markup Language (XML) data feeds, containing the reported vulnerabilities on a given period. Each NVD vulnerability receives a unique identifier, in the format CVE-*YEAR*-*NUMBER*, and a short description provided by the CVE [129]. The Common

Platform Enumeration (CPE) [128] provides the list of products affected by the vulnerability and the date of the vulnerability publication. Additionally, the CVSS [44] calculates the vulnerability severity considering several attributes, such as the attack vector, privileges required, exploitability score, and the security properties compromised by the vulnerability (i.e., integrity, confidentiality or availability).

We developed a program that collects, parses and inserts the XML data feeds into an SQL database, deployed with a custom schema to group vulnerabilities by affected products and versions.

3.1.2 Data Selection

Despite the vast amount of information about each vulnerability available in NVD, for this study, we are only interested in the name, publication date, summary (description), type of exploit (local or remote), and list of affected products. We have collected vulnerabilities reported for 64 CPE [128]. Each one of these describes a system, i.e., a stack of software/hardware components in which the vulnerability may be exploited. These CPE were filtered, resulting in the following information that was stored in our database:

- **Part:** NVD separates this in Hardware, OS and Application. For the purpose of this study we choose only enumerations marked as OS;
- **Product:** The product name of the platform;
- **Vendor:** Name of the supplier or vendor of the product platform.

In our previous work [65] we manually analysed those 64 CPE and grouped them in 11 OS distributions: *OpenBSD, NetBSD, FreeBSD, OpenSolaris, Solaris, Debian, Ubuntu, RedHat,*[1] *Windows2000, Windows2003* and *Windows2008*. These distributions cover the most used *OS products* of the BSD, Solaris, Linux and Windows families.

The use of an SQL database brought us at least three benefits when compared with analyzing the data directly from the XML feeds. First, it allows us to *enrich the data set* by hand, for example, by associating release times and family names to each affected OS distribution. Second, it lets us modify the CVE fields to correct problems. For instance, one of the problems with NVD is that the same product is occasionally registered with distinct names in different entries; For instance, (*debian_linux*, *debian*) and (*linux*, *debian*) are two (product, vendor) pairs we have found for the Debian Linux distribution. Other users of NVD data feeds previously observed this same problem [157]. Finally, an SQL database is much more convenient to work with than parsing the feeds on demand.

[1] *RedHat* comprises the "old" RedHat Linux (discontinued in 2003) and the newer RedHat Enterprise Linux (RHEL).

OS	Valid	Unknown	Unspecified	Disputed	Duplicate
OpenBSD	153	1	1	1	0
NetBSD	143	0	1	2	0
FreeBSD	279	0	0	2	0
OpenSolaris	31	0	52	0	0
Solaris	426	40	145	0	3
Debian	213	3	1	0	0
Ubuntu	90	2	1	0	0
RedHat	444	13	8	1	1
Windows2000	495	7	28	5	5
Windows2003	56	5	34	3	5
Windows2008	334	0	8	0	3
#distinct vulns.	2270	63	210	8	12

Table 3.1 – Distribution of OS vulnerabilities in NVD.

3.1.3 Filtering the Data

The following steps were done to keep the database updated. We selected 2563 vulnerabilities from a total of more than 44,000 vulnerabilities published by NVD in the period of 1994 to 2011. These vulnerabilities are the ones classified as OS-level vulnerabilities ("/o" in their CPE) for the OSes under consideration.

When manually inspecting the data set, we discovered and removed vulnerabilities that contained tags in their descriptions such as *Unknown* and *Unspecified*. These correspond to vulnerabilities for which NVD does not know precisely where they occur or why they exist (however, they are usually included in the NVD database because they were mentioned in some patch released by a vendor). We also found few vulnerabilities flagged as ***DISPUTED***, meaning that product vendors disagree that the vulnerability exists, and *Duplicate*, used for vulnerabilities in which the *summary* points to a duplicate entry or duplicate entry suspicion. Due to the uncertainty that surrounds these vulnerabilities, we decided to exclude them from the study as well.

Table 3.1 shows the distribution of these vulnerabilities across the analyzed OSes, together with the total number of valid vulnerabilities. An important observation about Table 3.1 is that the columns do not add up to the number of distinct vulnerabilities (last row of the table) because some vulnerabilities are shared among OSes and are counted only once. Notice that about 60% of the removed vulnerabilities affected Solaris and OpenSolaris. Moreover, these two systems are the only ones that have more than 10% of its vulnerabilities removed. We should remark that this manual filtering was necessary to increase the confidence that only valid vulnerabilities were used in the study.

3.2 OS Diversity Study

In the context of this thesis, we are focused on the dependability of replicated systems. The starting point of this analysis are vulnerabilities that were shared in OS pairs. In this study, we consider two possible server machine setups offering an increasingly more secure platform. This accommodates the case where system administrators create differentiated OS installations, which contain more or less vulnerabilities depending on the services and applications available in the server. Of course, other setups could be used, but we decided to concentrate on these configurations because they are quite generic and they lead to results that can be directly obtained from the NVD data. The setups are the following:

- **Fat Server:** The server contains most of the software packages for a given OS, and consequently, it can be used to run various kinds of applications by locally or remotely connected users. This server has potentially all vulnerabilities that were reported for the corresponding OS. Therefore, it provides an upper bound estimate on the number of vulnerabilities that can be exploited.

- **Isolated Thin Server:** This configuration corresponds to a platform that does not contain any applications (except for the replicated service). The server has a decreased security risk because the attack vectors related to applications have been mostly eliminated. Moreover, it is placed in a room physically protected from illegal accesses, with remote logins disabled, and therefore it can only be compromised by receiving malicious packets from the network. In this setting, we only consider remotely exploitable vulnerabilities (those with "Network" or "Adjacent Network" values in their CVSS_ACCESS_VECTOR field) that are not classified as *Applications*. Thus, this configuration provides a lower bound estimate on the number of common vulnerabilities that can be exploited.

In practice, when considering the second configuration, at least one application (e.g., name service or a distributed file service) would be deployed in an intrusion-tolerant system, and the vulnerabilities of this application would add up to the flaws that we will report. In any case, since we expect that most of the complexity is in the OS, we anticipate that a single application will have a small contribution to the overall number of vulnerabilities.

Intrusion-tolerant systems are usually built using four or more replicated servers [32]. Therefore, it is useful to understand if there are many vulnerabilities that involve groups of OSes larger than two – if this is the case, then it will be hard to find OS configurations for the various servers that do not share vulnerabilities, and a goal of using OTS diversity will be difficult to be achieved in practice. Figure 3.1 portrays the number of common vulnerabilities that exist simultaneously in increasingly more extensive sets of OSes (with Isolated Thin Servers). The graph shows a rapid

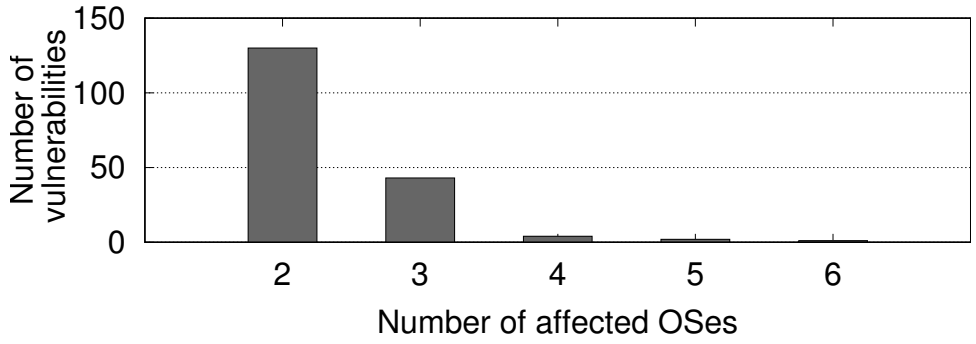


Figure 3.1 – Common vulnerabilities for *n* different OSes (with Isolated Thin Servers).

decrease in the shared vulnerabilities as the number of OSes grows. The largest group that was affected by the same vulnerability had six OSes, and this occurred only for a single flaw. There were also two vulnerabilities in sets with five OSes. Vulnerabilities in two and three OSes usually occur in systems from the same family, whose common ancestry implies the reuse of more significant portions of the code base.

Table 3.2 describes in more detail the vulnerabilities shared by larger groups (four to six) of OSes. The first three vulnerabilities have a considerable impact because they allow a remote adversary to run arbitrary commands on the local system using a high-privilege account. They occurred either in widespread login services (telnet and rlogin) or in a primary system function, and consequently, several products from the BSD family were affected, as well as Solaris. The NVD entry for the CVE-2001-0554 vulnerability also had external references to the Debian and RedHat websites, which could indicate that these systems might suffer from a similar (or the same) problem. Vulnerability CVE-2008-1447 occurs in a large number of systems because it results from a bug in the BIND implementation of the DNS. Since BIND is a highly popular service, more OSes could potentially be affected. A closer look at the corresponding NVD entry reveals external references to the sites of OpenBSD, NetBSD, and FreeBSD, indicating that they could be vulnerable in case this software is being used. This sort of vulnerability confirms that from an intrusion-tolerance perspective it is unwise to run the same server software everywhere, and that diverse implementations must be selected (in this case for recursive DNS servers).

The remaining three vulnerabilities are related to the protocol stack of TCP/IP. All of them affect system availability, allowing different forms of DoS attacks. CVE-2008-4609 is the vulnerability that affects more OSes according to the NVD database, because TCP/IP stack code is often reused across OSes.

Overall, the above results look encouraging because over a significant period (around 18 years) there are very few vulnerabilities that appear in many OSes. A good portion of them are in the TCP/IP stack implementation, which is probably the most shared software component across OSes.

CVE	#affected OS	Description
CVE-1999-0046	4	Buffer Overflow of *rlogin* allows admin access. Affects: NetBSD, FreeBSD, Solaris and Debian.
CVE-2001-0554	4	Buffer overflow in telnetd (telnet daemon) allows remote attackers to execute arbitrary commands. Affects: OpenBSD, NetBSD, FreeBSD and Solaris.
CVE-2003-0466	4	Off-by-one error in the Kernel function *fb_realpath()* allows admin access. Affects: OpenBSD, NetBSD, FreeBSD and Solaris.
CVE-2005-0356	4	TCP implementations allow a denial of service (DoS) via spoofed packets with large timer values, when used with Protection Against Wrapped Sequence Numbers. Affects: OpenBSD, FreeBSD, Windows2000 and Windows2003.
CVE-2008-1447	5	The BIND 8 and 9 implementation of the DNS protocol allow attackers to spoof DNS traffic via a birthday attack to conduct cache poisoning against recursive resolvers. Affects: Debian, Ubuntu, RedHat, Windows2000 and Windows2003.
CVE-2001-1244	5	TCP implementations allow a DoS by setting a maximum segment size very small to force the generation of more packets, amplifying network traffic and CPU consumption. Affects: OpenBSD, NetBSD, FreeBSD, Solaris and Windows2000.
CVE-2008-4609	6	TCP implementation allows a DoS via multiple vectors that manipulate TCP state table. Affects: OpenBSD, NetBSD, FreeBSD, Windows2000, Windows2003 and Windows2008.

Table 3.2 – Vulnerabilities that affect more than four OSes.

In addiction, they only impact on the availability of the system, leaving confidentiality and integrity of data unharmed.

3.3 Strategies for OS Diversity Selection

The preliminary analysis presented in the previous section indicates that it is possible to find that some OSes share fewer vulnerabilities than others. Therefore, in this section we present three alternative strategies to select OSes, based on the built dataset, to decrease the chance of common vulnerabilities on replicated systems. We start the section by first describing an approach we called the Common Vulnerability Indicator (CVI), which is used by one of the strategies. For each strategy, we then give example sets of OSes that exhibit a reasonable level of diversity, and perform an evaluation based on the collected data. Finally, we conclude the section with an analysis of potential diversity between releases of the same OSes (concentrating on the OSes that the three strategies picked as the best configuration).

3.3.1 Common Vulnerability Indicator

In our previous work [65] we have found that the number of common vulnerabilities that are observed between different OSes varies over time. Thus, in order to be able to evaluate which OS pairs are more (or less) likely to experience common flaws while taking into account the timing of vulnerability disclosures, we developed a new metric, called the *CVI*. This indicator is calculated for a given year y, based on the vulnerabilities that were shared by OSes A and B over a period of *tspan* previous years. CVI is built to ensure the following desirable properties:

1. $CVI_y(A,B) = 0$ if A and B have no common vulnerabilities in the *tspan* interval before year y;

2. $CVI_y(A,B) < CVI_y(C,D)$ if A and B shared less vulnerabilities than C and D in each year of the considered period;

3. $CVI_y(A,B) < CVI_y(C,D)$ if A and B had N common vulnerabilities in the distant past while C and D had N shared vulnerabilities more recently;

4. $CVI_{y_2}(A,B) < CVI_{y_1}(A,B)$, with $y_1 < y_2$, if the number of common vulnerabilities for A and B has decreased over the years.

Therefore, CVI is useful for comparison purposes, allowing the identification of OS pairs that have a smaller number of common flaws, while considering the instant when vulnerabilities were found. This last point is particularly crucial because OSes are continually evolving, potentially getting more (or less) diverse, and consequently, one should take into consideration the time dimension when selecting OS configurations (e.g., OS pairs that have had less common flaws recently are likely better candidates). CVI is computed as follows:

First, a weighting factor α_i is defined for each year $i \in \{y - tspan + 1, ..., y-2, y-1, y\}$ as defined in Equation 3.1:

$$\alpha_i = 1 - \frac{y - i}{tspan} \tag{3.1}$$

Then, CVI is obtained using the number of vulnerabilities $v_i(A,B)$ that appeared in both OSes A and B for every year i from the start of the time span up to reference year y (see Equation 3.2).

$$CVI_y(A,B) = \sum_{i=y-tspan+1}^{y} \alpha_i \cdot v_i(A,B) \tag{3.2}$$

	Fat Server			Isolated Thin Server		
OS	2009	2010	2011	2009	2010	2011
OpenBSD-NetBSD	17.1	13.8	14.8	8.4	7.1	6.9
OpenBSD-FreeBSD	22.2	18.0	18.1	14.1	11.6	10.3
OpenBSD-Solaris	4.0	3.1	3.3	1.8	1.4	0.9
OpenBSD-Debian	1.7	1.5	1.4	0.0	0.0	0.0
OpenBSD-RedHat	5.0	4.1	3.2	1.6	1.4	1.1
OpenBSD-Win2000	1.8	1.5	-	1.8	1.5	-
NetBSD-FreeBSD	19.7	18.3	18.8	11.0	9.3	8.6
NetBSD-Solaris	4.9	4.0	4.2	1.5	1.1	0.7
NetBSD-Debian	1.4	0.9	0.5	0.6	0.4	0.2
NetBSD-RedHat	1.8	1.1	0.5	0.6	0.4	0.2
NetBSD-Win2000	1.6	1.4	-	1.6	1.4	-
FreeBSD-Solaris	6.5	5.4	6.3	2.3	1.7	1.2
FreeBSD-Debian	1.3	0.8	0.5	0.0	0.0	0.0
FreeBSD-RedHat	5.6	4.4	3.3	1.7	1.4	1.1
FreeBSD-Win2000	2.3	1.9	-	2.3	1.9	-
Solaris-Debian	1.0	0.8	0.6	0.0	0.0	0.0
Solaris-RedHat	5.3	6.5	5.5	1.0	0.7	0.5
Solaris-Win2000	5.5	5.7	-	1.0	0.7	-
Debian-RedHat	26.1	20.5	15.7	3.2	2.1	1.4
Debian-Win2000	0.9	0.8	-	0.9	0.8	-
RedHat-Win2000	1.8	1.6	-	0.9	0.8	-

Table 3.3 – CVI for the years 2009 to 2011, with *tspan* of 10 years.

Table 3.3 presents CVI values for the years 2009 to 2011. We have excluded from this analysis OSes with vulnerability information missing for more than one year over the period, to avoid using incomplete data in the calculation of the indicators. Therefore, the following OSes were not considered in Table 3.3: Windows2003, Windows2008, Ubuntu, and OpenSolaris. The CVI values are computed for a *tspan* of 10 years to reflect a reasonable history. It is possible to see that, except for one system (Solaris with FreeBSD/RedHat/Windows2000 in the Fat Server), in all remaining cases CVI shows a decreasing trend. Several of the OSes that have evolved over a considerable period are having less reported vulnerabilities, and this causes a decline in shared vulnerabilities in recent years. For some of the OS pairs the drop in the CVI value is quite significant, becoming almost one-third of the 2009 value (NetBSD with Debian or RedHat). In the Isolated Thin Server case, there are three pairs with $CVI(A,B) = 0$, which shows that they have no shared vulnerabilities during the past 12 years, and are thus particularly good candidates to include in intrusion-tolerant configurations. These systems are Debian with either OpenBSD or FreeBSD or Solaris.

From the CVI values in Table 3.3, it is apparent that OpenBSD and RedHat have become more diverse, in recent years, than RedHat and Solaris, and to make it advisable, from a diversity standpoint, to choose the former OS pair over the latter.

3.3.2 Building Replicated Systems with Diversity

Indicators like CVI can be useful to devise strategies to select diverse sets of OSes. These strategies utilize the data analyzed earlier as a basis to make decisions, by assuming that the information reported by NVD on vulnerabilities can be correlated to the amount of diversity among OSes. Of course, there are some caveats associated with this approach, but the alternatives can be even harder to put in practice, especially if one wants to consider a large number of OSes. For example, for closed systems (e.g., Windows) it is challenging to determine the level of sharing of OS components, and therefore, diversity estimations based on the code cannot be performed. Moreover, even if this estimate could be obtained, there is the risk that it does not reflect the number of vulnerabilities that occur simultaneously in several OSes (e.g., two distinct implementations of the same flawed algorithm are vulnerable).

The first strategy, called Common Vulnerability Count Strategy (CVCst), is based on raw data collected over a considerable interval, and it is the most straightforward approach for selecting OS pairs. It should be used when one wants to treat all vulnerabilities, regardless of the time which they were reported, as equally important to make choices. The second strategy, Common Vulnerability Indicator Strategy (CVIst), uses the CVI described in the previous section to select OS pairs taking into account the incidence of common vulnerabilities over the years. It is indicated when one wants to give greater importance to more recent vulnerabilities. The third strategy, Inter-Reporting Times Strategy (IRTst), follows a different approach from the previous ones, focusing not so much on common vulnerabilities directly, but on the frequency in which vulnerabilities appear in the two OSes. If one wants to give more importance to the time interval between successive reports of common vulnerabilities, this is the best strategy. Since this last criterion complements the previous two, one could explore strategies CVCst and CVIst in conjunction with IRTst.

For every strategy, we present examples of OS sets for the Fat Server and Isolated Thin Server configurations. Fat Server configurations can be pessimistic in the sense that they may account for common vulnerabilities in applications that are not present in the servers, while Isolated Thin Server configurations reflect more accurately the expected setup of dedicated servers in a replicated system. An intrusion-tolerant system usually requires $3f+1$ replicas to tolerate f intrusions (e.g., [32]). Therefore, we will focus on sets with four OSes to deploy a hypothetical replicated system with four replicas, which allows one fault to be tolerated.

One should take into account that Ubuntu and Windows2008 were first released in 2004 and 2008 respectively, so the data for these two OSes was collected for a smaller number of years. Windows2000 is presented in the tables because there are published vulnerabilities until 2010, although it has been gradually replaced by Windows2003 and Windows2008 in the organizations. Consequently, we do not use Windows2000 when choosing the OS sets. We have excluded OpenSolaris from the study because there is data available for only a limited period. In each strategy and configuration, we

present two sets: *setCon* is more conservative, since it does not contain Ubuntu and Windows2008; and *setUpdt* is more up-to-date because it can include Ubuntu and Windows2008. When looking at these two sets, one should keep in mind that setCon is selected from a group of OSes for which there is a significant amount of NVD data, which contributes for higher confidence on the result. On the other hand, setUpdt uses OSes with different amounts of NVD data, which can cause small levels of inaccuracy when making comparisons (e.g., in the CVCst, any OS pair featuring Windows2008 has zero common vulnerabilities until 2007). One way to address this would be only to consider vulnerabilities that appear later than 2007 when choosing setUpdt. We opted not to follow this approach because it has the drawback of discarding too much data.

3.3.3 Common Vulnerability Count (CVCst)

The results from the previous section give a strong indication that it should be possible to choose groups of OSes with a few common vulnerabilities over reasonable intervals of time. However, we would like to understand if the data from the NVD database is effective at suggesting these groups of OSes. To address this point, we divided the data into two subsets: the *history period*, comprising the data for the interval between 2000 to 2009, and the *observed period*, from 2010 to 2011. The objective is to employ the historical period to pick the sets of OSes to use on the replicated system (as if the choice was made at the beginning of 2010). Then we use the data for the observed period to verify if these choices would have been adequate, i.e., if they have a small (preferably the smallest) number of common vulnerabilities in this period.

CVCst makes decisions based directly on the empirical data for the number of common vulnerabilities across all OS pairs. This data is displayed in Table 3.4 for OSes with a Fat Server configuration. Numbers to the right and above the diagonal line represent the history period, while numbers to the left and below the line stand for the observed period. For example, the entry corresponding to OpenBSD-RedHat to the right of the diagonal line has the number 10, which means that these OSes shared 10 vulnerabilities between 2000 and 2009. The equivalent entry, but to the left of the diagonal line, is 0 because they had no common flaws reported in 2010 and 2011. As expected, OS pairs from the same family had the highest counts of common vulnerabilities. The only case where there were more vulnerabilities in the observed period than the historical period is for the Windows2008–Windows2003 pair, which is explained by the recent release date of Windows2008. It is interesting to notice, however, that most pairs had zero common vulnerabilities in the observed period.

The strategy for building sets of OSes is based on a simple cost function. Given any potential OS pair A and B that could be added to the set, one can perform a lookup in Table 3.4 to determine the pair's number of common vulnerabilities in the historical period. This number corresponds to the cost of adding this OS pair to the group. Similarly, when including a third OS C, it is possible to

	OpenBSD	NetBSD	FreeBSD	Solaris	Debian	Ubuntu	RedHat	Win2000	Win2003	Win2008	
OpenBSD	-	33	43	9	2	3	10	3	2	1	
NetBSD	4	-	36	9	4	0	6	3	2	1	
FreeBSD	4	6	-	12	4	2	12	4	3	1	
Solaris	1	1	2	-	2	2	8	8	7	0	
Debian	0	0	0	0	-	14	52	1	1	0	
Ubuntu	0	0	0	0	0	-	27	1	1	0	
RedHat	0	0	0	2	0	0	-	2	2	0	
Win2000	0	0	0	1	0	0	0	-	216	42	
Win2003	0	0	0	1	0	0	0	49	-	53	
Win2008	0	0	0	1	0	0	0	38	229	-	
	2010-2011										2000-2009

Table 3.4 – History/observed period for CVCst with Fat Servers.

find in the table the entries for A–C and B–C and take their sum as the cost of integrating C in the group. When building a set with *n* OSes, the total cost is the addition of each individual cost for all combinations of OS pairs. The sets that lead to smaller values of total cost are considered the best choices for deployment in the replicated system. Accordingly, based on the table, the best groups of four OSes are:

- setCon = {*OpenBSD, Solaris, Debian, Windows2003*}, with a total cost of 23;
- setUpdt = {*NetBSD, Solaris, Ubuntu, Windows2008*}, with a total cost of 12.

One, however, should keep in mind that sometimes the total cost may be only an approximation of the actual number of shared vulnerabilities among the OSes in the set, as specific vulnerabilities might be counted more than once. This will likely not be a problem since overcounting vulnerabilities provides a conservative estimate, or an estimate worse than reality. For example, setUpdt only has 11 shared vulnerabilities for a total cost of 12, since one of the vulnerabilities appears in three of the OSes (and is therefore included in two table entries).

Next we can check to what extent our choice of the best group of four OSes that we would pick from the historical period (2000–2009), as prescribed by Common Vulnerability Count (CVC) cost calculation, remains consistent with the choice of the best group of four OSes from the observed period (2010–2011). We see that both setCon and setUpdt have only two shared vulnerabilities. They are not the best sets in the observed period (2010–2011), since there are groups of OSes with zero common vulnerabilities in the observed period (e.g., by replacing Solaris with RedHat), though they do exhibit a high level of diversity. A graphical representation of the sets as Venn diagrams is available in Figures 3.2(a) and 3.2(b). Below the OS name is the total number of vulnerabilities during the observed period, and the number inside each intersection shows the

	OpenBSD	NetBSD	FreeBSD	Solaris	Debian	Ubuntu	RedHat	Win2000	Win2003	Win2008	
OpenBSD	-	13	26	5	0	0	3	3	3	1	2000-2009
NetBSD	1	-	18	4	2	0	2	3	1	1	
FreeBSD	1	1	-	6	0	0	3	4	2	1	
Solaris	0	0	0	-	0	0	2	2	1	0	
Debian	0	0	0	0	-	2	8	1	1	0	
Ubuntu	0	0	0	0	0	-	1	1	1	0	
RedHat	0	0	0	0	0	0	-	1	1	0	
Win2000	0	0	0	0	0	0	0	-	81	13	
Win2003	0	0	0	0	0	0	0	4	-	14	
Win2008	0	0	0	0	0	0	0	3	26	-	
	2010-2011										

Table 3.5 – History/observed period for strategy CVCst with Isolated Thin Servers.

count of common flaws for the corresponding OSes. For example, in setCon with Fat Servers (Figure 3.2(a)) there is one vulnerability that appears both on Solaris and OpenBSD and another on Solaris and Windows2003.

