D05.5 Design and Concept of a Trusted Virtual Datacenter

Project number	IST-027635
Project acronym	Open_TC
Project title	Open Trusted Computing
Deliverable type	Report

Deliverable reference number	IST-027635/D05.5/FINAL
Deliverable title	Design and Concept of a Trusted Virtual Datacenter
WP contributing to the deliverable	WP05
Due date	Oct 2008 - M36
Actual submission date	November 21st, 2008

Responsible Organisation	IBM
Authors	Contributors listed alphabetically by organisation: CUCL (Theodore Hong, Eric John, Derek Murray); HP (Serdar Cabuk, David Plaquin); IBM (Bernhard Jansen, HariGovind V. Ramasamy, Matthias Schunter); RUB (Yacine Gasmi, Ahmad-Reza Sadeghi, Patrick Stewin, Martin Unger); POL (Gianluca Ramunno, Davide Vernizzi)
Abstract	This report describes the key concepts of the OpenTC Secure Virtual Datacenter.
Keywords	Virtual Datacenter, Proof-of-Concept

Dissemination level	Public
Revision	FINAL

Instrument	IP	**Start date of the project**	1st November 2005
Thematic Priority	IST	**Duration**	42 months

ABSTRACT

This report describes the key concepts of the OpenTC Secure Virtual Datacenter. It is structured into two parts.

Part I surveys the key concepts underlying the 2009 proof of concept “Trusted Virtual Datacenter” that demonstrates how to securely virtualize a datacenter while providing verifiable security.

Part II describes selected components and future directions in more detail.

ACKNOWLEDGMENTS

The following people were the main contributors to this report (alphabetically by organization): Theodore Hong, Eric John, Derek Murray (CUCL); Serdar Cabuk, David Plaquin (HP); Bernhard Jansen, HariGovind V. Ramasamy, Matthias Schunter (IBM); Yacine Gasmi (RUB), Ahmad-Reza Sadeghi (RUB), Patrick Stewin (RUB), Martin Unger (RUB); Gianluca Ramunno (Polito), Davide Vernizzi (Polito). We would like to thank our reviewer Peter Lipp from IAIK Graz for substantial feedback.

Furthermore, we would like to thank the other members of the OpenTC project for helpful discussions and valuable contributions to the research that is documented in this report.We would like to thank in particular Cataldo Basile from Politecnico di Torino, Italy, for valuable input on the policy framework.

This work has been partially funded by the European Commission as part of the OpenTC project [Ope08a] (ref. nr. 027635). It is the work of the authors alone and may not reflect the opinion of the entire project.

Contents

Part I

Main Concepts of the OpenTC Trusted Virtual Datacenter

Chapter 1

Introduction and Outline

1.1 Introduction

Hardware virtualization is enjoying a resurgence of interest fueled in part by its cost-saving potential. By allowing multiple virtual machines to be hosted on a single physical server, virtualization helps improve server utilization, reduce management and power costs, and control the problem of server sprawl.

A prominent example in this context is data centers. The *infrastructure provider*, who owns, runs, and manages the data center, can transfer the cost savings to its customers or *outsourcing companies*, whose virtual infrastructures are hosted on the data center's physical resources. A large number of the companies that outsource their operations are small and medium businesses or SMBs, which cannot afford the costs of a dedicated data center in which all the data center's resources are used to host a single company's IT infrastructure. Hence, the IT infrastructure belonging to multiple SMBs may be hosted inside the same data center facility. Today, even in such "shared" data centers, each run on distinct physical resources and there is no resource sharing among various customers. In this so-called *physical cages* model, the customers are physically isolated from each other in the same data center.

Limited trust in the security of virtual datacenters is one major reason for customers not sharing physical resources. Since management is usually performed manually, administrative errors are commonplace. While this may lead to downtimes in virtual datacenters used by a single customer, it can lead to information leakages to competitors if the datacenter is shared. Furthermore, multiple organizations will only allow sharing of physical resources if they can trust that security incidents cannot spread across the isolation boundary separating two customers.

Security Objectives Our main security objective is to provide isolation among different domains that is comparable[1] with the isolation obtained by providing one infrastructure for each customer. In particular, we require a security architecture

[1] Note that unlike physical isolation, we do not solve the problem of covert channels.

that protects those system components that provide the required isolation or allow to verifiably reason about their trustworthiness of and also of any peer endpoint (local or remote) with a domain, i.e., whether they conforms to the underlying security policy.

We achieve this by grouping VMs dispersed across multiple physical resources into a *virtual zone* in which customer-specified security requirements are automatically enforced. Even if VMs are migrated (say, for load-balancing purposes) the logical topology reflected by the virtual domain should remain unchanged. We deploy Trusted Computing (TC) functionality to determine the trustworthiness (assure the integrity) of the policy enforcement components.