Table 3.5 presents the common vulnerabilities with the Isolated Thin Server configuration data. This configuration represents a class of servers that have a dedicated function and are protected against physical intruders. The same approach can be applied as above: first, we choose the best pairs based on the historical period to build a set of four OSes; next, we evaluate the sets by comparing the results with the values for the observed period. The history period provides two candidate sets:

- setCon = {*NetBSD, Solaris, Debian, Windows2003*}, with a total cost of 9;
- setUpdt = {*Solaris, Debian, Ubuntu, Windows2008*}, with a total cost of 2.

In the observed period, setCon and setUpdt have no common vulnerabilities, showing that the strategy would have chosen sufficiently diverse groups of OSes. A graphical representation of the sets is displayed in Figures 3.2(c) and 3.2(d).

3.3.4 Common Vulnerability Indicator Strategy (CVIst)

This strategy employs the CVI value, defined at the beginning of this section, to make decisions about including/excluding particular OSes. Therefore, besides taking advantage of the available data on total counts of shared vulnerabilities, it also uses the information on how these numbers have evolved through the years.

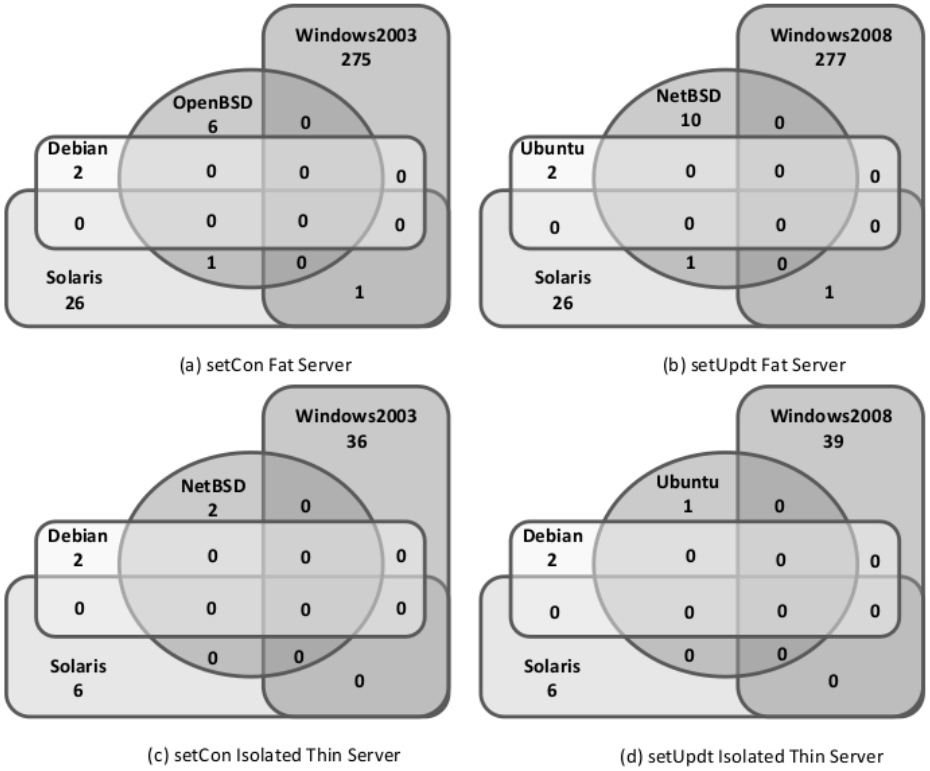


Figure 3.2 – Venn diagrams for vulnerabilities in setCon and setUpdt for strategies CVCst in Fat Server and Isolated Thin Server configurations.

CVIst is applied by executing the following method, which is based on minimizing a cost function. For a given year and time span, the CVI value is calculated for each of the OS pairs. Typically, one should use the most recent year for which there is available data. The time span should cover a reasonable interval so that the indicator reflects the trend of discovered vulnerabilities. In some cases, however, one may have to resort to smaller time spans due to lack of data, namely with OSes released recently. In this case, the indicator will give a higher weight to the vulnerabilities reported in the last year. In CVIst the cost of creating a group with two OSes A and B is $CVI(A,B)$. Extending this idea to a group of n OSes, the total cost becomes the sum of the individual CVI for all combinations of OS pairs. In order to choose the best groups, the strategy searches for sets of OSes that together have the smallest total cost.

To evaluate this strategy, we split the time into two intervals as we did for CVCst. Table 3.6 presents in the cells for the history period the $CVI_{2009}(A,B)$ for a time span of 10 years in a Fat Server configuration.[2] The cells at left and bottom of the diagonal line correspond to the observed period, and they count as before the number of shared vulnerabilities in 2010 and 2011. After applying CVIst, the following sets are the best with four OSes:

[2] In some cases, we had to use smaller time spans due to the more recent release date of the OSes (e.g., Ubuntu and Windows 2008). When this happened, the CVI value was calculated using the maximum time span that is allowed by the available data.

	OpenBSD	NetBSD	FreeBSD	Solaris	Debian	Ubuntu	RedHat	Win2000	Win2003	Win2008	
OpenBSD	-	17.1	22.2	4.0	1.7	2.5	5.0	1.8	1.5	0.9	
NetBSD	4	-	19.7	4.9	1.4	0.0	1.8	1.6	1.5	0.9	
FreeBSD	4	6	-	6.5	1.3	1.3	5.6	2.3	2.0	0.9	
Solaris	1	1	2	-	1.0	1.5	5.3	5.5	5.6	0.0	
Debian	0	0	0	0	-	10.5	26.1	0.9	0.9	0.0	
Ubuntu	0	0	0	0	0	-	18.5	0.9	0.9	0.0	
RedHat	0	0	0	2	0	0	-	1.4	1.8	0.0	
Win2000	0	0	0	1	0	0	0	-	163.6	39.5	
Win2003	0	0	0	1	0	0	0	49	-	0.0	
Win2008	0	0	0	1	0	0	0	38	229	-	
	2010-2011										CVI_{2009}(A,B)

Table 3.6 – History/observed period for CVIst with Fat Servers.

	OpenBSD	NetBSD	FreeBSD	Solaris	Debian	Ubuntu	RedHat	Win2000	Win2003	Win2008	
OpenBSD	-	8.4	14.1	1.8	0.0	0.0	1.6	1.8	1.8	0.9	
NetBSD	1	-	11.0	1.5	0.6	0.0	0.6	1.6	0.9	0.9	
FreeBSD	1	1	-	2.3	0.0	0.0	1.7	2.3	1.5	0.9	
Solaris	0	0	0	-	0.0	0.0	1.0	1.0	0.6	0.0	
Debian	0	0	0	0	-	1.9	3.2	0.9	0.9	0.0	
Ubuntu	0	0	0	0	0	-	0.9	0.9	0.9	0.0	
RedHat	0	0	0	0	0	0	-	0.9	0.9	0.0	
Win2000	0	0	0	0	0	0	0	-	58.7	12.5	
Win2003	0	0	0	0	0	0	0	4	-	13.5	
Win2008	0	0	0	0	0	0	0	3	26	-	
	2010-2011										CVI_{2009}(A,B)

Table 3.7 – History/observed period for CVIst with Isolated Thin Servers.

- setCon = {*OpenBSD, Solaris, Debian, Windows2003*}, with a total cost of 14.7;

- setUpdt = {*NetBSD, Solaris, Ubuntu, Windows2008*}, with a total cost of 7.3.

To verify if CVI is a good indicator for selecting diverse sets, we can look at the number of common vulnerabilities in the observed period (2010–2011). By analyzing Table 3.6, it is possible to see that setCon and setUpdt remain good sets, each one with two shared flaws. As before with CVCst, one can find better sets in observed period, where no common vulnerabilities appear for several pairs, for example by replacing Solaris with RedHat. The Venn diagrams for these two sets are shown in Figures 3.3(a) and 3.3(b).

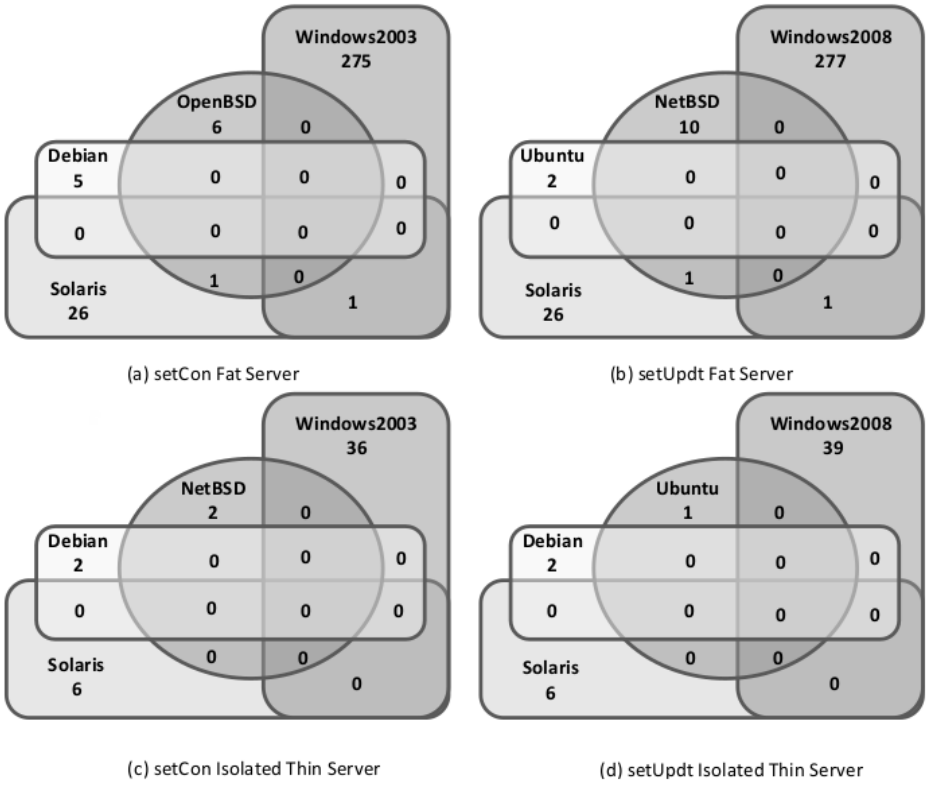


Figure 3.3 – Venn diagrams for vulnerabilities in setCon and setUpdt for strategies CVIst in Fat Server and Isolated Thin Server configurations.

Table 3.7 provides the data for applying CVIst in Isolated Thin Server configurations. It is possible to observe that CVI values have significantly decreased when compared to the previous table. The best groups of four OSes in the historical period are:

- setCon = {*NetBSD, Solaris, Debian, Windows2003*}, with a total cost of 4.5;
- setUpdt = {*Solaris, Debian, Ubuntu, Windows2008*}, with a total cost of 1.9.

By checking the data for the observed period, one can see that both sets do not share a single vulnerability, which indicates that the strategy would have made a good selection of OSes (see also the Venn diagrams in Figures 3.3(c) and 3.3(d)).

3.3.5 Inter-Reporting Times Strategy (IRTst)

This strategy is mainly concerned with the *IRT*, i.e., the number of days between successive reports of common vulnerabilities in different OS pairs, rather than vulnerability counts. The assumption underlying this strategy is that lower inter-reporting times suggest a greater similarity between OSes, and thus it would be advisable, from a diversity standpoint, to select OSes with higher IRT.

Table 3.8 presents the number of vulnerabilities for each pair of OSes in five IRT intervals, from 0 to 10000 days. The values in the table were obtained in the following manner: first, for a given OS pair A and B, we collected the dates for common vulnerabilities; next, we calculated the IRT in days of every two consecutive vulnerabilities; and then, we counted the number of vulnerabilities that were within each interval. The table is organized such that on the top are the OSes without common vulnerabilities, which are then followed by the ones that had larger IRT values. Therefore, each horizontal line separates groups of OS pairs that have positive IRT values in the same leftmost column, starting from the rightmost column (i.e., with the longer IRT). From a diversity perspective, it is interesting to notice that in the table there are 29% of the pairs that do not have two consecutive vulnerabilities, and that 11% only have consecutive vulnerabilities from 1000 days on (last column).

The IRTst strategy allows the selection of OSes with longer IRT. This criteria is essential if one wants to deploy a system that has a short lifetime, e.g., a batching process, which ideally would only be in operation between the discovery of common vulnerabilities. IRTst tries first to select OS pair with zero common vulnerabilities; when this is not possible, it chooses the next pair whose common vulnerabilities appear in the rightmost columns. By inspecting the table, we can see that the best two sets of four OSes are:

- setCon = {*OpenBSD, Solaris, Debian, Windows2003*};
- setUpdt = {*NetBSD, Solaris, Ubuntu, Windows2008*}.

Table 3.9 presents the IRT for an Isolated Thin Server configuration. Since each OS pair has less common vulnerabilities, this often translates to larger IRT. The percentage of lines with zero IRT in all intervals is higher, 51%, but remained the same for the OS pairs that share vulnerabilities with longer IRT (11%). When applying the strategy to this table, the best sets of OSes are:

- setCon = {*OpenBSD, Solaris, Debian, Windows2003*};
- setUpdt = {*OpenBSD, Debian, Ubuntu, Windows2008*}.

3.3.6 Comparing the three strategies

In one hand, the three strategies explore distinct characteristics of the data to pick the OSes to be deployed. Qualitatively they differ in the method of selection, and potentially the result of applying them to our data could lead to distinct sets being chosen. On the other hand, all of them try to find OSes that when placed together in the same system have a low probability of experiencing common vulnerabilities in the future. Therefore, if there is a small collection of OS sets with this

	$0 \leq$ IRT ≤ 1	1 <IRT ≤ 10	10 <IRT ≤ 100	100 <IRT ≤ 1000	1000 <IRT ≤ 10000
OpenBSD-Win2008	0	0	0	0	0
NetBSD-Ubuntu	0	0	0	0	0
NetBSD-Win2003	0	0	0	0	0
NetBSD-Win2008	0	0	0	0	0
FreeBSD-Win2008	0	0	0	0	0
Solaris-Win2008	0	0	0	0	0
Debian-Win2000	0	0	0	0	0
Debian-Win2003	0	0	0	0	0
Debian-Win2008	0	0	0	0	0
Ubuntu-Win2000	0	0	0	0	0
Ubuntu-Win2003	0	0	0	0	0
Ubuntu-Win2008	0	0	0	0	0
RedHat-Win2008	0	0	0	0	0
OpenBSD-Win2003	0	0	0	0	1
FreeBSD-Win2003	0	0	0	0	1
Solaris-Debian	0	0	0	0	1
RedHat-Win2000	0	0	0	0	1
OpenBSD-Win2000	0	0	0	0	2
OpenBSD-Debian	0	0	0	1	0
Solaris-Ubuntu	0	0	0	1	0
NetBSD-Win2000	0	0	0	1	1
FreeBSD-Win2000	0	0	0	2	1
FreeBSD-Ubuntu	0	0	1	0	0
RedHat-Win2003	0	0	1	0	0
OpenBSD-Solaris	0	0	3	4	2
FreeBSD-Solaris	0	0	5	8	0
FreeBSD-Debian	0	1	0	2	0
OpenBSD-Ubuntu	1	0	0	1	0
NetBSD-Debian	1	0	0	1	0
NetBSD-Solaris	1	0	3	4	1
Solaris-Win2003	1	1	1	4	0
Solaris-Win2000	1	1	1	4	1
NetBSD-RedHat	2	0	0	3	0
Solaris-RedHat	2	0	0	7	0
FreeBSD-RedHat	2	1	2	5	1
Debian-Ubuntu	3	2	3	5	0
OpenBSD-RedHat	4	0	1	4	0
NetBSD-FreeBSD	4	3	20	14	0
OpenBSD-NetBSD	7	3	14	12	0
Ubuntu-RedHat	11	2	7	6	0
OpenBSD-FreeBSD	11	5	16	14	0
Debian-RedHat	22	3	18	8	0
Win2000-Win2008	54	7	15	3	0
Win2000-Win2003	167	29	66	2	0
Win2003-Win2008	222	16	41	2	0

Table 3.8 – Number of two consecutive vulnerabilities occurring in each IRT period, between 2000 and 2011 (with Fat Servers).

property, then all strategies should elect one of these sets as the best choice. This is precisely what we observed with the NVD data, and consequently, the selected best sets are not too different from each other. Only when one needs to find many OS sets with reasonable levels of diversity, such as with the implementation of proactive recovery mechanisms in intrusion-tolerant systems [32, 171], then the distinctions among the strategies start to become apparent.

The OS sets that resulted from the execution of the strategies achieved reasonable levels of diversity when evaluated in the observed period (years 2010 and 2011). As expected from our analysis, several of the best sets contained an OS from each of the families. The exception to this rule occurred with the Linux family, wherein a few cases it had two representatives (Debian and Ubuntu) because these

	$0 \leq$ IRT ≤ 1	$1 <$IRT ≤ 10	$10 <$IRT ≤ 100	$100 <$IRT ≤ 1000	$1000 <$IRT ≤ 10000
OpenBSD-Debian	0	0	0	0	0
OpenBSD-Ubuntu	0	0	0	0	0
OpenBSD-Win2008	0	0	0	0	0
NetBSD-Ubuntu	0	0	0	0	0
NetBSD-Win2003	0	0	0	0	0
NetBSD-Win2008	0	0	0	0	0
FreeBSD-Debian	0	0	0	0	0
FreeBSD-Ubuntu	0	0	0	0	0
FreeBSD-Win2008	0	0	0	0	0
Solaris-Debian	0	0	0	0	0
Solaris-Ubuntu	0	0	0	0	0
Solaris-Win2003	0	0	0	0	0
Solaris-Win2008	0	0	0	0	0
Debian-Win2000	0	0	0	0	0
Debian-Win2003	0	0	0	0	0
Debian-Win2008	0	0	0	0	0
Ubuntu-RedHat	0	0	0	0	0
Ubuntu-Win2000	0	0	0	0	0
Ubuntu-Win2003	0	0	0	0	0
Ubuntu-Win2008	0	0	0	0	0
RedHat-Win2000	0	0	0	0	0
RedHat-Win2003	0	0	0	0	0
RedHat-Win2008	0	0	0	0	0
OpenBSD-Win2003	0	0	0	0	1
FreeBSD-Win2003	0	0	0	0	1
Solaris-RedHat	0	0	0	0	1
Solaris-Win2000	0	0	0	0	1
OpenBSD-Win2000	0	0	0	0	2
Debian-Ubuntu	0	0	0	1	0
NetBSD-Win2000	0	0	0	1	1
FreeBSD-Win2000	0	0	0	2	1
NetBSD-Solaris	0	0	1	2	0
OpenBSD-Solaris	0	0	1	3	0
FreeBSD-Solaris	0	0	1	4	0
NetBSD-Debian	1	0	0	0	0
NetBSD-RedHat	1	0	0	0	0
Debian-RedHat	1	0	1	3	2
OpenBSD-RedHat	2	0	0	0	0
FreeBSD-RedHat	2	0	0	0	0
OpenBSD-NetBSD	2	0	3	7	1
NetBSD-FreeBSD	2	0	6	9	1
OpenBSD-FreeBSD	6	0	9	10	1
Win2000-Win2008	8	1	3	3	0
Win2003-Win2008	16	2	19	2	0
Win2000-Win2003	35	8	36	5	0

Table 3.9 – Number of two consecutive vulnerabilities occurring in each IRT period, between 2000 and 2011 (Isolated Thin Servers).

OSes had very few vulnerabilities reported in the last three years. Even though the BSD family also had a small number of recent vulnerabilities, since these occasionally affected more OSes, the strategies opted for including just one of the BSD OSes.

In the next section, we will look into OS versions as a way to increase diversity. For this study, we will use the set that was most selected by the different strategies: {*OpenBSD, Debian, Solaris, Windows2003*} (4 out of 12 choices, considering both Fat Server and Isolated Thin Server configurations).

3.3.7 Exploring Diversity Across OS Releases

If one wants to build systems capable of tolerating a few intrusions, our results show that it is possible to select OSes for the replicas with a small collection of common vulnerabilities. It is hard, however, to support critical services that need to remain correct with higher numbers of compromised replicas or to use some BFT algorithms that trade off performance for extra replicas (e.g., [1, 108, 163]). The number of available OSes is limited, and consequently, one rapidly runs out of different OSes (e.g., 13 distinct OSes are needed to tolerate $f = 4$ faults in a $3f + 1$ system). However, our experiments are relatively pessimistic in the sense that they are based on long periods of time, and no distinctions are made between OS releases.

Newer releases of an OS can contain essential code changes, and therefore, old vulnerabilities may disappear and/or new vulnerabilities may be introduced. As a result, if we consider (OS, release) pairs, one may augment the number of different systems that do not share vulnerabilities.

3.3.7.1 Sets with Four Diverse OSes

The main goal of this thesis is to develop dependable BFT systems. Therefore, one first step towards that goal is to explore the diversity of a particular *4-diverse* set in the Isolated Thin Server configuration. In particular, we analyze in more detail the vulnerabilities for the set {*OpenBSD, Debian, Solaris, Windows2003*} across their releases between 2000 and 2011. Despite the year of the release, since some vulnerabilities can be inherited from older versions of the code, we will include all vulnerabilities no matter the published date (i.e., even flaws discovered before 2000).

From all releases available for our 4-version replicated system,[1] we looked at the major releases that had non-zero vulnerabilities. Since OpenBSD follows a fixed six-month release cycle, in this case, we selected one version every three years, which is reasonable given our 12-year time span (considering all 18 releases would require 154 entries in the table). Therefore, the OS releases that are taken into the study are: OpenBSD 5.0, OpenBSD 4.4, OpenBSD 3.8, OpenBSD 3.2, Solaris 8.0, Solaris 9.0, Solaris 10.0, Solaris 11.0, Debian 2.2, Debian 3.0, Debian 4.0, Debian 5.0, Debian 6.0 and Windows2003.

Table 3.10 shows the number of common vulnerabilities for each pair of OS-release (pairs with zero values are not displayed). The first observation is that there are many pairs of releases within this set of 4 OSes that appear to be free of common flaws. Second, these shared bugs occur more

[1] OpenBSD 2.7, OpenBSD 2.8, OpenBSD 2.9, OpenBSD 3.0, OpenBSD 3.1, OpenBSD 3.2, OpenBSD 3.3, OpenBSD 3.4, OpenBSD 3.5, OpenBSD 3.6, OpenBSD 3.7, OpenBSD 3.8 OpenBSD 3.9, OpenBSD 4.0, OpenBSD 4.1, OpenBSD 4.2, OpenBSD 4.3, OpenBSD 4.4, Solaris 10.0, Solaris 11.0, Solaris 8.0, Solaris 8.1, Solaris 8.2, Solaris 9.0, Solaris 9.1, Debian 2.2, Debian 2.3, Debian 3.0, Debian 3.1, Debian 4.0, Debian 6.0, Debian 6.2, and Windows 2003.

OS Versions	Total
Solaris 8.0-Solaris 9.0	21
Solaris 9.0-Solaris 10.0	8
Solaris 8.0-Solaris 10.0	7
OpenBSD 3.2-OpenBSD 3.8	4
OpenBSD 3.2-Solaris 9.0	2
OpenBSD 3.2-Windows2003	2
OpenBSD 3.2-Solaris 8.0	1
OpenBSD 3.8-Windows2003	1
Solaris 8.0-Windows2003	1
Solaris 9.0-Windows2003	1
Solaris 10.0-Windows2003	1
Solaris 10.0-Solaris 11.0	1
Solaris 8.0-Debian 2.2	1
Debian 4.0-Windows2003	1

Table 3.10 – Common vulnerabilities between OS releases.

often between releases of the same OS. This is anticipated because more code is re-used within the same OS. Additionally, one can notice that releases of the same OS typically have less shared vulnerabilities when comparing older and newer versions. This is particularly evident for the OpenBSD and Debian releases. This result is quite promising because it supports our thesis that one should be able to explore diversity across releases as a way to increase the number of available candidates for the construction of the diverse OS sets.

3.4 Decisions About Deploying Diversity

We have underscored that these results are only *prima facie* evidence for the usefulness of diversity. On average, we would expect our estimates to be conservative as we analyzed aggregated vulnerabilities across releases: common vulnerabilities could be much smaller in a "specific set" of diverse OS releases. However, there are limitations on what can be claimed from the analysis of the NVD data alone without further manual analysis (other than what we have done, e.g., developing/finding and running exploit scripts on every OS for each vulnerability). A better analysis would be obtained if the NVD vulnerability reports were combined with the exploit reports (including exploiting counts), and even better if they also had indications about the users' usage profile. Moreover, we have seen that NVD has some limitations, as we have found that some of the vulnerabilities were not reported in the NVD, but several security advisory websites have reported those vulnerabilities. Additionally, there are partial exploit reports available from other sites (e.g., [157]).

Given these limitations, *how can individual user organizations decide whether diversity is a suitable option for them, with their specific requirements and usage profiles?* The cost is reasonably easy to assess: costs of the software products, the required middleware (if any), added the complexity

of management, difficulties with client applications that require vendor-specific features, hardware costs, run-time cost of the synchronization and consistency enforcing mechanisms, and possibly more complex recovery after some failures. The gains in improved security (from some tolerance to zero-day vulnerabilities and easier recovery from some exploits, set against possible extra vulnerabilities due to the increased complexity of the system) are difficult to predict except empirically. In any case, it seems that automated diversity management, described in the next chapter, is needed.

3.5 Final Remmarks

In this chapter, we presented results from an analysis of 18 years (1994–2011) of vulnerability reports from the NVD database. We developed three strategies to deploy diverse sets, some of which will be used (in part) in Chapter 5. In particular, the CVIst, as it introduces the notion of time evolution, is fundamental for the following contributions. This chapter contributes to answer one of the main questions that drove our research: *what are the potential security gains that could be attained from using diverse OSes in a replicated intrusion-tolerant system?*

4 SIEVEQ: A BFT Firewall

In the previous chapter, we presented a study that demonstrates the potential gains of using diverse (OS) components in BFT replicated systems. Here, we present a BFT solution that provides fault and intrusion tolerance by employing an architecture based on two filtering layers, enabling efficient removal of invalid messages at early stages in order to decrease the costs associated with BFT replication in the later stages. This system is SIEVEQ, a message queue service that protects and regulates the access to critical systems, in a way similar to an application-level firewall.

4.1 Firewalls Limitations

Firewalls are one of the primary protection mechanisms against external threats, controlling the traffic that flows in and out of a network. Typically, they decide if a packet should go through (or be dropped) based on the analysis of its contents. Over the years, this analysis has been performed at different levels of the Open Systems Interconnection (OSI) model (see [99] for a comprehensive survey), but the most sophisticated rules are based on the inspection of application data included in the packets. State-of-the-art solutions for application-level firewalls include network appliances from several vendors, such as Juniper [95], Palo Alto [142], and Dell [48]. Such appliances are strategically placed on the network borders, and therefore, the security of the whole infrastructure relies on them. A skilled attacker, however, may find weaknesses to compromise the firewall's detection/prevention capabilities. When this happens, critical services under the protection of such devices may be affected, as in the SCADA systems targeted in the Stuxnet [57] or Dragonfly [176] attacks.

Most generic firewall solutions suffer from two inherent problems: First, they have vulnerabilities as any other system, and as a consequence, they can also be the target of advanced attacks. For example, the NVD [133] shows that there have been many security issues in commonly used firewalls. NVD's reports present the following numbers of security issues between 2010 and 2018: 205 for the Cisco Adaptive Security Appliance; 123 in Juniper Networks solutions; and 50 related to iptables/netfilter. Common protection solutions often have been the target of malicious actions as part of a wider scale attack (e.g., anti-virus software [34], IDS [7] or firewalls [37, 38, 97, 175]). Second, firewalls are typically a single point of failure, which means that when they crash, the ability of the protected system to communicate may be compromised, at least momentarily. Therefore, ensuring the correct

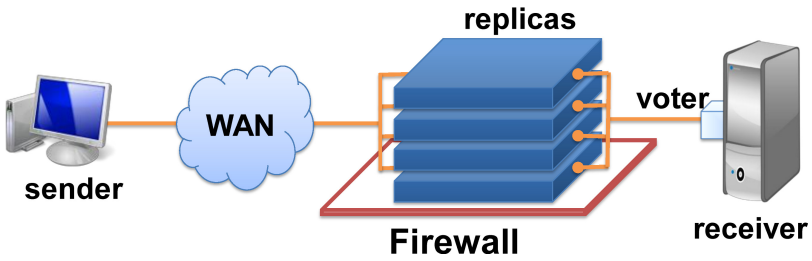


Figure 4.1 – Architecture of a state-of-the-art replicated firewall.

operation of the firewall under a wide range of failure scenarios becomes imperative. To tolerate faults, one typically resorts to the replication of the components.

In this chapter, we present a new protection system called SIEVEQ that mixes the firewall paradigm with a message queue service, with the goal of improving the state-of-the-art approaches under accidental failures and/or attacks. The solution has a fault- and intrusion-tolerant architecture that applies filtering operations in two stages acting like a sieve. The first stage, called *pre-filtering*, performs lightweight checks, making it efficient to detect and discard malicious messages from external adversaries. In particular, messages are only allowed to go through if they come from a pre-defined set of authenticated senders. DoS traffic from external sources is immediately dropped, preventing those messages from overloading the next stage. The second stage, named *filtering*, enforces more refined application level policies, which can require the inspection of some message fields or need the enforcement of specific ordering rules.

4.2 Intrusion-Tolerant Firewalls

In the last decade, several significant advances occurred in the development of intrusion-tolerant systems. However, to the best of our knowledge, very few works proposed intrusion-tolerant protection devices, such as firewalls. Performance reasons might explain this, as BFT replication protocols are usually associated with significant overheads and limited scalability. Additionally, achieving complete transparency to the rest of the system can be challenging to reconcile with the objective of having fast message filtering under attack.

Figure 4.1 shows an implementation of an intrusion-tolerant firewall, illustrating existing works in this area [160, 171]. In this design, a sender transmits the messages through the network (e.g., the internet) towards the receiver. As packets reach the firewall, they are disseminated to the replicas. Each replica applies the same filtering rules to decide whether the messages are acceptable. Invalid messages are discarded (and eventually logged). Messages deemed valid are conveyed to the receiver together with a proof of validity, which demonstrates that a sufficiently large quorum of replicas agrees on their validity. The proof of validity is checked by a voter module at the receiver, before

delivering the messages to the receiving application. Thus, if a compromised replica produces a message with malicious content, it will be eliminated as it lacks the necessary proof of validity or it is in conflict with the messages transmitted by the other correct replicas.

Although this architecture has interesting characteristics, such as an increased failure resilience, it suffers from some fundamental limitations:

1. The dissemination of a message to all replicas can be detrimental to the proper operation of the firewall. For example, a traffic replicator device (e.g., hub) can be placed at the entry of the firewall to reproduce all messages [160, 171] transparently. An obvious consequence of this approach is that malicious messages from an external attacker are also replicated, and therefore, all replicas have to spend the same effort to process them. As a consequence, the attack is amplified by the replicator device. Alternatively, a leader replica could receive the traffic and then disseminate the messages to the others [160]. The drawback is that the leader becomes a natural bottleneck, especially when under attack (instead of dispersing the attack load over all replicas [6]).

2. The support for stateful firewall filtering requires that all correct replicas process messages in the same order [162]. As a consequence, to ensure an agreement in a common sequence of messages, replicas need to continuously run a BFT consensus protocol [32] to establish message ordering. A significant amount of work can be wasted with malicious messages since all messages have to be agreed. This is particularly relevant because a consensus protocol consumes both computational and network resources.

3. The creation and check of the proof of validity can be a complex task. For example, one approach requires a trusted component to be deployed in the replicas to generate a Message Authentication Code (MAC) as a proof that a message is valid [171]. The component only returns the MAC when a quorum of replicas accepted the message. Another solution uses threshold cryptography to ensure that every replica can individually produce a partial signature (that corresponds to a part of the proof) [160]. To recreate the full proof, the voter needs to wait for the arrival of a quorum of partial proofs. When building a firewall, it would be useful if a more straightforward approach could be employed, with no need for specialized trusted components or expensive threshold cryptography.

These drawbacks can have a significant impact on the firewall performance depending on the considered setting. For example, a typical DoS attack can substantially decrease the throughput and lead to several orders of magnitude growth in the latency of message delivery. To illustrate this behavior we implemented the architecture of Figure 4.1 and launched a DoS attack on this system (see Section 4.6 for a description of the setup and environment). The results show that the system performance is significantly affected by the attack (see Figure 4.2).

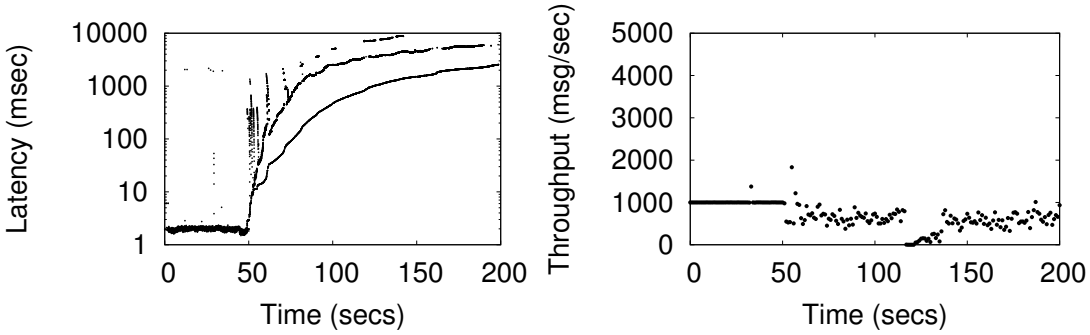


Figure 4.2 – Effect of a DoS attack (initiated at second 50) on the latency and throughput of the intrusion-tolerant firewall architecture displayed in Figure 4.1.

In SIEVEQ, we explore a different design for replicated protection devices, where we trade some transparency on senders and receivers for a more efficient and resilient firewall solution. In particular, we propose an architecture in which critical services and devices can only be accessed through a message queue and implement the application-level filtering in this queue. It is assumed that these services have a limited number of senders, which can be appropriately configured to ensure that only they are authorized to communicate through SIEVEQ.

4.3 Overview of SIEVEQ

Typical resilient firewall designs are based on primary-backup replication, and consequently, they are able to tolerate only crash failures. Therefore, more elaborated failure modes may allow an adversary to penetrate the protected network.

Some organizations deal with crashes (or DoS attacks) by resorting to several firewalls to support multiple entry points. This solution is helpful to address some (accidental) failures but is incapable of dealing with an intrusion in a firewall. In this case, the adversary gains access to the internal network, enabling an escalation of the attack, which at that stage can only be stopped if other protection mechanisms are in place.

SIEVEQ provides a message queue abstraction for critical services, applying various filtering rules to determine if messages are allowed to go through. SIEVEQ is not a conventional firewall, and we do not claim that it should replace existing firewalls in all deployment scenarios. We are focusing on service- or information-critical systems that require a high level of protection, and therefore, justify the implementation of advanced replication mechanisms. The system we propose is able to deliver messages while guaranteeing authenticity, integrity, and availability. As a consequence, and in contrast to conventional firewalls, we lose transparency on senders and receivers, since they are

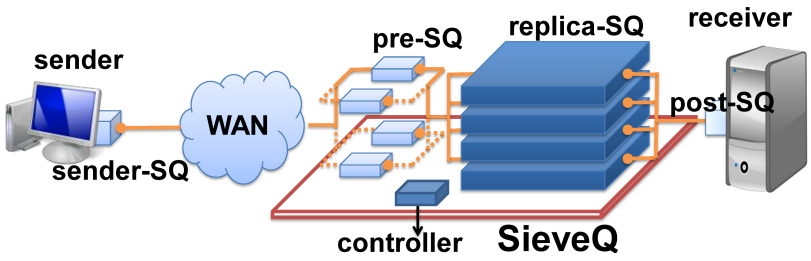


Figure 4.3 – SIEVEQ layered architecture.

aware of the SIEVEQ's end-points. The rest of the section explains how we address some of the mentioned issues and introduces the main design choices and the architecture of SIEVEQ.

4.3.1 Design Principles

Our solution was guided by the following principles:

- *Application-level filtering*: support sophisticated firewall filtering rules that take advantage of application knowledge. SIEVEQ implements this sort of rules by maintaining state about the existing flows, and this state has to be consistently replicated using a BFT protocol.

- *Performance*: address the most probable attack scenarios with highly efficient approaches, and as early as possible in the filtering stages; Reduce communication costs with external senders, as these messages may have to travel over high latency links (e.g., do not require message multicasts).

- *Resilience*: tolerate a broad range of failure scenarios, including malicious external/internal attackers, compromised authenticated senders, and intrusions in a subset of the SIEVEQ components; Prevent malicious external traffic from reaching the internal network by requiring explicit message authentication.

4.3.2 SIEVEQ Architecture

A fundamental difference between the SIEVEQ architecture and the other replicated firewall designs (see Figure 4.1), is the separation of filtering in several stages. The rationale for this change is to gain flexibility in the filtering operations while ensuring better performance under attack, retaining the ability to tolerate intrusions. As observed previously, despite the significant improvements in state-of-the-art BFT implementations, there is an inherent trade-off between the benefits of BFT replication and its performance, namely due to the need to disseminate (and eventually authenticate) all messages at the replicas, which includes both valid and invalid messages.

Figure 4.3 presents the architecture of SIEVEQ. In this architecture, message processing starts with a first filtering layer that implements a message authentication mechanism and is responsible for discarding most of the malicious traffic efficiently. This layer is based on a set of pre-SQ modules, each of them in charge of the communications with a subgroup of senders. During a typical operation, a sender only interacts with its own pre-SQ. The assignment of a sender-SQ to a pre-SQ is done during the channel setup. Initially, a sender connects with one of a few statically-configured pre-SQs. If a pre-SQ becomes overloaded, it will request the creation of more pre-SQs (see details in Section 4.4.4.2) and/or hand of the new sender-SQ channel to another node.

The messages are sent to the second filtering layer by the pre-SQ to perform a more detailed inspection, which can take advantage of state information kept from previous messages and application-related rules. This layer is implemented by a group of replica-SQs acting together as a BFT replicated state machine. They receive all accepted messages from the pre-SQs and process them in the same order, which guarantees that every replica-SQ reaches the same decision (discard or accept a message). However, if f replicas are faulty, their output could be different. Consequently, as long as more than two-thirds of the replica-SQs are correct, the right decision is taken by the post-SQ by performing a message voting.

In the following, we describe each module of SIEVEQ presented in Figure 4.3:

Sender-SQ. The sender nodes cooperate with SIEVEQ to secure the messages by deploying a sender-SQ module locally. Its primary role is to secure the messages and assist in the detection of some intruded SIEVEQ components. The module can be implemented inside the sender's OS (e.g., as a kernel module or a specialized device driver) or as a library to be linked with the applications. The decision to have this module corresponds to a trade-off in our design, where we are willing to lose some transparency to improve the system's resilience.

Pre-SQ. These are the SIEVEQ front-end, and although it only performs stateless filtering to improve efficiency, it can deter the most common attacks. Pre-SQ modules discard invalid messages, while the approved ones are forwarded to the replica-SQ using a Byzantine Total Ordered Multicast (TOM) protocol [22]. The pre-SQs can be deployed, for instance, as VMs. The effect of this layer is a significant reduction in the communication and computational overhead caused by malicious packets at the replica-SQ.

Replica-SQ. These components implement a replicated filtering service that tolerates Byzantine faults. The actual filtering rules can be more or less complex depending on the needs of the critical service. The TOM ensures that replica-SQs receive the messages in the same order. Consequently, identical rules are applied across the replica-SQs, and therefore, the same decision should be reached on the validity of messages. Each replica-SQ individually transmits approved messages to the final

receiver (the others are dropped). Overall, this layer allows for sophisticated filtering as the replicas are stateful.

Post-SQ. This module runs on the receiver side, and it is responsible for the delivery of messages to the application. A post-SQ carries out a voting operation on the arriving data because a replica-SQ might be intruded and corrupt messages. It delivers a message to the application only after receiving the same approved message from a quorum of replica-SQs. From a deployment perspective, this module can be implemented in the OS or as a library, as in the sender.

Controller. This module is a trusted component of SIEVEQ that runs with high privilege. It takes input from the replica-SQs to decide on the creation or destruction of pre-SQs if some misbehavior is observed. Depending on the actual SIEVEQ implementation, it can be developed in different ways. This sort of component was used in previous works, and it can be implemented both in a centralized [144, 160] or distributed [171] way.

4.3.3 Resilience Mechanisms

The SIEVEQ architecture is built to tolerate both faults with an accidental nature (e.g., crashes) and caused by malicious actions (e.g., a vulnerability is exploited, and a specific module is compromised). To be conservative, we assume that all failed components are controlled by a single entity, which will make them act together in the worst possible manner to defeat the correctness of the system. Therefore, failed components can, for instance, stop sending messages, produce erroneous information, or try to delay the system. SIEVEQ performs several mitigation actions to guarantee a valid operation (as long as the number of faults is within the assumed bounds, see Section 4.4.1).

The most common attack scenario occurs when an external adversary attempts to attack a system that is being protected by SIEVEQ. He can deploy many nodes, whose aim is to delay the communications or bypass SIEVEQ protection and reach the internal network. SIEVEQ addresses these attacks by discarding unauthenticated or corrupted messages with minimal effort at the pre-SQ filtering stage. As with any other firewall, if a DoS attack completely overloads the incoming channels, SIEVEQ cannot handle or react to the attack. The network needs to include other defense mechanisms to deal with this sort of problem [127].

As (authenticated) senders might be spread over many (outside) networks, it is advisable to consider a second scenario where an adversary is capable of taking control of some of these nodes. In this case, we assume that the adversary gains access to all data stored locally, including the sender-SQ keys. Thus, he will be able to generate traffic that is correctly authenticated, allowing these messages to go through the first filtering step. The messages are however still checked against the application-related rules (namely, the ones defined in the replica-SQ), which can cause most malicious traffic to be

dropped (e.g., a pre-defined sender-SQ can only send messages to a particular post-SQ accordingly to a specific application protocol). If the messages follow all the rules, the firewall has to forward them because they are indistinguishable from any other valid messages.

A third scenario occurs when the adversary can cause an intrusion in SIEVEQ and compromises a few of the pre-SQs and/or replica-SQs. When this happens, these components can act in an erroneous (Byzantine) way. However, unlike with an intruded sender-SQ, malicious pre-SQs cannot generate fully authenticated messages, since they lack all the required keys. They can still perform DoS attacks on the replica-SQs, e.g., by transmitting many messages, but this strategy creates apparent misbehavior allowing immediate discovery. Malicious pre-SQs are detected with the assistance of correct sender-SQ and replica-SQs, eventually leading to their substitution.

Replica-SQs modules are much harder to exploit because they do not face the external network. However, if they end up being intruded, replica-SQs can produce arbitrary traffic to the internal network. Post-SQ addresses this issue by carrying out a voting step, which excludes these messages. Moreover, an alarm is generated and sent to the *controller*.

The SIEVEQ architecture does not attempt to recover from intrusions in the controller and post-SQ. The first is assumed to be trusted, as it is deployed in a separated administrative domain and is to be used only in a few particular operations. Moreover, its simplicity allows the audit of its code and ensures correctness with a high level of confidence. The post-SQ already runs in the internal network, and therefore, SIEVEQ can not preclude its misbehavior.

4.4 SIEVEQ Protocol

This section details the SIEVEQ protocol and service properties. We conclude the section with an analysis of the behavior of the system under different kinds of attacks and component failures and highlight how the countermeasures integrated into our design mitigate such threats.

4.4.1 System and Threat Model

The system is composed of a (potentially) large number of external nodes, called *senders*, some internal nodes, called *receivers*, and SIEVEQ nodes. Senders run sender-SQ modules to be able to transmit packets through the SIEVEQ, while receivers receive validated messages by using post-SQ modules.

Communications can experience accidental faults or attacks. Thus, packets might be lost, delayed, reordered or corrupted, but we assume that if messages are retransmitted, eventually they will be

correctly received by SIEVEQ. The fault model also assumes that sender-SQ, pre-SQ, and replica-SQ nodes can suffer from arbitrary (Byzantine) faults. When this happens, failed nodes may perform actions that deviate from their specification, including colluding against the system. However, at most f_{ps} pre-SQs from a total of $N_{ps} = f_{ps} + k$ (with $k > 1$), and f_{rs} replica-SQ from a total of $N_{rs} = 3f_{rs} + 1$ may fail. Redundant components should fail independently by employing diversity techniques such as the ones described in Chapter 5. A component that is unable to communicate is also considered faulty because from a practical perspective it is indistinguishable from a crashed module.

The cryptographic operations used in the SIEVEQ protocol are assumed to be secure, and therefore, they cannot be subverted by an adversary. Consequently, traditional properties of digital signatures, MACs, and hash functions will hold as long as the associated keys are kept safe. The deployment of SIEVEQ requires a key distribution scheme to create shared keys between the sender-SQ and the pre-SQ and to periodically re-issue private-public key pairs for the sender-SQ. We assume that the key distribution scheme is similar to solutions that already address this sort of problem (e.g., [77]). If required, the key distribution infrastructure could also be made intrusion-tolerant (e.g., [109, 204]).

4.4.2 Properties

SIEVEQ protocol guarantees the following three properties for messages transmitted from a sender to a receiver:

Compliance. *If a message, transmitted by a correct sender, is delivered to a correct receiver then the message is in accordance with the security policy of* SIEVEQ.

Validity. *If a correct receiver delivers a message* `Msg.DATA`*, then the message was transmitted by* `Msg.sender`.

Liveness. *If a correct sender sends a message, then the message eventually will be delivered to the correct receiver.*

These properties require SIEVEQ to behave in a way similar to most firewalls while offering a few extra guarantees. Only external messages that are approved by the policies defined in SIEVEQ can reach the receivers, and the rest should be dropped (Compliance). Post-SQ can use the message field `Msg.sender` to find who transmitted the message contents (`Msg.DATA`), and accordingly decide if the message should be delivered to the receiver application (Validity). Progress is also ensured, as correct senders eventually can transmit their messages (Liveness).

Besides these functional properties (related to message filtering), SIEVEQ also ensures a *resilience* property related to the detection and recovery of components of the system that exhibit faulty behavior:

Resilience. *Every component exhibiting observable faulty behavior will be eventually removed or recovered.*

In the following, we present the mechanisms for implementing the SIEVEQ functionalities, i.e., the mechanisms for satisfying the three functional properties stated above. The mechanisms for ensuring resilience will be detailed after that.

4.4.3 Message Transmission

Sender-SQ processing. This module gets a buffer with the `DATA` to be transmitted to a particular application placed behind SIEVEQ. The buffer needs to be encapsulated in a message with some extra information required for protection (see Equation 4.1): we add a sender-SQ identifier S_i and a sequence number *sn* that is incremented on each message. This information is needed to prevent replay attacks, either from the network or from a compromised pre-SQ. Some information is also added to protect the integrity and authenticate the message. A signature sgn_{Si} is performed over the message contents, and a MAC mac_{ski} is computed using a shared key established with the pre-SQ. This MAC serves as an optimization to speed up checks [39].

$$\texttt{Msg} = \langle S_i, sn, \texttt{DATA}, sgn_{Si} \rangle_{mac_{ski}} \tag{4.1}$$

After constructing the message, it is sent to the pre-SQ assigned to the sender-SQ, and a timer is started. If this timer expires before the sender-SQ receives an acknowledgment message, it re-sends the `Msg` to another pre-SQ.

Pre-SQ filtering. The pre-SQ determines if an arriving message `Msg` should be forwarded or discarded (stages (a)–(d) in Figure 4.4). It applies the following checks to make this decision:

(a) **White list:** each pre-SQ maintains a list of the nodes that are allowed to transmit messages (i.e., which were authorized by the system administrator). Messages coming from other nodes are dropped. This check is based on the address of the message sender, and therefore it serves as an efficient first test, but it is vulnerable to spoofing.

(b) **Sequence number:** finds out if a message with sequence number *sn* from sender-SQ S_i was seen before. In the affirmative case, the message is discarded to prevent replay attacks.

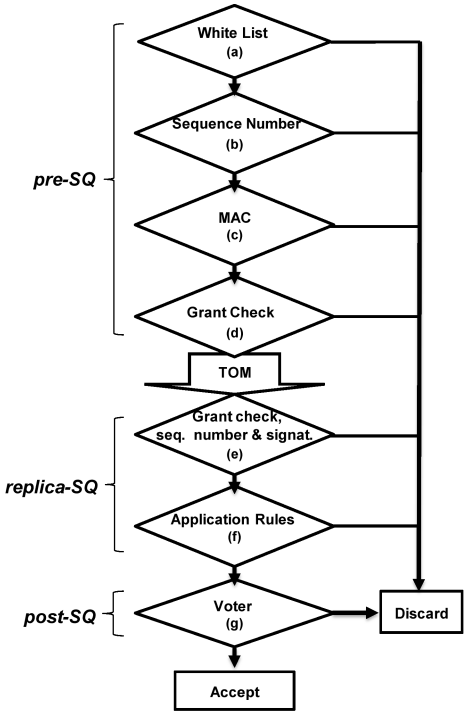


Figure 4.4 – Filtering stages at the SIEVEQ.

Messages are also dropped if their *sn* is much higher than the largest sequence number ever observed from that sender-SQ (a sliding window of acceptable sequence numbers is used).

(c) **MAC test:** MAC mac_{ski} is verified to authenticate the message contents, including to find out if the expected S_i is the sender. If the check is invalid, the message is dropped, and the sequence number information is updated to forget that this message was ever received (the update carried out in the previous step needs to be undone).

(d) **Grant check:** each pre-SQ controls the amount of traffic that a sender-SQ is transmitting. Messages that fall outside the allocated amount are dropped to ensure that all senders get a fair share of the available bandwidth (and to avoid DoS attacks by compromised senders). The amount of traffic that is allowed to each sender-SQ is adjusted dynamically based on the available and consumed resources.

Finally, the pre-SQ invokes the TOM primitive to forward the message to every correct replica-SQ.

Replica-SQ filtering. When a correct replica-SQ delivers a message to be filtered, the following checks are applied:

(e) **Grant check, sequence number, and signature:** since a pre-SQ may have been intruded and may collude with malicious sender-SQ, extra checks are required on the amount of forwarded

traffic and the integrity of the message. The grant check and the test on the sequence number are similar to the ones performed by the pre-SQ, and the signature ensures that all replica-SQs reach the same decision regarding the validity of the message content.

(f) **Application-level rules:** apply the application-defined filtering rules to determine if the message is compliant with the security policy of the firewall.

Although uncommon, replica-SQs may receive messages in a different order from what is defined in their sequence numbers. As a consequence, the replica-SQ's application-level rules may drop some of the out-of-order messages, which later on will have to be re-transmitted by the sender-SQ. For example, if messages `A` and `B` should appear in this sequence but are re-ordered, then the rules may consider `B` invalid and then accept `A`. At some point, the sender-SQ would consider `B` as lost, and re-transmit it.[1]

To address this issue, each replica-SQ enqueues messages with a sequence number greater than the expected for a while, as long as they do not exceed a threshold above the last processed sequence number. These messages are processed when either: 1) the missing messages with smaller sequence numbers arrive, and then they are all tested in order, or 2) the replica-SQ gives up on waiting and checks the enqueued messages. This last decision is made after processing a pre-determined number of other messages.

Valid messages are encapsulated in a new format (see Equation 4.2) and are sent to their receivers. Basically, replica-SQ RS_j substitutes the signature with a new MAC, mac_{skj}. This MAC is created with a shared key between the replica-SQ and the post-SQ.

$$\texttt{Msg}' = \langle S_i, sn, \texttt{DATA}, RS_j \rangle_{mac_{skj}} \tag{4.2}$$

Post-SQ processing. Post-SQ accumulates the messages that arrive from replica-SQs until enough evidence is collected to allow their delivery.

(g) *vote:* A message can be delivered to the application when it is received from $f_{rs}+1$ replica-SQs.

Algorithm 1 presents the post-SQ voting protocol. The post-SQ starts by checking if the message contains a valid MAC (lines 5 and 6). Then, it finds out if the message carries an acceptable sequence number before storing it in a `WaitingQuorum` set (lines 7 and 8). Notice that a different set is

[1] It is important to remark that, independently of any violation on the order of delivery of sender messages, all correct replica-SQs receive the messages in the same order.

used for each sender S_i and *sn* pair. Messages with sequence numbers already delivered or higher than a threshold (`snThreshold`) are discarded.

The expected sequence number is stored in the auxiliary variable k (line 9). Next, the post-SQ tries to find a message with this sequence number and with at least $f_{rs}+1$ votes (by searching the corresponding set and using function `equalMsg` — line 10). For each different `DATA` value that may exist in the set, the `equalMsg` function counts the number of times its appears, and returns the largest count.[2] Next, while there are `Msg`'s with a $f_{rs}+1$ quorum, post-SQ delivers `Msg`'s in order (line 10-13). The function `mostVotedMsg` returns the message with the `DATA` value with most votes (line 11). Then, the `deliver` function delivers `DATA` to the application on the receiver and deletes the `WaitingQuorum` set. Finally, the `snExpect` is incremented (line 12) and the k index is updated (line 13). This allows post-SQ to deliver messages in order while there are messages with the expected sequence number in its buffer.

Algorithm 1: post-SQ protocol

```
1  Init : executed only once
2  snExpect_Si, k ← 0;
3  WaitingQuorum_Si,sn ←⊥;
4  Function Filter (Msg')
5      if ( verifyMAC(Msg') = FALSE ) then
6          return errorMAC;
7      if (snExpect_Si ≤ Msg'.sn < (snExpect_Si + snThreshold)) then
8          WaitingQuorum_Si,sn ← WaitingQuorum_Si,sn ∪ {Msg'};
9      k ← snExpect_Si;
10     while ( equalMsg(WaitingQuorum_Si,k) ≥ f_rs + 1 ) do
11         deliver(mostVotedMsg(WaitingQuorum_Si,k)) ;
12         snExpect_Si ← snExpect_Si + 1 ;
13         k ← snExpect_Si;
```

4.4.3.1 Correctness Argument

In the following, we show that SIEVEQ design satisfies the three functional properties described in Section 4.4.2. The proofs work under the assumptions of our system and threat model (defined in Section 4.4.1).

Validity. *If a correct receiver delivers a message `Msg.DATA`, then the message was transmitted by `Msg.sender`.*

[2] Notice that all correct replica-SQs transmit messages with the same `DATA` value and that malicious replicas can send at most f_{rs} arbitrary `DATA` values. Therefore, eventually there will be a `DATA` value with at least $f_{rs}+1$ votes because there are at least $2f_{rs}+1$ correct replica-SQs.

Proof. Assume that a receiver R_j gets a message content `Msg.DATA` with the `Msg.sender` = `Msg.`S_i. For this to happen, the post-SQ of R_j waited for the arrival of at least $f_{rs}+1$ correctly authenticated messages[3] with equal `Msg.`S_i, `Msg.`*sn*, and `Msg.DATA`. Therefore, at least $f_{rs}+1$ replica-SQs received `Msg` signed by S_i, and verified the signature sgn_{Si} as valid. This indicates that `Msg.DATA` was not modified by the network or by any pre-SQ. Only a sender `Msg.`S_i (correct or not) can create and authenticate a `Msg` with its signature. Therefore, S_i is the `Msg.sender`, i.e., the creator of `Msg.DATA`. □

Compliance. *If a message, transmitted by a correct sender, is delivered to a correct receiver then the message is in accordance with the security policy of* SIEVEQ.

Proof. The proof of the *Compliance* property is very similar to the *Validity* proof. The difference is that, we also know that if $f_{rs}+1$ replica-SQs sent `Msg` to a post-SQ, then `Msg` was verified against the security policy in at least one correct replica-SQ, which approved it. □

Liveness. *If a correct sender sends a message, then the message eventually will be delivered to the correct receiver.*

Proof. For the sake of simplicity, our proof only considers nodes that drop or delay messages. Attacks to the integrity will make the message be discarded.

Assume that a sender S_i transmits a message `Msg` with the sequence number *sn* to a pre-SQ PS_u. Then S_i sets a timer $timer_{sn}$ for `Msg.`*sn*. If PS_u is correct, after it receives a message, it re-sends `Msg` via TOM to the replica-SQs. At least $f_{rs}+1$ correct replica-SQs will send `Msg` to the post-SQ, which will deliver `Msg.DATA` to the receiver R_j. If the PS_u is faulty, i.e., drops or delays messages, $timer_{sn}$ in S_i will eventually expire. When this happens, S_i re-transmits `Msg` to another pre-SQ. Eventually, this process will make some correct pre-SQ forward `Msg` to the replica-SQs using the TOM primitive, which will cause `Msg.DATA` to be delivered to R_j. □

4.4.4 Addressing Component Failures

In this section, we discuss the implications of failures in the different components of the SIEVEQ, and how they are handled for ensuring the *Resilience* property stated in Section 4.4.2.

In the Byzantine model, every failed component can behave arbitrarily, intentionally or accidentally. Therefore, the SIEVEQ design incorporates mechanisms that are resilient to different failure scenarios. Given the architecture of Figure 4.3, one has to address faults in authenticated sender-SQs, pre-SQs

[3] Note that replica-SQs send `Msg`′ (defined in (4.2)) instead of `Msg` (defined in (4.1)). Both are similar, but `Msg`' has a MAC instead of a signature to authenticate its contents with post-SQ. For the sake of simplicity we will only use the `Msg` notation in the rest of the proof.

and replica-SQs, as they are the main components subject to Byzantine failures in our model. The post-SQ is not considered in this section as it is co-located with the receiver. Therefore, we can not make further assumptions about it. We assume the *controller* as trusted in this chapter. In Chapter 6 we present an intrusion-tolerant solution for a different controller component that can be adapted for this *controller*.

In the following, we try to focus on complex scenarios whereas faulty components send syntactically-valid messages. Therefore avoiding cases that could be easily detected and recovered by existing network monitoring and protection tools (e.g., it is easy to discover that a pre-SQ is sending messages to another pre-SQ, something our protocol does not allow).

Since pre-SQs are directly exposed to the external network, there is a higher risk of them being compromised. Then, to keep the SIEVEQ operational, it is required that failed pre-SQs be identified and recovered. We leverage from the replica-SQ setup to perform failure detection, and then use the *controller* to restart erroneous pre-SQs. Replacing these components is almost trivial because they are stateless.

Replica-SQs execute as a BFT replicated state machine, processing messages in the same order and producing identical results. Consequently, replica-SQs faults can be tolerated by employing a voting technique on the post-SQ that selects results supported by a sufficiently large quorum (as explained above, an output with at least $f_{rs}+1$ votes). Below, we discuss in more detail a few failure scenarios.

4.4.4.1 Faulty Sender-SQ

A faulty sender-SQ is authorized to communicate while suffering from some arbitrary problem (e.g., intrusion). Therefore, it can produce correctly authenticated messages to attack the firewall. In some scenarios, it is possible to discard these messages. For example, if the SIEVEQ receives a correctly signed message with a sequence number is higher than what was expected, then it can be easily detected and eliminated (checks *(b)* and *(e)* in Figure 4.4).

A more demanding scenario occurs when a sender-SQ transmits faster than the allowed rate (verification (d) of Figure 4.4). In this case, some defense action has to be carried out, as these attacks can lead SIEVEQ to waste resources. To be conservative, we decided to follow a simple procedure to protect the firewall: SIEVEQ maintains a counter per sender that is incremented whenever new evidence of failure can be attributed to it, e.g., the faulty sender-SQ is overloading the system with invalid messages or if it is sending messages to pre-SQs which it was not assigned. When the counter reaches a pre-defined value, the sender-SQ is disallowed from communicating with SIEVEQ by temporarily removing it from the whitelist and adding it to a quarantine list (failing verification (a) of

Figure 4.4) and by giving a warning to the system administrator. *This ensures that faulty* sender-SQs *are eventually removed from the system.*

Excluded sender-SQs may regain access to the service later on because the counter is periodically decreased (when the counter falls below a certain threshold, the sender-SQ is moved back into the whitelist). Additionally, the administrator is free to update the white/quarantine lists. For instance, he may choose to manually add a faulty sender to the quarantine list or even deploy policies to do that under certain conditions (e.g., if the same sender is in the quarantine list for a certain number of times).

4.4.4.2 Faulty Pre-SQ

Addressing failures in pre-SQs is difficult because these components may look as compromised even when they are correct. Notably, when a pre-SQ is under a DoS attack, messages can start to be dropped due to buffer exhaustion, and this is indistinguishable from malicious behavior in which messages are selectively discarded. In the same way, a failed signature check at a replica-SQ indicates that either the pre-SQ is faulty (it is tampering/generating invalid messages) or that a sender-SQ is misbehaving (recall that a pre-SQ verifies the message MAC, but not its signature). Finally, a replica-SQ may also detect problems if it observes a sudden increase in the arrival of messages (above the grant check), which could indicate a DoS attack by a malicious pre-SQ (maybe colluding with a compromised sender-SQ). This kind of ambiguity precludes accurate failure detection, and consequently, we aim to provide a mechanism that allows SIEVEQ to recover from end-to-end problems and continue to deliver a correct service.

An initial step to deal with these complex failure scenarios is to make pre-SQs evaluate their own state. This is done by analyzing the amount of arriving traffic and by observing if it could overload the pre-SQ. The analysis can be done by measuring the inter-arrival times of messages over a specified period. If those intervals are small (on average), there is a chance that the pre-SQ is working at its full capacity or is even overloaded. When this happens, the pre-SQ broadcasts (using the TOM primitive) a `WARNREQ` message to the replica-SQs, so that they may take some action to solve the problem (see below).

When the pre-SQ is faulty, the sender-SQ and replica-SQs need to detect it together. SIEVEQ provides a procedure to find how many messages are being discarded on the pre-SQ:

1. Periodically, the sender-SQ sends a special `ACKREQ` request to replica-SQs, in which it indicates the sequence number of the last message that was sent (plus a signature and a MAC). This request is first sent to the preferred pre-SQ, but if no answer is received within some time

window, and then it is forwarded to another pre-SQ. The waiting period is adjusted in each retransmission by doubling its value.

2. When the replica-SQs receive the request, the included sequence number together with local information is used to find how many messages are missing. The local information is the set of sequence numbers of the messages that were correctly delivered since the last `ACKREQ`.

3. Based on the number of missing messages, the replica-SQs transmit through the same pre-SQ a response `ACKRES` to the sender, where they state the observed failure rate and other control information (plus a signature). Replica-SQs may also perform some recovery action if the failure rate is too high.

Additionally, if a replica-SQ detects that a signature is invalid or that it is receiving more messages than the expected (check (e) in Figure 4.4), it suspects the pre-SQ that sent the messages and takes some action.

Once the problem is detected, the replica-SQs should attempt to fix the erroneous behavior by employing one of three possible remediation actions, depending on the extent of the perceived failures:

- *Redistribute load:* if a pre-SQ has sent a warning about its load, or a high failure rate related with this component is observed, the first course of action is to move some of the messages flows from the problematic component to other pre-SQ. This is achieved by specifying, in the `ACKRES` response to a sender-SQ, the identifier of a new pre-SQ that should be contacted. At that point, the sender-SQ is expected to connect to the indicated pre-SQ and begin sending its traffic through it.

- *Increase the* pre-SQs *capacity:* if the existing pre-SQs are unable to process the current load, then the SIEVEQ needs to create more pre-SQs (depending on the available resources). To do that, replica-SQs contact the *controller* informing that an extra pre-SQ should be started. When the controller receives $f_{rs}+1$ messages, it performs the necessary steps to launch the new pre-SQ (which are dependent on the deployment environment). The new pre-SQ begins with a few startup operations, which include the creation of a communication endpoint, and then it uses the TOM channel to inform the replica-SQ that it is ready to accept messages from sender-SQs.

- *Kill the* pre-SQ*:* when there is a significant level of suspicion on a pre-SQ, the safest course of action is for replica-SQs to ask the controller to destroy it. Moreover, if the load on the firewall is perceived as having decreased substantially, the replica-SQs select the oldest pre-SQ for elimination, allowing future aging problems to be addressed. The controller carries out the

needed actions when it gets $f_{rs}+1$ of such requests (once again, which depend on how SIEVEQ is deployed). The affected sender-SQs will be informed about the pre-SQ replacement through the ACKREQ mechanism, i.e., they will eventually use another pre-SQ to send a request, and get the information about their newly assigned pre-SQ in the response. Moreover, the new pre-SQ is informed about the expected sequence number for each sender-SQ. This information is stored by replica-SQs, which contrary to pre-SQs are stateful.

Together, these mechanisms ensure that *a faulty* pre-SQ *affecting the* SIEVEQ *performance will be eventually removed from the system.*

4.4.4.3 Faulty Replica-SQ

A post-SQ only delivers a message if it receives $f_{rs}+1$ matching approvals for this message. Given the number of replica-SQs, this quorum is achievable for a correct message even if up to f_{rs} replica-SQs are faulty. However, a faulty replica-SQ can create a large number of messages addressed to other components of the system, effectively causing a DoS attack. Therefore, we need countermeasures to disallow a faulty replica-SQ to degrade the performance of the system in a similar way as illustrated in Figure 4.2. For example, a faulty replica-SQ can send an unexpected amount of messages to a pre-SQ, making it slower and triggering suspicions that may lead it to be killed. Similarly, it can attack other replica-SQs to make the system slower. Finally, a faulty replica-SQ can also overload the post-SQ with invalid messages.

Each of these attacks requires a different detection and recovery strategy:

- When a pre-SQ is being attacked it complains to the controller, which first requests the pre-SQ replacement (assuming it might be compromised) and increases a suspect counter against the replica-SQ. If $f_{ps}+1$ pre-SQs also complain about the same replica-SQ, the controller starts an *individual recovery* in this replica-SQ (see below).

- If more than f_{rs} other replica-SQs are being attacked, they will probably become slower. In this case, it is possible to detect such attacks if $f_{rs}+1$ replica-SQs complain about a single replica-SQ. This would be possible because target replica-SQs would observe unjustifiable high traffic coming from a single replica and because such spontaneously generated messages would be deemed invalid. When this attack is detected, the controller starts an individual replica-SQ recovery.

- If only up to f_{rs} other replica-SQs are being attacked it is still possible to make the system slower without being detected by the previous mechanism. This happens because $N_{rs}-f_{rs}$

replicas must participate in the TOM protocol [22], and the target f_{rs} plus the attacker intersect this quorum in a least one component. This intersecting component will define the pace of the messages coming, which typically will be slow. We can mitigate this attack as each replica-SQ periodically informs the post-SQ about its throughput (number of processed messages per second), piggybacking this value in some approved messages submitted for voting. The post-SQ verifies that there are replica-SQs presenting throughputs lower than expected and initiates a *recovery round* on all the replica-SQs (as described below).

- When the post-SQ is being attacked it detects the abnormal behavior. Then, it requests the individual recovery of the compromised replica.

The previous mitigation mechanisms suggest two kinds of recovery actions. First, an individual recovery, where the machine is rebooted with clean code (we addressed this in Chapter 5) and then is reintegrated in the system. Second, a recovery round is used when a performance degradation attack is detected, but there is no certainty about which replica-SQ was compromised.

4.5 Implementation

We implemented a prototype of SIEVEQ following the specification of the previous section to validate our design. The sender-SQ and post-SQ were developed as libraries that are linked with the sender and receiver applications. The libraries offer an interface similar to the TCP sockets to simplify the integration and minimize changes both in the client and server applications. A sender can provide a buffer to be transmitted, and the receiver can indicate a buffer where the received data is to be stored. Internally, the sender-SQ library adds a MAC and a signature to each message. The MAC is created using Hash-based Message Authentication Code (HMAC) with the Secure Hash Algorithm (SHA) (256) hash function and a 256-bit key, and the signature employs Rivest–Shamir–Adleman (RSA) with 512-bit keys. Messages are authenticated at the post-SQ also using HMAC. The RSA keys were kept relatively small for performance reasons. However, since they should be updated periodically (e.g., every few hours), this precludes all practical brute force attacks [2].

The pre-SQs operate as separate processes receiving the messages and forwarding them to the replica-SQs. We resorted to BFT-SMART [22] to implement the TOM and manage the replica-SQs. BFT-SMART, like most SMR systems (e.g., PBFT [32], ZYZZYVA [108], PRIME [6]) follows a client-server model, where a client transmits request messages to a group of server replicas and then receives the output messages with the results of some computation. We had to modify BFT-SMART because this model does not fit well with the message flow of SIEVEQ. Therefore, we have decoupled the client-server model into a client-server-client model. The client sends messages (but does not wait for responses as in traditional SMR), and the server forwards them (after validation) to another

client, which is the last receiver. A reverse procedure is carried out for the traffic originating from the receiver. Furthermore, in BFT-SMART the replicated servers are typically designed with a single-thread to process requests. To improve performance, we also modified the system to allow CPU-costly operations (like a signature verification) to occur concurrently with the rest of the checks performed by replica-SQs.

In the prototype, a pre-SQ can be replaced on two occasions: first, voluntarily by asking for a substitution to the replica-SQs, when it is flooded with unauthorized messages (DoS attack); and second, when a replica-SQ detects message corruptions by a pre-SQ. In both situations, the replica-SQs make a request to the *controller*, which will replace a pre-SQ instance. Notice that the *controller* has to wait for $f_{rs} + 1$ messages, requesting a pre-SQ replacement, to ensure that a faulty replica-SQ cannot force the recovery of a correct pre-SQ. The replica-SQs are recovered when the collected information indicates that some component might be attacking other components. The information is collected and sent to the trusted controller to evaluate and decide if the replicas are making progress as expected. Based on this information, the controller can suspect on f replica-SQs and recover them avoiding the need to recover all of them at once.

Since BFT-SMART is programmed in Java, we decided to use the same language to develop the various SIEVEQ components. If the sender and receiver applications are coded in other languages, they can still be supported by implementing specific sender-SQ and post-SQ libraries.

4.6 Evaluation

In this section, we present the evaluation of SIEVEQ under different network and attack conditions. We present the results of four types of experiments. In the first one, we evaluate the latency for different sender-SQ workloads, assessing the performance of SIEVEQ in the absence of failures. The second experiment assesses the effect of filtering rules complexity on the performance of the system. In the third experiment, we assess the throughput in three scenarios: *i)* the normal case, *ii)* during a DoS attack without countermeasures; and *iii)* during a DoS with all the resilience mechanisms enabled (in fact we considered two DoS attacks: external, from a malicious sender-SQ, and internal, from a compromised replica-SQ). The last experiment considers the capability of SIEVEQ to safeguard a SIEM system under a similar workload as the one observed in the 2012 Summer Olympic Games.

4.6.1 Testbed Setup

Figure 4.5 illustrates the testbed, showing how the various SIEVEQ components were deployed in the machines. We consider one sender-SQ and one post-SQ deployed in different physical nodes,

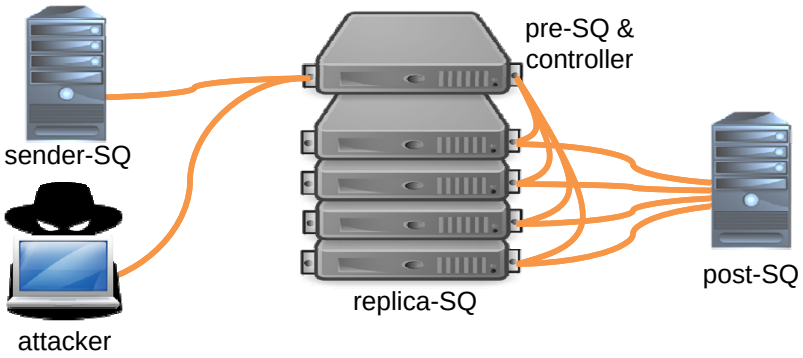


Figure 4.5 – The SIEVEQ testbed architecture used in the experiments.

and an additional host acting as a malicious external adversary. The *controller* and pre-SQs were located in the same physical machine for convenience but in different VMs. Four replica-SQs were placed in distinct physical nodes. Every machine had two Quad-core Intel Xeon 2.27 GHz CPUs, with 32 GB of memory, and a Broadcom NetXtreme II Gigabit network card. All the machines were connected by a 1Gbps switched network and run Ubuntu 10.04 64-bit LTS (kernel 2.6.32-server) and Java 7 (1.7.0_67).

4.6.2 Methodology

SIEVEQ acts as a highly resilient protection device, receiving messages on one side and forwarding them to the other side. Therefore, the performance of SIEVEQ is assessed with latency/throughput measurements that can be attained under different network loads. In the experiments, the sender transmits data at a constant rate, i.e., 100 to 10000 messages per second, with three different message payload sizes, i.e., 100 bytes, 500 bytes, and 1k bytes. We used the Guava library [72] to control the message sending rate.

Latency measures the time it takes to transmit a message from sender-SQ until it is delivered to the application on the post-SQ. The following procedure was employed to compute the latency: the sender-SQ obtains the local time before transmitting a message. When the message arrives and is ready to be delivered to the receiver application (after voting), the post-SQ returns an acknowledgment over a dedicated UDP channel. The Sender-SQ gets the current time again when the acknowledgment arrives. The latency of a message is the elapsed time calculated at sender-SQ (receive time minus send time) subtracted by the average time it takes to transmit a UDP message from the post-SQ to the sender-SQ.

Throughput gives a measure of the number of messages per second that can be processed by SIEVEQ. It was calculated at the post-SQ using a counter. This counter is incremented every time a message is delivered to the receiver application, and the counter is reset to zero after one second. Consequently, the server can calculate the number of messages delivered every second. The throughput is computed

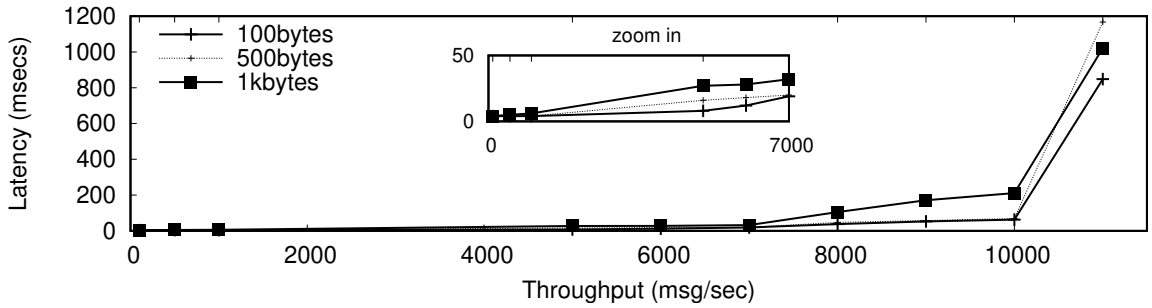


Figure 4.6 – SIEVEQ latency for each workload (message size and transmission rate).

as the average value of the individual measurements collected over a period of time (in our case, 5 minutes after the steady state was reached).

In some experiments, we wanted to assess the behavior of SIEVEQ under a DoS attack. The attack was made using `PyLoris` [148], a tool built to exploit vulnerabilities on TCP connection handling. The tool implements the Slowloris attack method, which opens many TCP connections and keeps them open. The tool allows the user to define parameters like group size of attack threads, the maximum number of connections, and the time interval between connections among others. In our setup, `PyLoris` was configured to perform an unlimited number of connections, with 0.1 milliseconds between each connection.

In all experiments, measurements were taken only after the Java Virtual Machine (JVM) was warmed-up, and the disks were not used (all data is kept in memory).

4.6.3 Performance in Failure-free Executions

This experiment measures the latency of SIEVEQ with several message sizes and distinct message transmission rates. It demonstrates the overall performance of SIEVEQ in different scenarios, gradually stressing the post-SQ side as the workload is slowly increased. Measurements were collected after the system reached a steady state. The experiments were repeated 10 times for every workload, and the average result is reported.

Figure 4.6 shows how the latency is affected by the transmission rate and message size. As expected, when the system becomes increasingly loaded, the latency grows proportionally because resources have to be shared among the various messages. The latency increase is approximately linear for the messages with 100 and 500 bytes until the throughput reaches $10k$ messages per second. The messages with $1k$ bytes have a linear increase on latency until the throughput reaches approximately $7k$ messages per second, and then it has a higher increase as more load is put on the system. This means that very high workloads can only be supported if applications have some tolerance to network

Payload size (*bytes*)	Non-optimized (*msg/sec*)	Optimized (*msg/sec*)
100	1360	10682
500	1320	10618
1000	1311	10332

Table 4.1 – Maximum load induced by the sender-SQ library with various message sizes.

delays. Overall, the performance degrades gracefully when varying the message payload sizes, for rates under $7k$ messages per second.

We performed a more detailed analysis of the overheads introduced by the various components of SIEVEQ. We observed that sender-SQ performs the most expensive operations, which is interesting because it shows that our design offloads part of the effort to the edges, reducing bottlenecks. The most significant overheads were caused by the tasks associated with securing the message payload (which are the most costly operations in the system). Several optimizations were made to mitigate the performance penalties during the message serialization (e.g., the creation of the signature), including the use of parallelization to take advantage of the multicore architecture (as done, for example, in [103]). Table 4.1 shows the gain of using the optimized version of the sender-SQ library. Similar optimizations were employed in other components.

4.6.4 Effect of Filtering Rules Complexity

The results presented in the previous section do not consider any complex filtering rule set. This section presents experiments with a fully loaded system and application-level filtering rules with different complexity at the replica-SQs.

Given the diverse requirements imposed by application-level firewalls, we decided to approximate the complexity of the filtering rules by considering a variable number of string matchings on processed messages. It is well recognized that the most expensive aspect of message filtering is exactly finding (or not) specific strings in the packet contents (besides crypto verifications, which were included in all our experiments). The high cost of running such algorithms leads for instance to several implementations in Field-Programmable Gate Arrays (FPGAs) and Graphics Processing Units (GPUs) to improve performance in firewalls and IDS (e.g., [114, 131]).

We used a classical algorithm for string matching (Knuth–Morris–Pratt [106]) at the replica-SQs to implement the filtering rules. This algorithm is employed in IDSs [146] and firewalls like `iptables` [137]. The algorithm employs a pre-computed table to execute string matching with $O(n+k)$ comparisons, where n is the string length, and k is the pattern length.

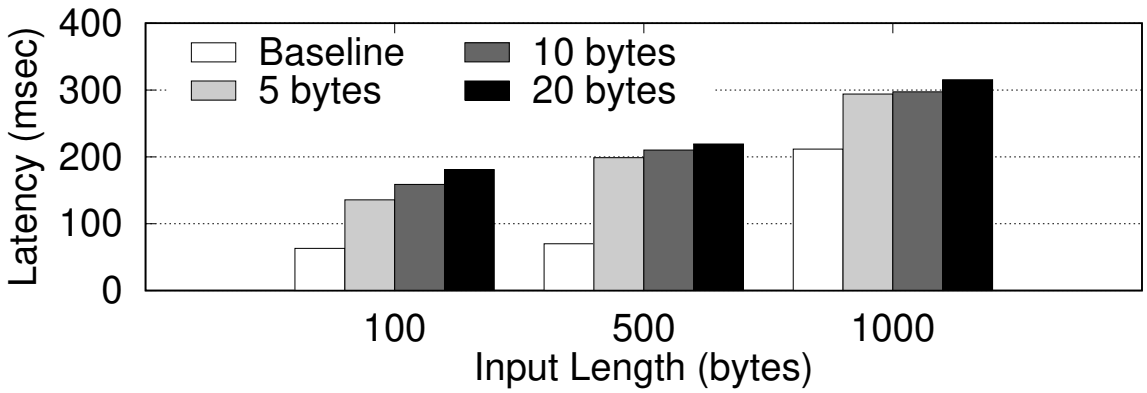


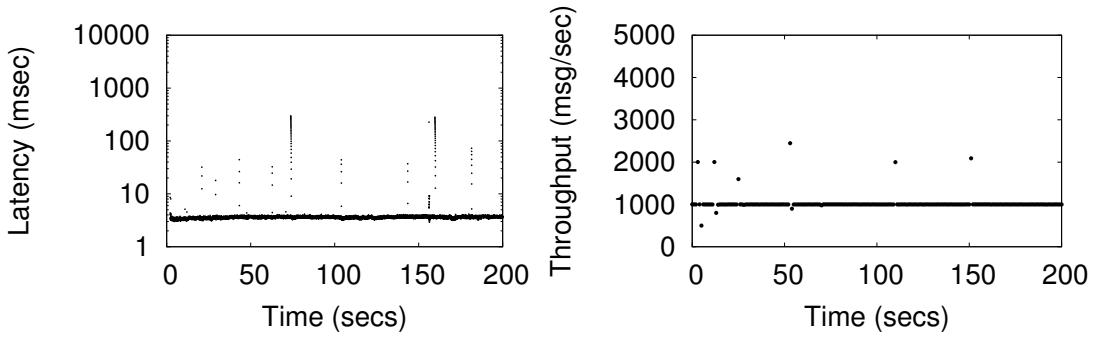
Figure 4.7 – Comparison of the SIEVEQ's latency between the baseline and filtering rules with patterns of different sizes.

We measured the latency of the system by varying the message size from 100 to 1000 bytes and the string pattern size from 5 to 20 bytes. Both the message content and the strings were randomly generated. The experiments were performed with the maximum throughput of 10000 messages per second, as identified in the previous section. Figure 4.7 shows the latency of SIEVEQ without message filtering (Baseline) and string matching of different sizes. In the last group of experiments, where the message size is 1000 bytes, and the pattern is 20 bytes, the latency increases by 50%. In other cases, sometimes higher overheads were observed, e.g., with 500 bytes messages and 20 bytes pattern the overhead is approximately 200%. This result is expected as string matching is a slow operation and it needs to be performed in the critical path of message processing. Implementations with hardware support (as mentioned before) could be integrated with SIEVEQ to reduce these delays significantly.

4.6.5 SIEVEQ Under Attack

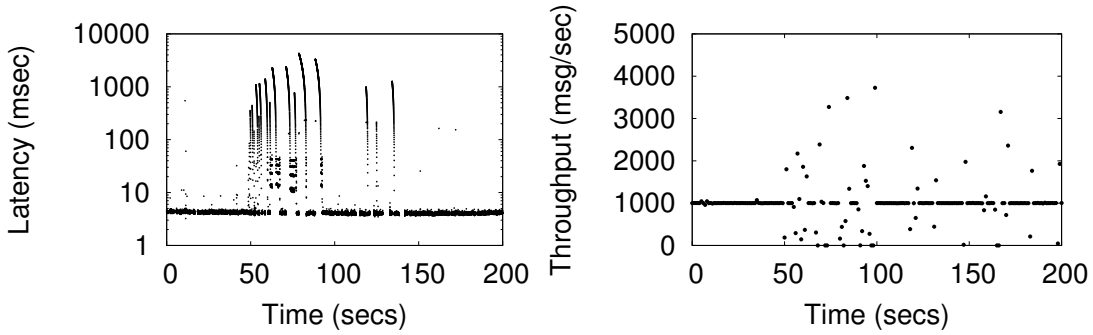
Our next set of experiments aims to evaluate the system under different attack scenarios. Here, the sender-SQ creates a steady load of 1000 500-byte messages per second. We measured the latency and throughput of the system in three conditions: failure-free operation, a malicious external and internal DoS attack, and a malicious attack with remediation mechanisms. Before presenting the results, we need to stress that these experiments must be compared with the results displayed in Figure 4.2, which were obtained in the same way but with a different architecture (see Figure 4.1).

Figures 4.8a and 4.8b show the latency and throughput observed in the failure-free scenario. One can observe that latency stays (on average) around 3.4 milliseconds. The throughput is approximately constant during the whole period. It is possible to observe some momentary spikes in the latency and throughput, which happens due to Java garbage collector and a queuing effect from the SMR.



(a) Baseline latency. **(b)** Baseline throughput.

Figure 4.8 – Performance of SIEVEQ in fault-free executions.

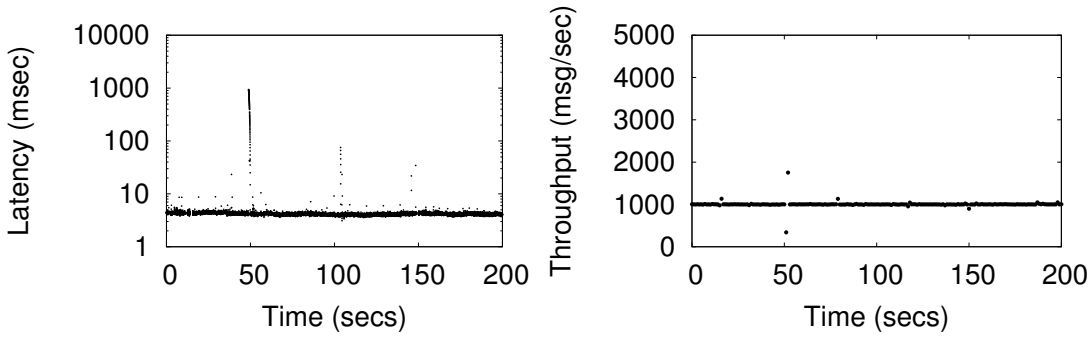


(a) DoS w/ no recovery. **(b)** DoS w/ no recovery.

Figure 4.9 – Performance of SIEVEQ under DoS attack conditions.

The behavior of SIEVEQ during a DoS attack is displayed in Figures 4.9a and 4.9b. In this scenario, we have disabled the SIEVEQ capability of replacing pre-SQs at runtime. The attack consists in stressing the TCP socket interface of the pre-SQs by creating many TCP connections, which consumes network bandwidth and wastes resources at system and application levels. When the attack is started, it executes for 50 seconds. The latency graph displays a reasonable impact regarding an increase in the delays for message delivery. In some cases, the latency is not too affected, but in others, there is a drastic delay, with some messages taking more than 3 seconds to be received. The attack also has consequences on the throughput as it is possible to observe an oscillation between 0 to 4000 messages per second (which correspond to the situation when the post-SQ processes a batch of messages that have been accumulated).

Figures 4.10a and 4.10b show the latency and throughput when a similar DoS was carried out, but in this case the SIEVEQ replaced the pre-SQ under attack with a new pre-SQ. When the pre-SQ finds out that it is being overloaded with messages coming from non-authorized senders, it asks for a replacement. After that, the controller replaces the faulty pre-SQ, and the existing sender-SQs are contacted to migrate their connections. As the figures show, the impact of the attack is minimized, since only a few messages are delayed, and throughput is only affected momentarily while the pre-SQ is switched. Once the new pre-SQ takes over, the messages lost during the switching period



(a) DoS w/ recovery.

(b) DoS w/ recovery.

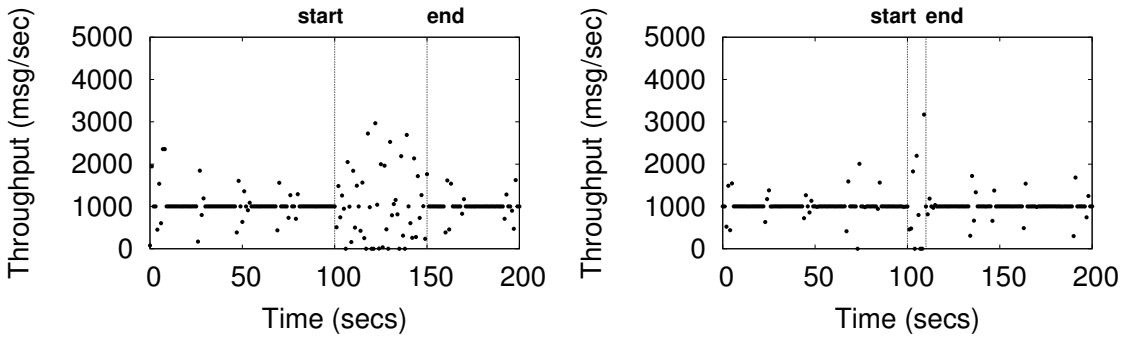
Figure 4.10 – Performance of SIEVEQ under DoS attack conditions with recovery.

are retransmitted and delivered. In practice, the attack becomes ineffective because, although it continues to consume network bandwidth, there is no longer a pre-SQ to process the malicious messages. An adversary could increase the attack sophistication and try to find a new pre-SQ target. However, even in this case, the attack has a limited effect because during an interval of time (while there is a search for a fresh target) the system can make progress.

Figures 4.11a and 4.11b shows the SIEVEQ throughput when an internal attack is carried out by a compromised replica-SQ. The experiment was made with a replica-SQ ($r1$) launching a DoS to another replica-SQ ($r2$). The attack consists in overloading a replica-SQ with *state transfer* requests, which are the most demanding request a replica can receive in BFT-SMART [21]. Figure 4.11a shows the impact on the SIEVEQ throughput during an attack lasting 50 seconds, without any recovery capability on the system. As can be seen, the performance of the system is severely disrupted during the attack. Figure 4.11b shows the same attack but with the detection and recovery mechanism described in Section 4.4.4.3. The post-SQ detects the problem by noticing that $f_{rs}+1$ replica-SQs are sending fewer messages than the others and then requests a recovery. When the replica-SQ is recovered, it requests the state from the other replicas, and then after applying the new state, the replica resumes the normal execution (end line in the figure). In the experiment of Figure 4.11b we show a case in which the faulty replica-SQ is the first to be recovered. It could happen that SIEVEQ recovered f_{rs} replica-SQs before the faulty one. This would take $(f_{rs}+1)\times$ 3 seconds (in our setup) before the system resumes the normal execution.

4.6.6 SIEVEQ to Protect a SIEM System

SIEM systems offer various capabilities for the collection and analysis of security events and information in networked infrastructures [125]. Organizations are employing these systems as a way to help with the monitoring and analysis of their infrastructures. They integrate an extensive range of security and network capabilities, which allow the correlation of thousands of events and the reporting of attacks and intrusions in near real-time.



(a) Internal DoS execution without recovery actions.

(b) Internal DoS execution with recovery actions.

Figure 4.11 – Performance of SIEVEQ under internal DoS attack conditions without and with recovery.

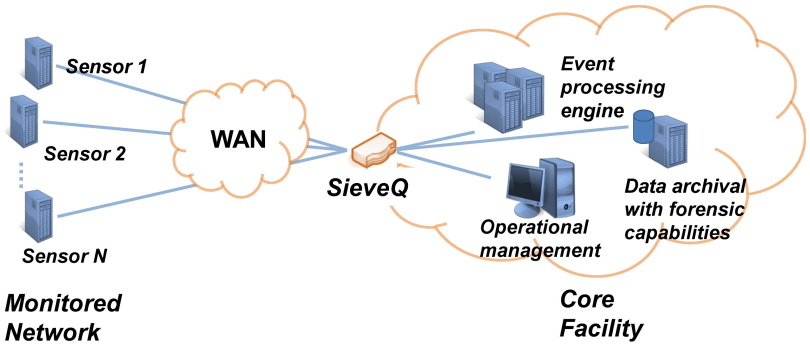


Figure 4.12 – Overview of a SIEM architecture, showing some of the core facility subsystems protected by the SIEVEQ.

A SIEM operates by collecting data from the monitored network and applications through a group of sensors, which then forward the events towards a correlation engine at the core facility. The engine performs an analysis of the stream of events and generates alarms and other information for post-processing by other SIEM components. Examples of such components are an archival subsystem for the storage of data needed to support forensic investigations, or a communication subsystem to send alarms to the system administrators.

As part of the MASSIF European project [186], we have implemented a resilient SIEM system where SIEVEQ was used to protect the access to the core facility (see Figure 4.12). In the SIEVEQ architecture, the sensors integrate the sender-SQ while the post-SQ was placed in the correlation engine. Additionally, we had access to an anonymized trace with the security events collected during the 2012 Olympic Games. Each event corresponds basically to a string describing some observed problem by a sensor. The strings of text had lengths varying between a minimum of 551 bytes and a maximum of 2132 bytes, with an average length of 1990 bytes (and a standard deviation of 420 bytes). Based on this log, we built a sensor emulator that generates traffic at a pre-defined rate. Basically, when it is time to produce a new event, the emulator selects an event from the trace and feeds it to the sender-SQ.

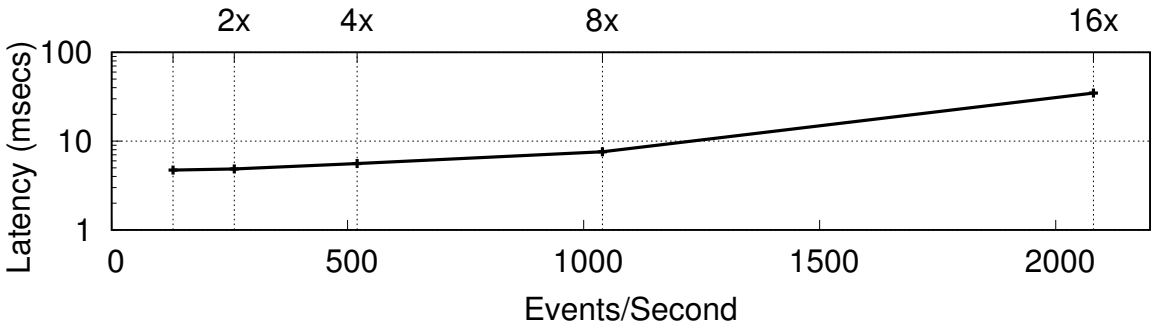


Figure 4.13 – SIEVEQ latency for the 2012 Summer Olympic Games scenario throughput requirement (127 events per second) and how the SIEVEQ scale.

During the 2012 Olympic Games, the workload was approximately 11 million events per day, i.e., around 127 events per second. Figure 4.13 shows the latency imposed by SIEVEQ for this workload, and when it is scaled up from 2 to 16 times more. As can be observed, the latency is in the order of 4 milliseconds for the emulated scenario. Even with the highest load (16 times), the observed values had a latency below 70 milliseconds. This means that SIEVEQ could potentially deliver 176 million events per day, which is more than enough to accommodate the expected growth in the number of events for the next Olympic Games.[4]

4.7 Discussion

SIEVEQ differs from standard firewalls like `iptables` [137] that do not need client- or server-side code modifications. However, our system requires these modifications to ensure end-to-end message integrity and tolerance of compromised components. Complete transparency would be hard to achieve mainly due to the use of voting. Nonetheless, it is worth stressing that SIEVEQ is to be used as an additional protection device in critical systems, not as a substitute to regular L3 firewalls. SIEVEQ provides a protection similar to an application-level/L7 firewall, as one can implement arbitrary rules on the replica-SQ module.

State machine replication is a well-known approach for replication [162]. In this technique, every replica is required to process requests in a deterministic way. This requirement traditionally implies in two limitations: (1) replicas cannot use their local clock during request processing, and (2) all requests are executed sequentially. The first limitation can affect the capacity of SIEVEQ to process rules that use time. We remove this limitation by making use of the timestamps generated by the leader replica and agreed upon on each consensus, as proposed in PBFT [32] and implemented in BFT-SMART [22]. The second limitation can constraint the performance of the system, especially when CPU-costly operations such as signature verifications are executed. One of the optimizations

[4] In 2016 Rio's Olympic Games the number of events per second was approximated 174, source: `https://diginomica.com/2016/11/24/securing-the-olympics-lessons-for-enterprise-cyber-security/`

we implemented in SIEVEQ was to add multi-threading support to the BFT-SMART replicas. More precisely, the signature verification is done by a pool of threads that either accept or discard messages. Once accepted, a message is added to a processing queue following the order established by the total order multicast protocol. A single thread consumes messages from this queue, verifies them against the security policy, updates the firewall state (if needed) and forwards them to their destinations, without violating the determinism requirement.

4.8 Final Remarks

We presented SIEVEQ, a new intrusion-tolerant protection system for critical services, such as Industrial Control Systems (ICS) and SIEM systems. Our system exports a message queue interface which is used by senders and receivers to interact in a regulated way. The main improvement of the SIEVEQ architecture, when compared with previous systems, is the separation of message filtering in several components that carry on verifications progressively more costly and complex. This allows the proposed system to be more efficient than the state-of-the-art replicated firewalls under attack. SIEVEQ also includes several resilience mechanisms that allow the creation, removal, and recovery of components in a dynamic way, to respond to evolving threats against the system effectively. Experimental results show that such resilience mechanisms can significantly reduce the effects of DoS attacks against the system.

5 Diversity Management for BFT Systems

This chapter presents the design of a control plane, named LAZARUS, to manage the diversity in BFT services. The design improves the work presented in the previous chapters. First, it adds new data and clustering techniques, introducing a new metric to evaluate vulnerabilities severity, and second, it proposes a strategy to minimize the risk of having common failure modes in replicated systems. In the end, we validate this proposal against other strategies.

5.1 Overview

LAZARUS is a control plane solution that automatically changes the attack surface of a BFT system in a dependable way. LAZARUS continuously collects security data from OSINT feeds on the internet to build a knowledge base about the possible vulnerabilities, exploits, and patches related to the systems of interest. This data is used to create clusters of similar vulnerabilities, which potentially can be affected by (variations of) the same exploit. These clusters and other collected attributes are used to analyze the risk of the BFT system becoming compromised due to common vulnerabilities. Once the risk increases, the control plane replaces a potentially vulnerable replica by another one, trying to maximize the failure independence of the replicated service. Then, the replaced node is put on quarantine and updated with the available patches, to be re-used later.

In a nutshell, as displayed in Figure 5.1, LAZARUS provides a distributed operating system for BFT-replicated services. The system manages a set of nodes that run *unmodified replicas* (encapsulated in VMs or containers) in its execution plane. Each node must have a small Logical Trusted Unit (LTU) that allows the activation and deactivation of replicas as demanded by the LAZARUS *Controller*, in the control plane. The controller decides which software should run at any given time by monitoring the vulnerabilities that potentially exist in the pool of replicas, aiming to minimize the risk of having several nodes being compromised by the same attack.

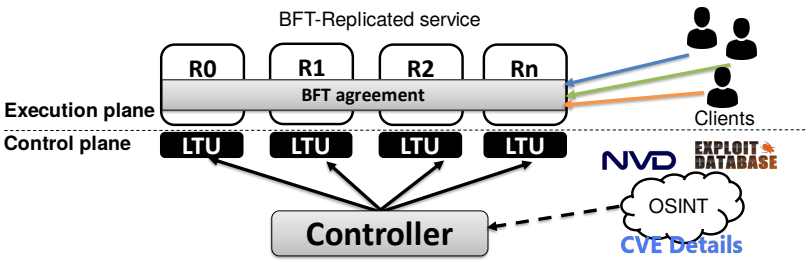


Figure 5.1 – LAZARUS overview.

5.2 System Model

LAZARUS system model shares some similarity with previous works on the proactive recovery of BFT systems [32, 50, 144, 160, 171]. More precisely, we consider a *hybrid distributed system model* composed of two planes with different failure models:

- **Execution Plane:** replicas are subject to *Byzantine failures* and communications go through an asynchronous network that can delay, drop or modify messages [10, 22, 31, 108]. This plane hosts n replicas from which at most f can be compromised at any given moment. In this chapter, we consider the typical scenario in which $n = 3f + 1$ [10, 32, 108].
- **Control Plane:** Each *node* hosting a replica contains a LTU, which is a fundamental trusted component [173] required for *safe proactive recoveries* [32, 50, 144, 160, 171]. Each LTU receives power on/off commands from a *logically-centralized controller* to reconfigure their replicas. As in previous works [144, 160, 171], this controller is assumed to be trusted. Such assumption can be substantiated by running it in an isolated control network (similarly to cloud resource managers) our by building it in a trustworthy manner (tolerating Byzantine failures, as discussed in Section 6.1.3).

Besides the execution and control planes, we assume the existence of two types of external components: (1) clients of the replicated service, which can be subject to Byzantine failures; (2) OSINT sources (e.g., NVD, ExploitDB) that cannot be subverted and controlled by the adversary. In practice, this assumption led us to consider only well-established and authenticated data sources. Dealing with untrusted sources is an active area of research in the threat intelligence community (e.g., [119, 161]), which we consider out of the scope of this thesis.

5.3 Diversity of Replicas

For our purposes, each *replica* is composed of a stack of software, including an OS (kernel plus other software contained in an OS distribution), execution support (e.g., JVM, Databases Management

Systems (DBMS)), a BFT library, and the service that is provided by the system. The set of n replicas is called a CONFIG.

The fault independence of the replicas is improved when different OTS components are employed in the software stack [49]. For example, it has been shown that using distinct databases [68], OSes [66], and filesystems [15, 33], can yield important benefits in terms of fault independence. In addition, automatic techniques could enhance diversity, like randomization/obfuscation of OSes [160], applications [191], and BFT libraries [144]. Although LAZARUS can also exploit these automatic techniques, in this chapter we center our attention on diverse OTS components. In particular, LAZARUS monitors the disclosed vulnerabilities of all elements of the replicas' software stacks to assess which of them may contain common vulnerabilities.

In the experimental evaluation, however, we focus on the diversity of OSes (*not only their kernel*, but the whole OS distribution) because: (i) by far, most of the replica's code is the OS; (ii) such size and the role played in the stack, makes the OS a significant target, with new vulnerabilities and exploits being discovered every day; and (iii) there are many alternative OSes to bring variety. The two last factors are particularly important to enrich the validity of our analysis. Consequently, we will not explicitly consider the diversity of the BFT library (i.e., the protocol implementation) or the service code implemented on top of it. Three arguments justify this decision: (1) N-version programming is too costly [12]; (2) the small size of such components[1] makes them relatively simpler to test and assess with some confidence [115, 122]; and (3) a few works show that such protocol implementations can be generated from formally verified specifications, resulting in no vulnerabilities at this level [79, 149]; Notice that, although we do not explicitly consider the diversity of BFT libraries, nothing prevents LAZARUS from monitoring them in a similar way as the OSes. However, there are no reported vulnerabilities about these to support our study.

5.4 Diversity-aware Reconfigurations

One of the goals of this thesis is to maintain the fault independence of the running CONFIG given the present knowledge about vulnerabilities. The core of this chapter is the *vulnerability evaluation method* used to assess the risk of having replicas with shared vulnerabilities, and an algorithm to trigger replacements when necessary.

5.4.1 Finding Common Vulnerabilities

The first step of our method is to query vulnerability databases on the internet to find the common vulnerabilities that may affect the BFT system.

[1] For example, a BFT key-value store based on BFT-SMaRt has less than 15k lines of code in total [22].

CVE (affected OS)	Description
CVE-2014-0157 (Opensuse 13)	Cross-site scripting (XSS) vulnerability in the Horizon Orchestration dashboard in OpenStack Dashboard (aka Horizon) 2013.2 before 2013.2.4 and icehouse before icehouse-rc2 allows remote attackers to inject arbitrary web script or HTML via the description field of a Heat template.
CVE-2015-3988 (Solaris 11.2)	Multiple XSS vulnerabilities in OpenStack Dashboard (Horizon) 2015.1.0 allow remote authenticated users to inject arbitrary web script or HTML via the metadata to a (1) Glance image, (2) Nova flavor or (3) Host Aggregate.
CVE-2016-4428 (Debian 8.0)	XSS vulnerability in OpenStack Dashboard (Horizon) 8.0.1 and earlier and 9.0.0 through 9.0.1 allows remote authenticated users to inject arbitrary web script or HTML by injecting an AngularJS template in a dashboard form.

Table 5.1 – Similar vulnerabilities affecting different OSes.

Previous studies on diversity count the CVE entries that list multiple OSes, as they should represent vulnerabilities that are shared, assuming that less common vulnerabilities imply a smaller probability of compromising $f+1$ replicas [66]. Although this intuition may seem acceptable, in practice it underestimates the number of vulnerabilities that compromise two or more OSes due to imprecisions in the data source. For example, Table 5.1 shows three vulnerabilities, affecting three different OSes at distinct dates. At first glance, one may consider that these OSes do not have the same vulnerability. However, a careful inspection of the descriptions shows that they are very similar. Moreover, we checked this resemblance by searching for additional information on security web sites, and we found out that CVE-2016-4428, for example, also affects Solaris.[2]

Even with these imperfections, NVD is still the best data source for vulnerabilities. Therefore, we exploit its curated data feeds for obtaining the unstructured information present in the vulnerability text descriptions and use this information to find similar weaknesses. A usual way to find similarity in unstructured data is to use clustering algorithms [92]. Clustering is the process of aggregating related elements into groups, named clusters, and is one of the most popular unsupervised machine learning techniques. We apply this technique to build clusters of similar vulnerabilities (see Chapter 6 for details), even if the data feed reports that they affect different products. For example, the vulnerabilities in Table 5.1 will be placed in the same cluster as there is a significant resemblance among the descriptions, and they can potentially be activated by (variations of) the same exploit.

5.4.2 Measuring Risk

Once the set of common vulnerabilities is found, our method assigns a score to each vulnerability in the set.

[2] `https://www.oracle.com/technetwork/topics/security/bulletinjul2016-3090568.html`

Rating	CVSS Score
NONE	0.0
LOW	0.1-3.9
MEDIUM	4.0-6.9
HIGH	7.0-8.9
CRITICAL	9.0-10.0

Table 5.2 – Qualititative CVSS severity rating scale.

As presented in Chapter 3, each vulnerability in NVD has associated a few CVSS severity scores and metrics [45]. The scores provide a way to marshal several vulnerability attributes in a value reflecting various aspects that impact security. The score value can also be translated into a qualitative representation to assist on the vulnerability management process, i.e., from NONE (0.0) to CRITICAL (9.0 to 10.0) as presented in Table 5.2.

CVSS has some limitations that can make it inappropriate for managing the risk associated with a replicated system: (1) there is no correlation between the CVSS exploitability score and the availability of exploits in the wild for the vulnerability [27]; (2) CVSS does not provide information about the date when a vulnerability starts to be exploited and when the patch becomes ready; and (3) CVSS does not account for the vulnerability age, which means that severity remains the same over the years [62]; therefore, a very old vulnerability can end up being considered as critical as a recent one, even though for the former there has been plenty of time to update the component and/or the defenses.

Given these shortcomings, we propose a CVSS extension and use it to measure the risk of a BFT system configuration having replicas with shared vulnerabilities. This extension is mostly focused on differentiating vulnerabilities by their current *potential exploitability*, aiming to surpass the limitations identified above. In this process, (1) and (2) are addressed by using additional OSINT sources (e.g., other security databases and vendor sites) that provide information about exploits and dates. In fact, often vendor sites also give additional product versions compromised by the vulnerability, thus improving the accuracy of the analysis. Limitation (3) is settled by decreasing the criticality of a vulnerability gradually through time.

Our CVSS extension uses four factors that together contribute to the overall score. The starting factor is the CVSS core score, as it is a good basis that takes into consideration several attributes of the vulnerability. The other three factors adjust the score taking into account the age and the availability of a patch and an exploit. The rationale is to allow the ranking of vulnerabilities according to their possible exploitation at a given moment in time. The worst scenario (higher severity score) corresponds to a vulnerability that is new (N) (i.e., recently published), for which there is an exploit already being distributed (E), and that is not yet patched – called NE. The best scenario (lowest score) is when a vulnerability is old (O) and there is a patch (P), and apparently, no viable exploit has

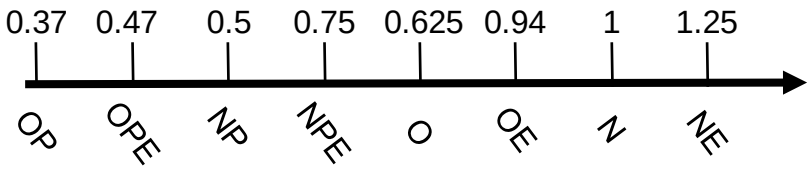


Figure 5.2 – Scoring system of vulnerabilities based on age, patch, and exploit.

been crafted – named OP. Between the two extremes, several cases of vulnerabilities are considered, with their scores calculated accordingly (see Figure 5.2).

The metric is defined in Equation 5.1. It is a multiplication of the CVSS core score [45] by three adjusting factors. The first is *Oldness*, which causes criticality to decrease over time. It is harmonized by the *Oldness Threshold* and the interval[3] that has passed since the vulnerability publication (Equation 5.2). In addition, this factor is bounded by a minimum value that impedes it from reaching zero (which would cause the vulnerability to be left unnoticed). The second is *Patched*, which reduces the severity by half when a patch is available (Equation 5.3; $v_i.patched$ is an on/off flag). Finally, the *Exploited* factor grows severity by a quarter when an exploit is made available (Equation 5.4; $v_i.exploited$ is again a on/off flag). The constants in these equations were defined to ensure the aggregated modifiers correspond to Figure 5.2.

$$\text{score}(\text{v}_i) = \text{CVSS}(\text{v}_i) \times \text{oldness}(\text{v}_i) \times \text{patched}(\text{v}_i) \times \text{exploited}(\text{v}_i) \tag{5.1}$$

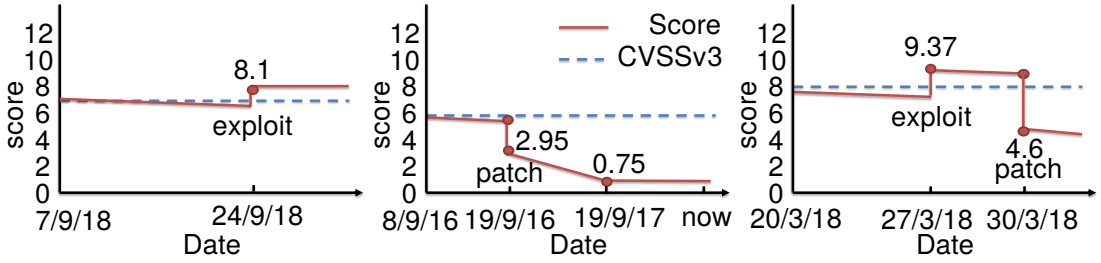
$$\text{oldness}(\text{v}_i) = \max\left((1 - 0.25 \times \frac{(\text{now}() - \text{v}_i.\text{published\_date})}{\text{Oldness Threshold}}), 0.75\right) \tag{5.2}$$

$$\text{patched}(\text{v}_i) = 0.5^{\text{v}_i.\text{patched}} \tag{5.3}$$

$$\text{exploited}(\text{v}_i) = 1.25^{\text{v}_i.\text{exploited}} \tag{5.4}$$

Figure 5.3 displays our score and CVSS for three example vulnerabilities: (a) NE is a vulnerability that is new and has no patch yet, but an exploit was made available a few days after publication. Our score starts by decaying slowly but then there is a jump on severity when the exploit is published; (b) OP represents the best scenario, where the vulnerability is *old* and a patch was eventually distributed (and no exploit is available). Here, the severity decreases once there is a patch, losing its relevance over time from a security perspective; and (c) NPE illustrates a vulnerability that has an exploit a few days after publishing and then a patch is also created. First, the score is raised once the exploit starts

[3] *Oldness Threshold* is set to 365 in our calculations; *now()* and $v_i.published\_date$ return the current day and the day when the vulnerability was published, respectively.



(a) CVE-2018-8303. **(b)** CVE-2016-7180. **(c)** CVE-2018-8012.

Figure 5.3 – Examples of *score*(v_i) for three vulnerabilities.

to be distributed, next it decreases three days later after the patch is released, and then continues to decay over time.

5.4.3 Measuring Configurations Risk

The third step of our method is to calculate the *risk of a set of replicas* according to the score of the common weaknesses. The risk associated with a `CONFIG` with n replicas is given by Equation 5.5. It sums up the score (Equation 5.1) of the vulnerabilities that would allow an attack to compromise simultaneously a pair of replicas $r_i, r_j \in$ `CONFIG`. More precisely, the vulnerabilities in $\mathscr{V}(r_i, r_j)$ aggregate: (i) the vulnerabilities that affect the software running in both replicas as listed in NVD (and other OSINT sites); and (ii) groups of vulnerabilities that are placed in the same cluster and affect each replica in the pair (as explained in Section 5.4.1).

$$risk(\texttt{CONFIG}) = \sum_{r_i, r_j \in \texttt{CONFIG}} \sum_{v \in \mathscr{V}(r_i, r_j)} score(v) \tag{5.5}$$

This metric penalizes configurations that include replica pairs containing more common weaknesses, as this is an indication that they are less fault-independent. In addition, the level of penalty is kept proportional to the severity of these vulnerabilities as observed at the time of the calculation. For example, replicas that share weaknesses only in the distant past are considered less risky than replicas with recently highly exploitable common vulnerabilities.

5.4.4 Selecting Configurations

The final step of our method is to periodically assess the risk of a deployed configuration and its future replacement of replicas according to the score evaluation of our metric.

Algorithm 2 details the procedure that is taken to select the running CONFIG. If its risk exceeds a predefined *threshold*, a mechanism is triggered to replace replicas and reduce the overall risk. When this happens, the algorithm picks a new replica from the available candidates (POOL) to join CONFIG. In addition, it removes the replica that reduces the overall risk and sets it aside (i.e., in QUARANTINE) to impede its re-selection. There, the replicas wait for patches before they re-join POOL and become ready to be chosen again. Moreover, the algorithm ensures that the running replicas will eventually be replaced, despite their overall score.

Function *Monitor()* (line 5) is called on each monitoring round (e.g., at midnight every day) to evaluate the current configuration. If the risk of CONFIG is greater or equal than a certain *threshold* (line 6), the algorithm will assess which replica should be replaced. First, it initializes two variables, the candidates list (line 7) and all possible combinations of $n-1$ out of n elements of CONFIG (line 8). Then, each element r in POOL (line 9) is tested as a potential substitute, i.e., as the n^{th} element that would complete each of the combinations COMB with $n-1$ replicas (line 10). Next, we define a CONFIG' as the union of COMB and r (line 11). The risk of CONFIG' is calculated (line 12) and added to a list that stores the tuple ⟨CONFIG', score⟩ (line 13). At the end of the these nested loops, we have a list with all the possible combinations of CONFIG and POOL together with their risk. Then, the function rand selects a configuration randomly from the list of candidates (line 14). Although it is not present in the algorithm, it only selects configurations which are below the *threshold* score. Then the algorithm updates all the sets (line 15) using the function updateSets (lines 36-40). To decide which element needs to be removed from CONFIG it makes the difference between the current CONFIG and RAND_CONFIG (line 37) and the contrary to select the element to join the CONFIG (line 38). Then, toRemove is added to QUARANTINE (line 39), removed from CONFIG and the new element is added to the CONFIG (line 40).

If the risk of CONFIG is lower than the *threshold* (line 16), the algorithm assess if a reconfiguration is needed. In this scenario, we start by initializing the variable toRemove as empty (line 17) and maxScore with the value of the CVSS score rating HIGH (line 18). For each element of CONFIG (line 19) the algorithm calculates the average score of the vulnerabilities affecting r using Equation 5.1 (line 20). Then, if the average vulnerability score is equals or greater than HIGH (line 21), the variable toRemove is set to the element r (line 22) and the value of maxScore with the avgScore (line 23). At the end of the loop, the algorithm knows which is the element r from CONFIG that has vulnerabilities with a highest average score. If toRemove is empty, the algorithm proceeds to line 32. Otherwise, there is an element that is a candidate to leave CONFIG and a new replica, that improves the overall score will be selected (line 24). First, the candidate_list is set as empty (line 25). Next, for each element r' in POOL (line 26) the algorithm tests a CONFIG' with r' instead of toRemove (line 27). Then, the score for this configuration is calculated (line 28) and together with the CONFIG' is stored in a list of candidates (line 29). As already described, the function updateSets updates the elements of the sets (line 31).

Algorithm 2: Replica Set Reconfiguration

```
1  CONFIG: set replicas executing ;
2  n: number of replicas in CONFIG;
3  POOL: set with the available replicas (not in use);
4  QUARANTINE: set of quarantine replicas;
5  Function Monitor()
6      if risk(CONFIG) ≥ threshold then
7          cadidates_list ← ⊥;
8          COMBINATIONS = (n choose n−1) CONFIG;
9          foreach r in POOL do
10             foreach COMB in COMBINATIONS do
11                 CONFIG' ← COMB ∪ {r};
12                 score ← risk(CONFIG');
13                 cadidates_list.add(⟨CONFIG', score⟩);
14         RAND_CONFIG ← rand(cadidates_list) ;
15         updateSets(RAND_CONFIG);
16     else
17         toRemove ← ⊥;
18         maxScore ← HIGH;
19         foreach r in CONFIG do
20             avgScore ← scoreAVG(r);
21             if avgScore ≥ maxScore then
22                 toRemove ← r;
23                 maxScore ← avgScore;
24         if toRemove ≠ ⊥ then
25             cadidates_list ← ⊥;
26             foreach r' in POOL do
27                 CONFIG' ← (CONFIG \ {toRemove}) ∪ {r'};
28                 score ← risk(CONFIG');
29                 cadidates_list.add(⟨CONFIG', score⟩);
30             RAND_CONFIG ← rand(cadidates_list) ;
31             updateSets(RAND_CONFIG);
32     foreach r in QUARANTINE do
33         if isPatched(r) = TRUE then
34             QUARANTINE ← QUARANTINE \ {r};
35             POOL ← POOL ∪ {r};
36 Function updateSets(RAND_CONFIG)
37     toRemove ← x ∈ (CONFIG \ RAND_CONFIG);
38     toJoin ← y ∈ (RAND_CONFIG \ CONFIG);
39     QUARANTINE ← QUARANTINE ∪ {toRemove};
40     CONFIG ← (CONFIG \ {toRemove}) ∪ {toJoin};
```

Finally, the POOL and QUARANTINE are updated. Each QUARANTINE element (line 32) is checked if it is fully patched (line 33). In the affirmative case, the element is removed from QUARANTINE (line 34) and added to the POOL again (line 35). We did not present two unlikely corner cases where a *system admin* may need to intervene: if the POOL runs out of elements or *rand()* cannot return a configuration that minimizes the risk of the system. We propose at least two actions to preserve

availability under some risk of becoming compromised: increase the *threshold* or removing the elements with fewer unpatched vulnerabilities from QUARANTINE to POOL.

5.5 Evaluation

This section evaluates how our method performs on the selection of dependable replica configurations. As discussed in Section 5.3, we focus our experimental evaluation solely on the OS diversity. In particular, we considered 21 OS versions of the following distributions: OpenBSD, FreeBSD, Solaris, Windows, Ubuntu, Debian, Fedora, and Redhat.

These experiments emulate live executions of the system by dividing the collected data into two periods. The goal is to create a knowledge base in a *learning phase* that is used to assess LAZARUS' choices during an *execution phase*. (1) The *learning phase* comprises all vulnerabilities between *2014-1-1* and the beginning of the *execution phase*; and (2) the *execution phase* is divided into monthly intervals, from January to August of 2018, allowing for eight independent tests. A run starts on the first day of the *execution phase* and then progresses through each day until the end of the interval. Every day, we check if the executing replica set could be compromised by an attack exploring the vulnerabilities that were published in that month. We take the most pessimistic approach, which is to consider the system as broken if a single vulnerability comes out affecting at least two OSes executing at that time. Therefore, if one of the OSes already has a patch for the tested vulnerability, it is not counted as compromised.

Four additional strategies, inspired by previous works, were defined to be compared with LAZARUS (Section 5.4.4):

- **Equal:** all the replicas use the same randomly-selected OS during the whole execution. This corresponds to the scenario where most past BFT systems have been implemented and evaluated (e.g., [6, 10, 17, 18, 22, 40, 108, 118, 185, 199]). Here, compromising a replica would mean an opportunity to intrude the remaining ones.

- **Random:** a configuration of n OSes is randomly selected, and then a new OS is randomly picked to replace an existing one each day. This solution represents a system with proactive recovery and diversity, but with no informed strategy for choosing the next CONFIG.

- **Common:** this strategy is the straw man solution to prevent the existence of shared vulnerabilities among OS. This strategy minimizes the number of common vulnerabilities for each set and was introduced in previous vulnerability studies [65].

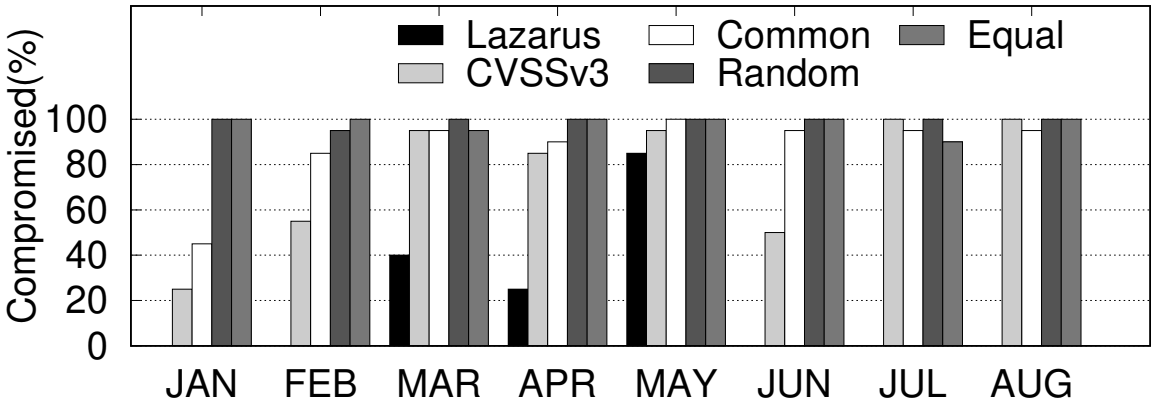


Figure 5.4 – Compromised system runs over eight months.

- **CVSS v3:** this strategy is very similar to ours as it tries different combinations to find the best one that minimizes the sum of CVSS v3 score.

5.5.1 Diversity vs Vulnerabilities

We evaluate how each strategy can prevent the replicated system from being compromised. Each strategy is analyzed over 1000 runs throughout the execution phase in monthly slots. Different runs are initiated with distinct random number generator seeds, resulting in potentially different OS selections over time. On each day, we check if there is a vulnerability affecting more than one replica in the current `CONFIG`, and in the affirmative case the run is stopped.

Results: Figure 5.4 compares the percentage of compromised runs of all strategies. Each bar represents the percentage of runs that did not terminate successfully (lower is better). LAZARUS presents the best results for every month. The *Random* and *Equal* strategies perform worse because eventually, they pick a group of OSes with common vulnerabilities as they do not make decisions with specific criteria. Although some criteria guide the other strategies, most of them present a majority of executions compromised during the experiments. This result provides evidence for the claim that LAZARUS improves the dependability, reducing the probability that $f+1$ OSes eventually become compromised and contrary to intuition, changing OSes every day with no criteria will always create unsafe configurations.

Nonetheless, the results from May deserve a more careful inspection. We have identified some CVEs that make it very difficult to survive to common vulnerabilities even using the LAZARUS strategy. For example, CVE-2018-1125 and CVE-2018-8897 affect a few Ubuntu and Debian releases simultaneously. There are also a set of vulnerabilities affecting several Windows releases (e.g., CVE-2018-8134 and CVE-2018-0959). We also found a vulnerability (CVE-2018-1111) that affects few Fedora releases and one Redhat release.

Attack name	Attack Summary
Wanna Cry	*On Friday, May 12, 2017, the world was alarmed to discover a widespread ransomware attack that hit organizations in more than 100 countries. Based on a vulnerability in Windows' SMB protocol (nicknamed EternalBlue), discovered by the NSA and leaked by Shadow Brokers.*
Stackclash	*In its 2017 malware forecast, SophosLabs warned that attackers would increasingly target Linux. The flaw, discovered by researchers at Qualys, is in the memory management of several operating systems and affects Linux, OpenBSD, NetBSD, FreeBSD and Solaris.*
Petya	*A new strain of the Petya ransomware started propagating on June 27, 2017, infecting many organizations. Petya uses the EternalBlue exploit as one of the means to propagate itself. However, it also uses classic SMB network spreading techniques, meaning that it can spread within organizations, even if they have patched against EternalBlue.*

Table 5.3 – Notable attacks during 2017.

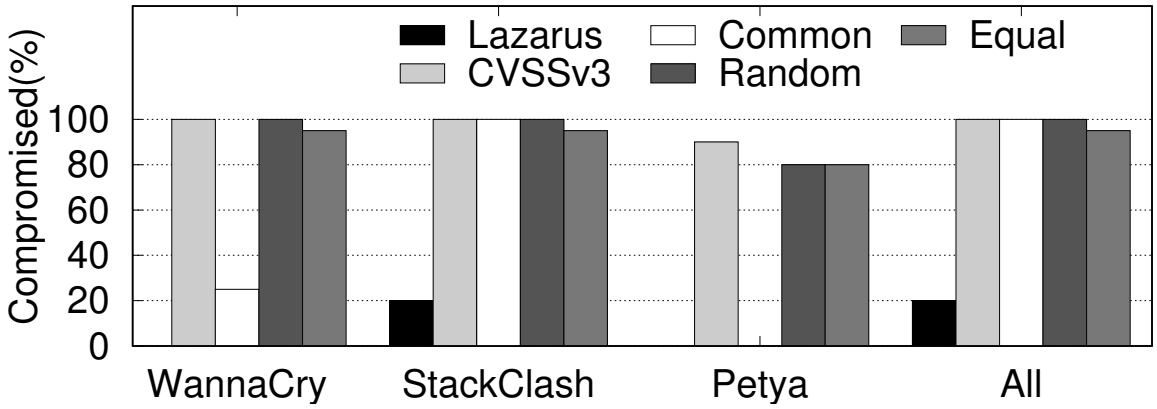


Figure 5.5 – Compromised runs with notable attacks.

5.5.2 Diversity vs Attacks

This experiment evaluates the same strategies when facing notable attacks that appeared in 2017. Each attack potentially exploits several flaws, some of which affecting different OSes. The attacks were selected by searching the security news sites for high impact problems, most of them related to more than one CVE. As some of the CVEs include applications, we added more vulnerabilities to the database for this purpose. We have considered the following attacks: WannaCry [110], Stackclash [14], and Petya [178]. Table 5.3 provides a summary of these attacks.

Since some of these attacks might have been prepared months before the vulnerabilities are publicly disclosed, we augmented the execution phase to the full eight months. Therefore, we set *learning phase* to begin *2014-1-1* and to end on *2017-12-31*. The *execution phase* period that starts on 2018 January and finishes on August 2018. As before, the strategies are executed over 1000 runs.

Results: Figure 5.5 shows the percentage of compromised runs for each attack and all attacks put together. LAZARUS is the best at handling the various scenarios, with almost no compromised executions. The StackClash is the most destructive attack as it is the one affecting more OSes. Therefore, decisions guided by a criteria that aim to avoid common vulnerabilities may also fail. Nevertheless, the results show that such strategies do improve the resilience to attacks.

5.6 Final Remarks

LAZARUS addresses the long-standing open problem of evaluating, selecting, and managing the diversity of a BFT system to make it resilient to malicious adversaries. This chapter shows an approach to select the best replicas to run together given the current threat landscape and evaluate the proposed strategy. In the next chapter, we discuss how this strategy can be implemented and the overhead of using OS diversity.

6 LAZARUS Implementation

This chapter presents the LAZARUS solution and evaluation. It implements the design described in the previous chapter in a centralized controller. In addition, we also discuss an alternative implementation based on a distributed intrusion-tolerant controller. LAZARUS currently manages 17 OS versions, supporting the BFT replication of a set of representative applications. The replicas run in VMs, allowing provisioning mechanisms to configure them in a fully automated way. We conducted experiments that reveal the potential negative impact that virtualization and diversity can have on performance. However, we also show that if naive configurations are avoided, BFT applications in diverse configurations can perform close to our homogeneous bare metal setup.

6.1 Implementation

LAZARUS is a control plane solution that collects data from OSINT and uses this data to build diverse replica sets for BFT systems. Over time, it monitors the OSINT sources and the BFT replicas to enhance the failure independence of the replicas based on a risk metric. Once the risk increases above a certain level, LAZARUS must replace replicas with different ones. In this section, we detail the implementation of each component of LAZARUS. We also present other aspects and design decisions that were taken into account while building the prototype.

6.1.1 Control Plane

Figure 6.1 shows LAZARUS control plane with its four main modules described below:

❶ ***Data manager.*** This component collects vulnerability data from several OSINT sources and stores this data in a database to be analyzed by another LAZARUS component. In particular, it only collects data for the software of interest. We utilized the names included in the list of software products provided by the CPE Dictionary [128], which is also used by NVD. Then, an administrator selects all the software that runs in each replica from this list and indicates the time interval (in years) during which data should be obtained from NVD. The *Data manager* parses the NVD feeds considering only the vulnerabilities that affect the chosen products. The processing is carried out with several threads cooperatively assembling as much data as possible about each vulnerability – a queue is populated with requests pertaining a particular vulnerability, and other threads will look

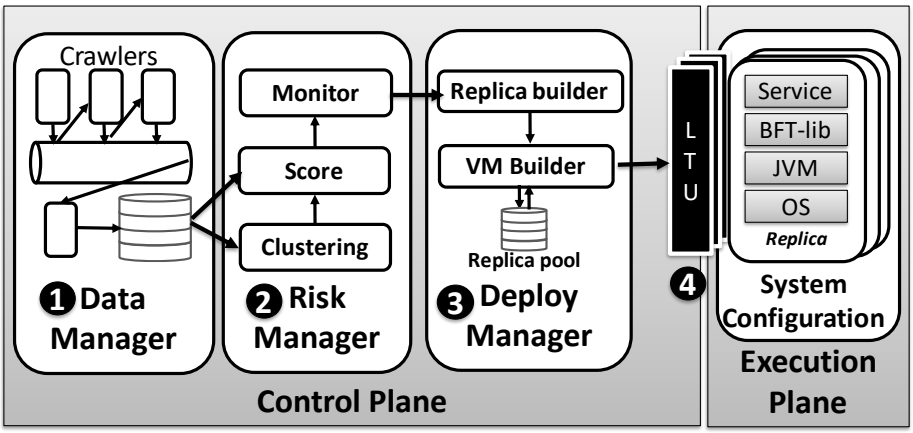


Figure 6.1 – LAZARUS architecture.

for related data in additional OSINT sources. Typically, the other sources are not as well structured as NVD, and therefore we had to develop specialized HTML parsers for them. Currently, the prototype supports eight other sources, namely Exploit DB [158], CVE-details [157], Ubuntu [182], Debian [46], Redhat [151], Solaris [141], FreeBSD [60], and Microsoft [124]. The collected data is stored in a relational database (MySQL). For each vulnerability, the manager keeps its CVE identifier, the published date, the products it affects, its text description, the CVSS attributes, exploit and patching dates.

❷ ***Risk manager.*** This component finds out when it is necessary to replace the currently running group of replicas and discovers an alternative configuration that decreases the risk. As explained in Section 5.4.2, the risk is computed using score values that require two kinds of data: the information about the vulnerabilities, which is collected by the *Data manager*, and the vulnerability clusters. A vulnerability cluster is a set of vulnerabilities that are related accordingly to their description. We used the open-source machine learning library Weka [155] to build these clusters. In a first phase, the vulnerability description needs to be transformed into a vector, where a numerical value is associated with the most relevant words (up to 200 words). This operation entails, for example, converting all words to a canonical form and calculating their frequency (less frequent words are given higher weights). Then, the K-means [92] algorithm is applied to build the clusters, where the number of clusters to be formed is determined by the elbow method [180].

❸ ***Deploy manager.*** This component automates the setup and execution of the diverse replicas. It creates and deploys the replicas in the execution environment implementing the decisions of the *Risk manager*, i.e., it dictates when and which replicas leave and join the system. This sort of behavior must be initiated in a synchronous manner from a trusted domain. One way to achieve this is to employ virtualization, leveraging on the isolation between the untrusted and the trusted domains [50, 144, 171]. Therefore, we developed a replica builder on top of the Vagrant [78] provisioning tool, which allows fast deployment of ready-to-use OSes and applications on VMs

(e.g., VirtualBox, VMware, and Docker). From the available alternatives, we chose VirtualBox [156] because it supports a larger set of different guests OSes.

❹ **LTUs.** Each node that hosts a replica has a Vagrant daemon running on its trusted domain. This component is isolated from the internet and communicates only with the LAZARUS controller through Transport Layer Security (TLS) channels.

6.1.2 Execution Plane

Despite the amount of relevant research on BFT protocols, only a few open-source libraries exist. In theory, LAZARUS can use any of these, as long as they support replica set reconfigurations. More specifically, to manage the *replicas*, we need the ability to add first a new *replica* to the set and then remove the old *replica* to be quarantined. Therefore, we employ BFT-SMART [22], a stable BFT library that provides reconfigurations on the *replicas* set. The protocol we used can be briefly described as follows: *(i)* Once a new replica joins the group, it queries the other replicas about their last finished consensus instance; *(ii)* If the replica finds that the others also did not execute any instance, then no state transfer is required. Otherwise, the replica requests the state corresponding to the consensus instance it was in step *(i)*. *(iii)* The other replicas verify if they have the state requested (i.e., a checkpoint and a log up to the specified consensus instance). If they do, they reply with the respective checkpoint and log – only one replica sends a full checkpoint and the other $2f$ replicas send a hash of the checkpoint. Otherwise, they reply to the new replica with a void state. *(iv)* If the replica receives $2f+1$ matching replies for the requested state, it installs the received checkpoint and applies the operations in the log. If the $2f+1$ replies include a void state, the replica requests the state up to the consensus instance preceding the one being executed (thus beginning a new iteration of the protocol). This is repeated until the other replicas have the requested state.

6.1.3 Alternative Control Plane Design

So far we have been describing the LAZARUS control plane as a logically centralized component, and in fact, our current prototype is implemented as a single server (e.g., [144, 160]). This design was selected for two reasons. First, it allowed us to focus on the main contributions of this work: runtime diversity assessment and performance. Second, it matches the classical scenario where a single organization deploys an *intrusion-tolerant service* [184], such as the managed (permissioned) blockchain services offered by major cloud providers (e.g., [5, 90]). In both scenarios, replica resources are already managed by a single organization that can host a LAZARUS control plane.

However, such design makes the controller a single point of compromise and prevents decentralized deployments where replicas are managed by different organizations. In this section, we introduce an alternative approach based on a distributed intrusion-tolerant solution. This solution envisions a

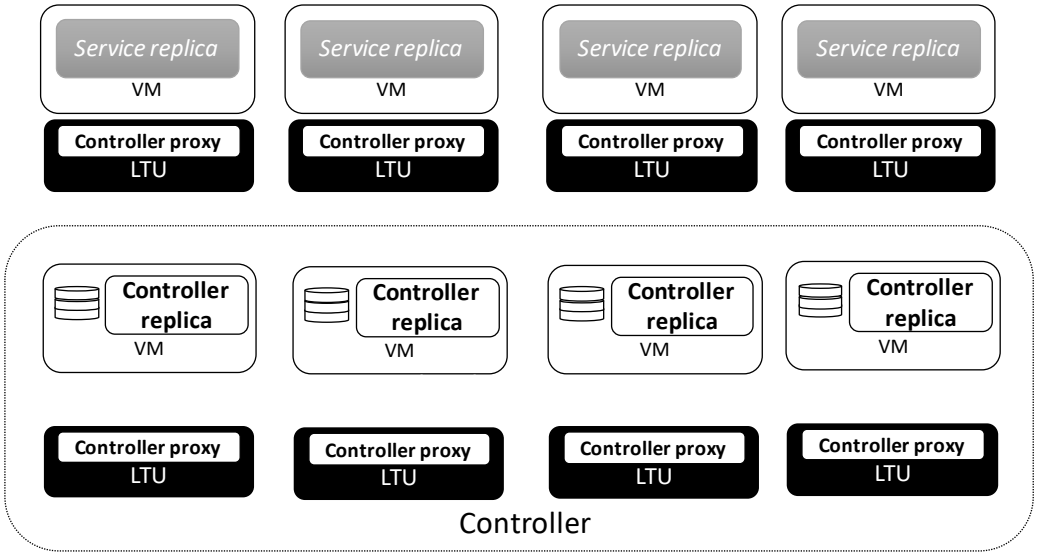


Figure 6.2 – Distributed LAZARUS architecture.

set of servers, named *controller replicas*, that run LAZARUS in a coordinated manner. Therefore, these servers can manage the replicas in the *Execution Plane* as before and cooperate to keep the *Control Plane* operational despite failures. This version introduces some significant modifications to the previous architecture as illustrated in Figure 6.2. Moreover, a few changes were made on the system model, which are explained below.

6.1.3.1 System Model

This LAZARUS version attempts to minimize the changes to the centralized version. For instance, the Execution Plane remains practically unmodified. On the contrary, the Control Plane suffers some changes. The new Control Plane is composed of replica processes, named *controller replicas*, which can be subject to Byzantine failures. Therefore, a Byzantine replica can try to mislead other replicas. This plane hosts n controller replicas from which at most f can be compromised at any given moment. Each replica has a LTU co-located that is assumed to be trusted. The actions of this component cannot deviate from the expected behavior, which is especially important for the implementation of the recovery of replicas.

6.1.3.2 Distributed Intrusion-tolerant Solution Challenges

The design of a distributed intrusion-tolerant LAZARUS introduces a few modifications. Most of these arise from the need to transfer the execution and storage logic from a single (and trusted) controller to n replicated controllers. In this process, we identify a few challenges: (1) the need

to ensure that a Service replica is asked to recover only when there is agreement among correct controller replicas; (2) all controller replicas must have the same view of the database, thus, they need to collect OSINT data in a synchronous way; (3) in the LAZARUS monitoring algorithm a few decisions require a random selection, thus, in this version, all controller replicas must agree on the same random number without introducing biases; (4) the replication of the controllers also brings storage problems, namely how to store the VM images over the controllers; and (5) applying patches on replicated VM images introduces determinism problems as these images may not match after being patched. In the following, we detail each challenge and provide possible solutions.

Recovery Protocol. Contrary to the centralized LAZARUS, where decisions to reconfigure are taken alone by the trusted controller, the replicated version needs a recovery protocol to ensure that a service replica is reconfigured if only and only if the operation was issued by correct controller replicas. The communication between a LTUs and the controller replicas is made via a total-order-multicast channel and it is used solely to trigger recoveries both on controller replicas and service replicas. Each LTU runs a controller proxy that can invoke controller replicas commands in a coordinated way, and it receives messages from controller replicas. It has to wait for $f+1$ matching messages to know that the message is correct. Therefore, the controller proxy is ready to trigger a recovery on a service replica or on a controller replica. Contrary to the usual request-response of SMR, here, the controller proxy receives "responses" without a prior request.

Replica Synchronization Protocol. In its centralized version, a single LAZARUS controller takes decisions alone. For example, it decides when it is the time to contact OSINT sources to look for new data, or when it is the time to substitute service replicas. On the contrary, in a distributed setup, the replicas must be coordinated to execute the same command *at the same time*. One way to do that is to assume that replicas have synchronous clocks, and then, all the requests are synchronized. However, we want to make as few time assumptions as possible. Moreover, by using the internet to communicate with OSINT sources, LAZARUS communication is subject to different levels of delays. Therefore, we propose a solution that uses a logical timeout protocol to (logically) synchronize replicas. This protocol was proposed by Kirsch *et al.* [103] to coordinate replicas on polling requests to a sensor in the context of SCADA systems. The decentralized LAZARUS can employ this protocol to guarantee that all controller replicas poll OSINT at the same logical time. This protocol can be described in the following way: All controller replicas run an algorithm that periodically sends a `SYNC` message among them. This message is used to inform other replicas of the current timeouts that a controller replica has. Each controller replica will set their own timeouts by setting up a timeout $\mathtt{T}_x$ with the local time c_i and the local expiration time d to a controller replica i, where $i \in \{1,...,n\}$. Then, it sends to the others the c_i and d within a `SYNC` message. This allows every replica to update their own list of timeouts, and each one sets the expiration time as $c_i + d$ for $\mathtt{T}_x$. When a `SYNC` message from i says that the local clock is greater than $c_i + d$, then the timeout $\mathtt{T}_x$ was expired. When a logical timeout is triggered in $f+1$ different controller replicas, the timeout

$\mathtt{T}_x$ is delivered to the application. In this way, it is guaranteed that replicas will poll OSINT sources only when $f+1$ controller replicas had $\mathtt{T}_x$ expired.

Distributed Random Generation Protocol. As explained in Chapter 5, LAZARUS selects random configurations to prevent attackers from guessing which will be the next configuration. In the centralized version of the system, it is simple to select random values. However, random number generation is a challenge for distributed systems. In particular, it is difficult to determine a random value among the replicas without prior knowledge of anyone and guaranteeing that the random value is not biased, i.e., that a malicious replica is not influencing the final value. There are already algorithms that can be employed to address this problem. For example, RandShare [179] ensures unbiasability, unpredictability, and availability on random number generation. The protocol was developed in such a way that after a protocol barrier, honest replicas will eventually output the previously decided value despite the adversary's behavior. The protocol uses secret sharing [165] and polynomial commitments to create shares of a local random number and distributes them among the peers. With the polynomial commitment, a replica is able to verify if the share is valid without revealing information about the secret. When all their verifications are made, each replica informs the others about the validations, then any peer knows all the validations done by the others. After this stage, all replicas can recover the secrets via Lagrange interpolation. Finally, the random number is generated through a `xor` operation with the different recovered secrets.

Distributed Storage. Another modification that we have identified is the storage location. In a centralized solution, the storage is a single pool that is accessed by the controller. A straw-man solution would be to use full replication of the pool and each controller proxy would wait for $f+1$ responses (the actual replica image and a cryptographic hash of the image to verify). However, this solution is not resource efficient as it requires that all replica images be copied on all controller replicas. A more sophisticated solution would take advantage of erasure codes (e.g., [152]) with secret sharing. This approach would minimize the use of resources, as each controller replica would store only parts of the complete image. Moreover, it would simplify the recovery of these replicas as they would only need to recover parts of the original image instead of the complete image. Nevertheless, this approach implies additional complexity on the controller proxy as it needs to rebuild the blocks and verify them.

Deterministic Image Patching. One of the main problems that the distributed solution brings is to guarantee that the images are loaded in a deterministic way. SMR requires that the replicas start from an equal state and apply the same operations to the state in such a way that the replicas reply with the equivalent answers to the clients. Therefore, it is a challenge to create VM images that have exactly equal binaries. Moreover, once a replica is patched it becomes hard to ensure that it is equal across the controller replicas and this can prevent appropriate voting operations. For the moment, the proposed solution is to rely on a trusted VM maintainer whose role is to update and distribute the

VM images through the different controller replicas. In this way, every controller replica receives the same VM image.

6.2 Application and Parameter Details

In this section, we detail some configuration and parameters used on the LAZARUS components. First, we describe each step of the clustering process. Then, we explain how the replicas are built using the Vagrant provisioning tool.

6.2.1 Clustering

Clustering is the process of aggregating the different elements into groups, which are named clusters. The aim is to ensure that two elements from the same cluster have a higher probability of being similar than two elements from different clusters. We apply this technique to build clusters of vulnerability entries in our database. One of the benefits of applying clustering techniques to information about vulnerabilities is that the algorithm does not need prior knowledge about the data. It is the process alone that discovers the hidden knowledge in the data. Each cluster is used as a hint that similar vulnerabilities are likely to be activated through the same (or near identical) exploit. We considered the vulnerability description and published date to build the clusters. In the end, it is expected that clusters have a minimal number of elements that represent approximately the same vulnerability.

A few steps are carried out to create the vulnerability clusters. First, the vulnerability description needs to be transformed into a vector, where a numerical value is associated with the most relevant words. This operation entails, among other tasks, converting all words to a canonical form and calculating their frequency (less frequent words are given higher weights). Then, the clustering algorithm is applied to aggregate the vulnerabilities. We used the open-source machine learning library Weka [155] to prepare the data and build the clusters as described in the following:

1) Data representation We transform the data that is stored in the database into a format that is readable by the clustering algorithm. Since we are using Weka, the data must be represented in the Attribute-Relation File Format (ARFF). Basically, this is a CSV file with some meta data information as exemplified in Listing 6.1.

This file contains all the vulnerabilities entries in the database. As we are interested in the vulnerability similarities, we select only the CVE identifier, the text (as it contains the most relevant and nonstructured information) and the published date. These attributes add meaning and temporal reference to the clustering algorithm.

```
@RELATION vulnerabilities
@ATTRIBUTE cve string
@ATTRIBUTE description string
@ATTRIBUTE published_date date "yyyy-MM-dd"
@DATA
CVE-2017-3301, 'vulnerability in the solaris component of oracle sun systems
    products suite subcomponent kernel the supported version that is [...]
    attacks of this vulnerability can result in unauthorized update insert or
    delete access to some of solaris accessible data cvss base score integrity
    impacts', '2017-01-27'
... more
```

Listing 6.1 – ARFF file describing a vulnerability.

2) Data preparation In general, machine learning algorithms do not handle raw information, and therefore the data needs to be prepared: First, we transform the CVE string into a number, ensuring that there is a real number that corresponds to each CVE unequivocally. This attribute is translated into a numeric value using the *StringToNominal* filter. Second, we also transform the published date into a number format using the *NumericToNominal* filter. Third, the text description must be transformed into a vector representation using the *StringToWordVector* filter. This vector has the frequencies of each word in the whole text description. A few steps are taken in this filtering process. First, all the words are converted to lower case and certain special characters are removed to reduce the noise and differences among the words. From this sequence of words only the ones that are not in the stop word list (e.g., a, an, the) are kept. Then, it the TF- and IDF-Transform [116] is used to measure how relevant a word is to a vulnerability entry in the whole collection. The relevance increases proportionally to the number of times a word appears in the vulnerability description but is offset by the frequency of the word in the whole body of text. For example, words that appear in all vulnerability descriptions, are less relevant than the ones that appear only in few vulnerabilities. In the end, only a pre-defined number of words is saved. In our current implementation, we empirically found that 200 is the best number of words to represent the description of vulnerabilities after removing the *stopwords*.

Our goal is to build clusters in such a way that similar vulnerabilities, even if they affect different products, are put together in the same group. For instance, recall the example vulnerabilities in Table 5.1, which should be placed together in the same cluster as they are alike. To achieve this, some of the parameters listed above had to be tuned. We observed that before the tuning, some of the clusters were very generic representing large classes of vulnerabilities, e.g., buffer overflow and cross-site scripting. Since we are not interested in this sort of classification, we have refined the *stopword list* to make the description vocabulary contain only what matters for our goal. This was done by checking an intermediary Weka's output that shows the most used words to build the clusters. Then, we picked the most relevant words from this list and added them to the stop word list to prevent the creation of clusters by vulnerability class.

When the pre-filtering ends, Weka presents a file, similar to the previous ARFF file, where the features represent the relevance of the words of all description texts for each entry as shown in Listing 6.2 (e.g., apache is more relevant in CVE-2017-5884 description than in CVE-2015-0001).

```
@relation 'vulnerabilities-weka.filters.unsupervised.attribute.Remove-R3-weka.
    filters.unsupervised.attribute.StringToNominal ..more

@attribute cve {CVE-2017-3301,CVE-2017-5884,CVE-2015-0001 ...more}
@attribute access numeric
@attribute application numeric
@attribute apache numeric
@attribute arbitrary numeric
...more
@data
{CVE-2017-5884, 0.212441,6 0.1924,10 1.3516,15 0.527593,21 1.550981 ...more }
{CVE-2015-0001, 0.930885,6 0.12374,8 0.347466,10 0.869272,17 1.088708 ...more }
...more
```

Listing 6.2 – ARFF file after data preparation.

3) Building the clusters K-means is an unsupervised machine learning algorithm that groups data in K clusters [92]. This algorithm has two important parameters: the number of clusters to be formed and the *distance function* used to calculate the distance between each data entry. The K-means computes the distance from each data entry to the cluster center (randomly selected in the first round). Then, it assigns each data entry to a cluster based on the minimum distance (i.e., Euclidean distance) to each cluster center. Then, it computes the centroid, that is the average of each data attribute using only the members of each cluster. Next, it calculates the distance from each data entry to the recent centroids. If there is no modification (i.e., re-arrangement of the entries in the cluster), then the clusters are complete. Otherwise, it recalculates the distance that best fits the elements. When the K-means finishes the execution, we take the cluster assignments of each vulnerability. The assignments will be added to a new ARFF file, similar to the first one but with a new attribute that is the cluster name (e.g., cluster1, cluster2). In our setup, we used the elbow method [180] to decide K= 220.

6.2.2 Replica Virtualization and Provision

In this section we describe the parameters and configurations used to implement the *Deploy manager* with the support of Vagrant and Virtualbox.

Setup. A VM configuration is defined in a file, named *Vagrantfile*, as displayed in the example of Listing 6.3. In this file, it is possible to set all the options to build a VM, like: the number of CPUs, the amount of memory RAM, the IP, the type of network, and the sync folders between the host and the VM. Since Vagrant supports different VM providers (e.g., libvirt, VMware, VirtualBox, Parallels,

Docker, etc), we selected VirtualBox as displayed in line 4 of Listing 6.3. Additionally, it is also possible to pass some VM-specific parameters, namely the CPU/mother board flags that enable for instance the VT-x technology – consider the `modifyvm` fields in Listing 6.3 (lines 8-13).

```
1  Vagrant.configure(2) do |config|
2   config.vm.box = "geerlingguy/ubuntu1604"
3   config.ssh.insert_key = false
4   config.vm.provider "virtualbox" do |v|
5    v.customize ["modifyvm", :id, "--cpus", 4]
6    v.customize ["modifyvm", :id, "--memory", 22000]
7    v.customize ["modifyvm", :id, "--cpuexecutioncap", 100]
8    v.customize ["modifyvm", :id, "--ioapic", "on"]
9    v.customize ["modifyvm", :id, "--hwvirtex", "on"]
10   v.customize ["modifyvm", :id, "--nestedpaging", "on"]
11   v.customize ["modifyvm", :id, "--pae", "on"]
12   v.customize ["modifyvm", :id, "--natdnshostresolver1", "on"]
13   v.customize ["modifyvm", :id, "--natdnsproxy1", "on"]
14  end
15  config.vm.network "public_network", ip:"192.168.2.50", bridge:"em1"
16  config.vm.provision :shell, path: "run_debian.sh", privileged: true
17 end
```

Listing 6.3 – Ubuntu 16.04 Vagrantfile

Download. One of the fields of the Vagrantfile is the `box` field, which identifies the OS release that will be downloaded – line 2 in Listing 6.3. There are many of OSes and versions ready-to-use, and the same OS/version can have different manufacturers – some of which are made available by the vendor itself.

Deploy and provision. Although Vagrant supports complex provisions mechanisms, such as Chef or Puppet, a shell script was sufficient for us. This parameter is set in the Vagrantfile `provision` field, where one puts the path to the script file – line 16 in Listing 6.3. Then, when the OS is booting, the OSes will execute the provision script after the basic setup. In this script, we define which software will be downloaded and run in the VMs and what configurations are needed. We have developed shell scripts for each OS, some of which shared as in Debian and Ubuntu. Since OSes have different commands to execute the same instructions, it is necessary to customize these scripts. These scripts install software like Java 8, `wget`, `unzip`, and any additional packages that one wants to install/run after the OS boot.

Command and Control. There are some simple commands to boot and halt a VM, e.g., `vagrant up` and `vagrant halt`. Vagrant also provides a secure shell command (`vagrant ssh`) that allows the host to connect to the VM. Our manager component makes the bridge between the *Risk manager* and the execution environment. We developed an API on top of Vagrant to allow replica management.

ID	Name	Cores	JVM	Mem.
UB14	Ubuntu 14.04	4	Java Oracle 1.8.0_144	15GB
UB16	Ubuntu 16.04	4	Java Oracle 1.8.0_144	15GB
UB17	Ubuntu 17.04	4	Java Oracle 1.8.0_144	15GB
OS42	OpenSuse 42.1	4	Openjdk 1.8.0_141	15GB
FE24	Fedora 24	4	Openjdk 1.8.0_141	15GB
FE25	Fedora 25	4	Openjdk 1.8.0_141	15GB
FE26	Fedora 26	4	Openjdk 1.8.0_141	15GB
DE7	Debian 7	4	Java Oracle 1.8.0_151	15GB
DE8	Debian 8	4	Openjdk 1.8.0_131	15GB
W10	Windows 10	4	Java Oracle 1.8.0_151	1GB
WS12	Win. Server 2012	4	Java Oracle 1.8.0_151	1GB
FB10	FreeBSD 10	4	Openjdk 1.8.0_144	15GB
FB11	FreeBSD 11	4	Openjdk 1.8.0_144	15GB
SO10	Solaris 10	1	Java Oracle 1.8.0_141	15GB
SO11	Solaris 11	1	Java Oracle 1.8.0_05	15GB
OB60	OpenBSD 6.0	1	Openjdk 1.8.0_72	1GB
OB61	OpenBSD 6.1	1	Openjdk 1.8.0_121	1GB

Table 6.1 – The different OSes used in the experiments and the configurations of their VMs and JVMs.

6.3 Evaluation

In this section, we evaluate the performance of LAZARUS while managing diverse replicated systems. First, we run the BFT-SMART microbenchmarks in our virtualized environment to understand how the performance of a BFT protocol varies with different OSes. In addition, we compare the performance of the virtualized deployment with an homogeneous bare metal setup. Second, we use the same benchmarks to measure the performance of specific diverse setups (e.g., the fastest and slowest set of OSes). Third, we analyze the overheads introduced in the system by the LAZARUS-managed reconfigurations. In particular, we measure the time it takes for each OS to boot. Finally, we evaluate the performance of three BFT services running in the LAZARUS infrastructure.

These experiments were conducted in a cluster of Dell PowerEdge R410 machines, where each one has 32 GB of memory and two quad-core 2.27 GHz Intel Xeon E5520 processors with hyper-threading, i.e., supporting 16 hardware threads on each node. The machines communicate through a gigabit Ethernet network. Each server runs Ubuntu Linux 14.04 LTS (3.13.0-32-generic Kernel) and VirtualBox 5.1.28, for supporting the execution of VMs with different OSes. Additionally, Vagrant 2.0.0 was used as the provisioning tool to automate the deployment process. In all experiments, we configure BFT-SMART v1.1 with four replicas ($f = 1$), one replica per physical machine.

Table 6.1 lists the 17 OS versions used in the experiments and the number of cores made available to their corresponding VMs. These values correspond to the maximum number of CPUs supported by VirtualBox with that particular OS. The table also shows the JVM used in each OS, and the amount of memory supported by each of these VMs. Given these configurations we setup our environment

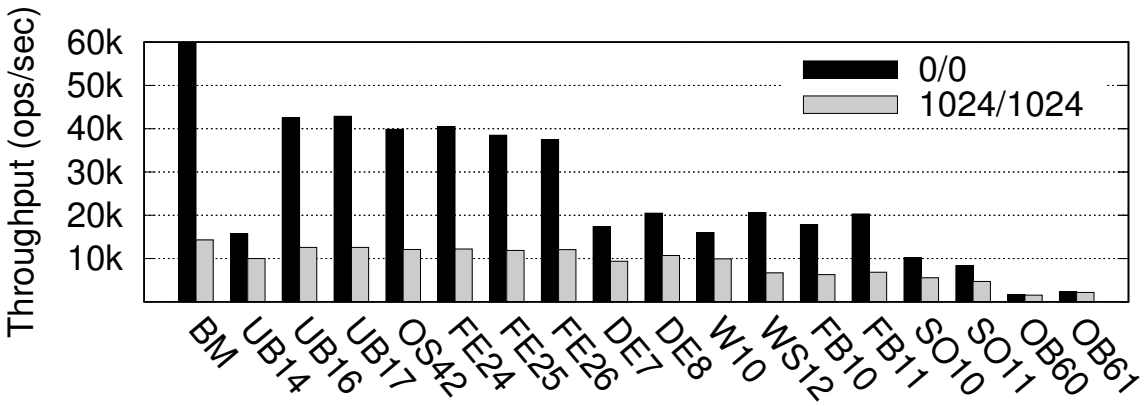


Figure 6.3 – Microbenchmark for 0/0 and 1024/1024 (request/replying) for homogeneous OSes configurations.

to establish a fair baseline by setting up an *homogeneous* Bare Metal (BM) environment that uses only four cores of the physical machine.

6.3.1 Homogeneous Replicas Throughput

We start by running the BFT-SMART microbenchmark using the *same OS version* in all replicas. The microbenchmark considers an empty service that receives and replies variable size payloads, and is commonly used to evaluate BFT state-machine replication protocols (e.g., [17, 18, 22, 31, 118]). Here, we consider the $0/0$ and $1024/1024$ workloads, i.e., 0 and 1024 bytes requests/response, respectively. The experiments employ up to 1400 client processes spread on seven machines to create the workload.

Results: Figure 6.3 shows the throughput of each OS running the benchmark for both loads. To establish a baseline, we also executed the benchmark in our bare metal Ubuntu, without LAZARUS virtualization environment.

The results show that there are some significant differences between running the system on top of different OSes. This difference is more significant for the $0/0$ workload as it is much more CPU intensive than the $1024/1024$ workload. Ubuntu, OpenSuse, and Fedora OSes are well supported by our virtualization environment and achieved a throughput around $40k$ and $10k$ ops/sec for the $0/0$ and $1024/1024$ workloads, which corresponds to approx. 66% and 75% of the bare metal results, respectively. For Debian, Windows, and FreeBSD, the results are much worse for the CPU-intensive $0/0$ workloads but close to the previous group for $1024/1024$. Finally, single core VMs running Solaris and OpenBSD reached no more than 3000 ops/sec with both workloads.

These results show that the virtualization platform introduces a few limitations on supporting different OSes, and strongly constrains the performance of specific OSes in our testbed.

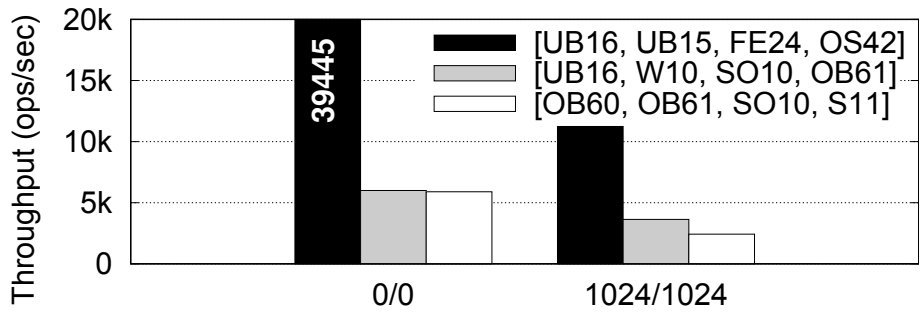


Figure 6.4 – Microbenchmark for 0/0 and 1024/1024 (request/reply) for three diverse OS configurations.

6.3.2 Diverse Replicas Throughput

The previous results show the performance of BFT-SMaRt when running on top of different OSes, but with all replicas running in the same environment. In this experiment, we evaluate three diverse sets of four replicas, one with the fastest OSes (UB17, UB16, FE24, and OS42), another with one replica of each OS family (UB16, W10, SO10, and OB61), and a last one with the slowest OSes (OB60, OB61, SO10, and SO11). The idea is to set an upper and lower bound on the throughput of all possible diverse replica sets.

Results: Figure 6.4 shows that throughput drops from $39k$ to $6k$ for the $0/0$ workload (65% and 10% of the bare metal performance), and from $11.5k$ to $2.5k$ for the $1024/1024$ workload (82% and 18% of the bare metal performance). When comparing these two setups with the non-diverse configurations of Figure 6.3, the fastest set is in 7^{th}, and the slowest set is in 16^{th} in terms of the achieved throughput. It is worth to stress that the slowest set is composed of OSes that only support a single CPU – due to the VirtualBox limitations – therefore the low performance is somewhat expected. The set with OSes from different families is very close to the slowest set, as two of the replicas use single-CPU OSes, and BFT-SMaRt always makes progress at the speed of the 3rd fastest replica (a Solaris VM), since its Byzantine quorum needs three replicas for ordering the requests. These results show that running Lazarus with current virtualization technology results in a significant performance variation, depending on the configurations selected by the system. This opens interesting avenues for future work on protocols that consider such performance diversity, as will be discussed in Chapter 7.

6.3.3 Performance During Replicas' Reconfiguration

Another relevant feature of Lazarus is to adapt the replicas over time. Lazarus leverages on the BFT-SMaRt reconfiguration protocol [22] to add and remove replicas while BFT state is maintained correct and up to date.

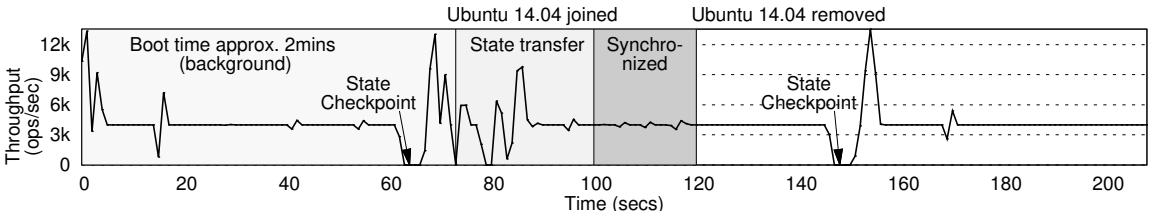


Figure 6.5 – Bare Metal reconfiguration KVS performance on a 50/50 YCSB workload, 1kB-values and with $\approx$ 500MBs state size.

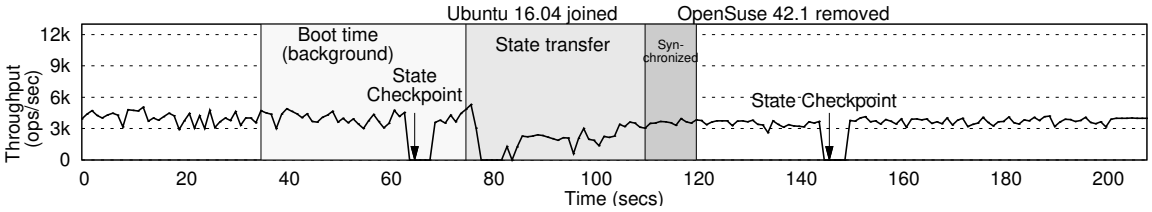


Figure 6.6 – LAZARUS reconfiguration KVS performance on a 50/50 YCSB workload, 1kB-values and with $\approx$ 500MBs state size..

In this experiment, we want to compare the replicas reconfiguration in the homogeneous BM environment with the LAZARUS environment (the initial OS configuration is DE8, OS42, FE26, and SO11). Our goal is to evaluate the two different environments with the same experimental setup to measure the overhead of LAZARUS-induced reconfigurations. We execute this experiment with an in-memory Key-Value Store (KVS) service that comes with the BFT-SMART library. The experiment was conducted with a Yahoo! Cloud Serving Benchmark (YCSB) [41] workload of 50% of reads and 50% of writes, with values of 1024 bytes associated with small numeric keys, varying the state size of the KVS. Since the virtualization environment limits the performance (as shown in the previous experiments), we used a workload that best fits both environments. Then we setup the benchmark to send $\approx$ 4000 operations per second over a state of 500MBs. We selected a time frame of 200 seconds to show the performance during a reconfiguration.

Results: Figures 6.5 and 6.6 show the replicas throughput measured with YCSB benchmark which runs in the client side. In both figures, there are two types of performance drops. The first one, named state checkpoint, is the period in which the BFT-SMART replicas trim their operation logs. During these periods there are no messages processed. The second ones, composed of the state transfer and the synchronization, were already identified, and mitigated in previous works [21].[1]

There are some differences between both executions, in particular, the throughput variation and the time each phase takes to finish. Both experiments were made to represent the same behavior, therefore the different actions start approximately at the same time. For example, in both cases,

[1] We employ the standard checkpoint and state transfer protocols of BFT-SMART and not the ones introduced in [21] as it is more stable.

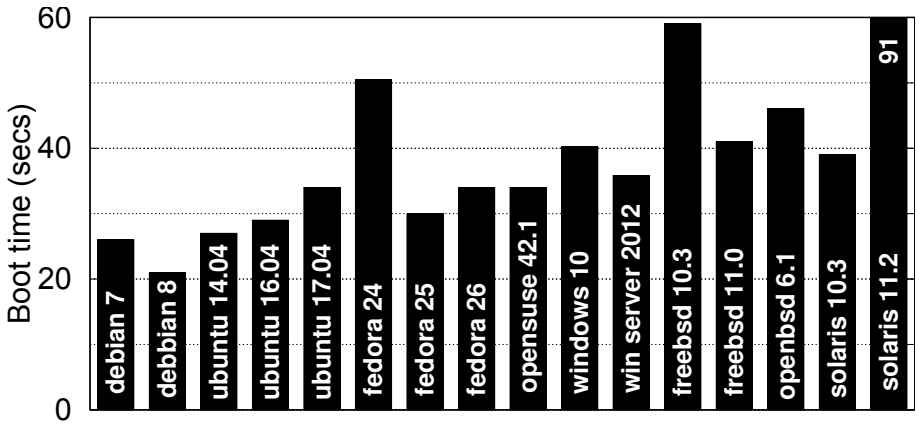


Figure 6.7 – OSes boot times (seconds).

the state checkpoint is made almost at the same time as it is triggered by the number of processed messages on each replica.

In the BM experiment (Figure 6.5) the state checkpoint occurs around the second 60. After a few seconds, the new replica (i.e., Ubuntu 14.04) joins the system, and a state transfer begins. It takes almost 30 seconds to get the state and then it takes approx. 20 seconds to execute the log and reach the other replicas state. Only then one of the *old* replicas is removed. The booting time for Ubuntu 14.04 was more than 2 mins in our testbed.[2]

In the LAZARUS setting experiment (Figure 6.6), it is possible to see a little variance on the throughput overall but it has a significant impact during the reconfiguration. However, the throughput and the time it takes to finish the state reconfiguration is close to the previous experiment. Finally, the booting takes approx. 40 seconds.

Additionally, we have conducted a more straightforward experiment to measure the boot time of the OSes supported by LAZARUS prototype. Figure 6.7 shows the average boot time of 20 executions boot for each OS. As can be seen, most OSes take less than 40 seconds to boot, with the exceptions of Fedora 24 (50 seconds), FreeBSD 10.3 (59 seconds), and Solaris 11.2 (91 seconds). In any case, these results together with the reconfiguration times of the previous section show that LAZARUS can react to a new threat in less than two minutes (in the worst case).

6.3.4 Application Benchmarks

Our last set of experiments aims to measure the throughput of three existing BFT services built on top of BFT-SMART when running in LAZARUS. The considered applications and workloads are:

[2]This time is due to special verification tests that machines in a cluster typically do before booting.

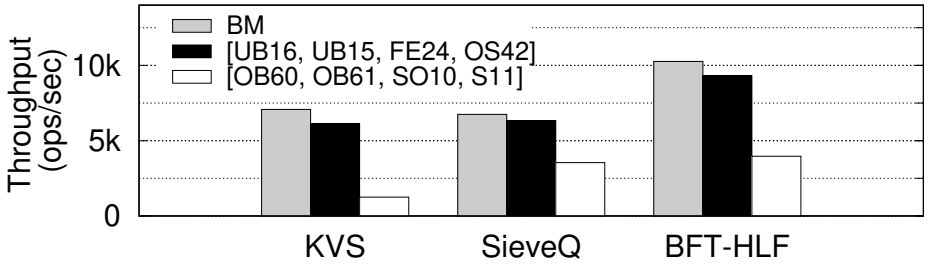


Figure 6.8 – Different BFT applications running in the bare metal, fastest and slowest OS configurations.

- *KVS* is the same BFT-SMART application employed in Section 6.3.3. It represents a consistent non-relational database that stores data in memory, similarly to a coordination service (an evaluation scenario used in many recent papers on BFT [18, 118]). In this evaluation, we employ the YCSB 50%/50% read/write workload with values of 4k bytes.

- SIEVEQ [67] was presented in detail in Chapter 4. In this evaluation, we consider that all the layers were running on the same four physical machines as the diverse BFT-SMART replicas (under different OSes). The workload imposed on the system is composed of messages of 1k bytes.

- *BFT ordering for Hyperledger Fabric* [170] is the first BFT ordering service for Fabric [8]. Fabric is an extensible blockchain platform designed for business applications beyond the basic digital coin. The ordering service is the core of Fabric, being responsible for ordering and grouping issued transactions in signed blocks that form the blockchain. In our evaluation, we consider transactions of 1k bytes, blocks of 10 transactions and a single block receiver.

As in Section 6.3.2, we run the applications on the fastest and slowest diverse replica sets and compare them with the results obtained in bare metal.

Results: Figure 6.8 shows the peak sustained throughput of the applications. The KVS results show a throughput of 6.1k and 1.2k ops/sec, for the fastest and slowest configurations, respectively. This corresponds to 86% and 18% of the 7.1k ops/sec achieved on bare metal.

The SIEVEQ results show a smaller performance loss when compared with bare metal results. More specifically, SIEVEQ in the fastest replica set reaches 94% of the throughput achieved on the bare metal. Even with the slowest set, the system achieved 53% of the throughput of bare metal. This smaller loss happens due to the layered architecture of SIEVEQ, in which most of the message validations happen before the message reaches the BFT replicated state machine (which is the only layer managed by LAZARUS).

The Fabric ordering service results show that running the application on LAZARUS virtualization infrastructure lead to 91% (fastest set) to 39% (slowest set) of the throughput achieved on bare metal. Nonetheless, even the slowest configurations would not be a significant bottleneck if one takes into consideration the current performance of Fabric [170].

6.4 Final Remarks

In this chapter, we focused on the implementation details of LAZARUS and its evaluation as a practical system. We described each component and how they all cooperate together. Then, we evaluated the performance of using LAZARUS, i.e., what is the overhead of running diverse OSes in a virtualized environment under various benchmarks and applications. Some of the limitations that we have identified in the evaluation are further discussed in Chapter 7.

7 Conclusion and Future Research Directions

7.1 Conclusions

The correctness of BFT systems is tied to the assumption that replicas fail independently. Otherwise, once a replica is intruded, the next $f + 1$ replicas could be compromised within virtually the same time. In this thesis, we addressed the long-standing open problem of many works on BFT replication research: evaluate, select, and manage the failure independence (through diversity) of the replicas.

The first step to achieve this objective was to validate the diversity hypothesis. To this end, we leveraged on NVD data about OSes vulnerabilities to conduct an analysis of groups of OSes that could provide dependable configuration sets for replicated systems. In particular, we presented several strategies to choose the most diverse OSes. These strategies comprised different approaches to make decisions based on the data depending on whether one (i) considers all common vulnerabilities as being of equal importance; (ii) place greater emphasis on more recent shared vulnerabilities; or (iii) is primarily interested in the common vulnerabilities being reported less frequently in calendar time. The experiments shown that it is possible to build sets of OSes with no or just a few shared vulnerabilities across long periods of time. All strategies delivered the same best combination of OSes, and this emphasizes the importance of carefully selecting OSes that minimize the number of common weaknesses on BFT replicated systems. These results were encouraging for diversity selection approaches as a way to achieve replicas' failure independence.

The additional costs of maintaining a system with diversity cannot be ignored. Therefore, critical systems are a first major target for deploying such mechanisms. For example, replicated firewalls stand as a critical component in a network as they often correspond to the main line of defense. We presented SIEVEQ a multi-layer firewall-like application that was designed to tolerate internal and external attacks with additional resilient mechanisms. The main improvement of the SIEVEQ multi-layered architecture, when compared with previous systems, is the separation of message filtering in several components that carry on verifications progressively more costly and complex. This allows the proposed system to be more efficient than the state-of-the-art replicated firewalls under attack. SIEVEQ also includes several resilience mechanisms that allow the creation, removal, and recovery of components in a dynamic way, to respond adequately to evolving threats against

the system. Experimental results show that such resilience mechanisms can significantly reduce the effects of DoS attacks against the protected network.

Despite the good results that we have achieved in the first contribution, we have identified some problems that lead us to pursue further analysis. Namely, our and a few other works that used NVD as a primary data source were missing essential data. In particular, NVD does not report all products that are affected by a particular vulnerability. We addressed this issue by using clustering techniques to group similar vulnerabilities. Moreover, we added other data sources that bring additional relevant data (that NVD does not provide) to enrich the information associated with vulnerabilities. We devised a new metric that uses the vulnerability attributes provided by NVD and CVSS, and other attributes added from extra OSINT sources. This metric is used by an algorithm that builds and reconfigures replica sets of BFT systems. The algorithm decides when and which replica should be replaced by estimating the risk of the BFT system being vulnerable to compromise. The results show that our algorithm supports better decisions when selecting OSes to run in the replicated system. For example, for our approach the *compromised rate* varies between 2%-5% of the total of executions while in a random selection the rate stays between 98%-99%.

As a final step, we implemented LAZARUS to manage BFT systems according to security data available online, which is analyzed to trigger replicas' recoveries. We conducted an extensive evaluation of the costs of using real OS diversity in BFT systems. In the experiments, we have found a significant limitation on the virtualization technology, forcing us to limit the evaluation setup by reconfiguring the bare metal machines (e.g., limit the number of CPUs). Therefore, we manage to make a fair comparison (for some of the cases) between a bare metal configuration with a virtualized (yet limited) solution that accommodates LAZARUS. Although most of the results show a non-negligible overhead, we have shown that for OSes that did not suffer virtualization limitations the overhead is minimal. In these cases, the performance of the system managed by LAZARUS is 86%-94% of the bare metal, which runs a replicated non-virtualized homogenous OS configuration.

7.2 Future Work

The results of this thesis open many avenues for future work:

Integration of prevention techniques: In Chapter 2, we have briefly described a few prevention techniques. Although we did not address them here, they could be integrated in our control plane solution. LAZARUS replicas have two states where they are dormant, namely when they are in quarantine or before they are deployed in the execution plane. Thus, this time could be used to apply a sequence of automatic procedures (e.g., vulnerability detectors) that would (1) detect additional weaknesses, which could be reported to NVD, and (2) remediate these weaknesses with mechanisms

like automatic patching [88]. Moreover, although limited to open source products, it could use vulnerable code clone detectors, that would indicate potentially shared vulnerabilities [102, 196]. Such mechanisms would decrease the vulnerability surface, especially if common flaws are detected. Although we are mostly concerned with more complex attacks (e.g., Advanced Persistent Threats), using automatic attacks [85] could activate some common vulnerabilities before replicas are deployed. These would trigger the algorithm to adjust the risk associated with such replicas avoiding their selection.

Extending the LAZARUS source types and sensors: LAZARUS monitors nine security data feeds on the internet to collect data about vulnerabilities, exploits, and patches for the OSes it manages. However, it could be extended to monitor other indicators of compromise (e.g., Internet Protocol (IP) blacklists) extracted from a much richer set of sources [117, 161]. Additionally, LAZARUS could use the IDSs outputs to assess the BFT system behavior and trigger replica's reconfigurations in case of need. Finally, it may be interesting to mine black market data sources to discover new threats that may compromise several replicas [4].

Virtualization technology: Our prototype implements the LTU as a trusted component isolated from the rest of the replica in a VM, in the same way as many works on hybrid BFT [50, 144, 160, 171, 185]. However, one of the main limitations of LAZARUS is its performance overhead due to the use of virtualization. In one hand, it allows LAZARUS to run 17 OS versions on top of VirtualBox. But in the other hand, it brings a significant impact on the performance as it limits the CPU/memory resources available. Nevertheless, the results also show that less resource-limited OSes have a similar performance. Thus, the main overhead is due to virtualization and not (so much) to diversity. We are currently working on a bare metal LTU implementation based on Razor [147] and developing the BFT control plane outlined in Section 6.1.3 to integrate LAZARUS in decentralized Hyperledger Fabric deployments.

Diversity-aware replication: In the same line, the evaluation of BFT-SMART on top of LAZARUS shows that different replica set configurations can impact on the performance of applications, mostly due to the heterogenous overheads of the different OSes. It would be interesting to consider protocols in which this heterogeneity is taken into account. For example, the leader could be allocated in the fastest replica, or weighted-replication protocols such as WHEAT [169] could be used to assign higher weights to the replicas running in faster replicas. These approaches would reduce the impact of running OSes that suffer from resource limitations.

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