Such a model would provide better flexibility, adaptability, cost savings than today's physical cages model while still providing the main security guarantees required for applications such as datacenters.

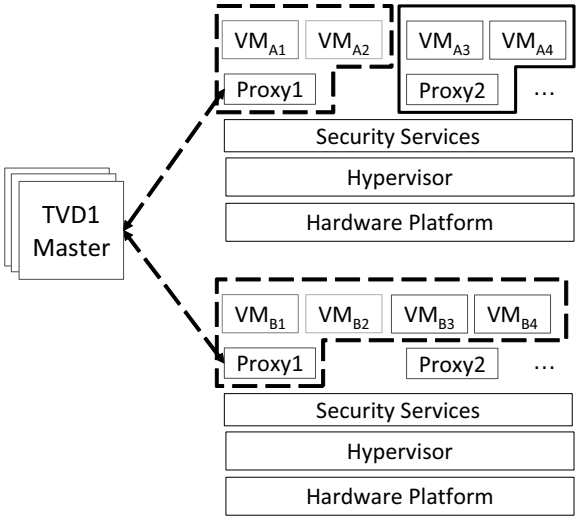


Figure 1.1: TVD Architecture: High-Level Overview.

Contribution In this deliverable, we provide a blueprint for realizing a logical cages model, in particular for virtualized data centers, based on a concept called Trusted Virtual Domains or TVDs [BGJ+05]. Based on previous work, we describe a security management framework that helps to realize the abstraction of TVDs by guaranteeing reliable isolation and flow control between domain boundaries. Our framework employs networking and storage virtualization technologies as well as Trusted Computing for policy verification. Our main contributions are (1) combining these technologies to realize TVDs and (2) orchestrating them through a management framework that automatically enforces isolation among different zones. In particular, our solution aims at automating the verification, instantiation and deployment of the appropriate security mechanisms and virtualization

technologies based on an input security model, which specifies the required level of isolation and permitted information flows.

1.2 Outline of this Report

This deliverable is structured into three parts.

Part I introduces the objectives and main concepts of a trusted virtual datacenter. This includes the the high-level architecture documented in Chapter 2 and the policy enforcement, refinement, and management in Chapter 3.

Part II then documents details of two building blocks, namely networking and dependability. Chapter 4 describes our revised and detailed description of automated provisioning of virtual networks and their security elements such as firewalls and Virtual Private Networks (VPN). Chapter 5 investigates how to increase the dependability of datacenters in order to allow virtualization of mission-critical applications. This chapter concludes by proposing a dependability-enhanced architecture for the Xen hypervisor where different virtual machines monitor each other. Whenever failures are detected, the machines are then dynamically rejuvenated to retain service.

Part III concludes this report, contains an appendix with an extensive bibliography of related work.

Chapter 2

Secure Virtualized Datacenters

We now outline the OpenTC 2009 proof of concept prototype and its main architectural elements.

2.1 Objectives & Proof-of-concept Scenario

2.1.1 Main Objectives

We have built a virtual datacenter that should be comparable with a consolidated and simplified version of today's datacenters. Like today, a datacenter will e used by many customers. As a consequence, customer isolation is of paramount importance.

The next important observation is that customers are usually transitioned from their own legacy datacenters into a shared datacenter. As a consequence, each customer usually has a legacy way of managing its datacenter. This legacy way should be supported by the new datacenter. Ideally, whatever hard- and software as well as management infrastructure a customer had should be virtualized and supported by the new virtual datacenter.

2.1.2 Virtual Datacenter Scenario

The scenario we want to demonstrate has multiple sub-scenarios with increasing complexity:

"Physical Systems" Management The first scenario is the provisioning of formerly physical systems. The scenario we build is a customer who boots a server and installs this server from the network. For this scenario, virtualization should be transparent.

Hosting Media Services The second scenario is to use the datacenter to host media services. The goal is to allow outsiders to play media iff their platform has been validated and deemed trustworthy.

Virtual Systems Management The third scenario aims at virtualizing virtual systems. The key idea is that today, customers will have virtualized systems such as Xen that need to be embedded and managed as a part of our virtual datacenter.

We do this by migrating a Xen installation into our datacenter and then computing a view of the datacenter that corresponds to the former Xen installation.

2.2 High-level Architecture

We now describe the architecture of our demonstrator. This architecture has several components, namely hosts, networks, storage, virtual machines, and software.

2.2.1 Network Architecture

We use the trusted virtual domain model to isolate different networks. In this model each domain is isolated from other domains while being only permitted to communicate via well-defined gateways.

In order to structure the demonstrator, we have defined the following domains (see Figure 2.1):

Customer application zone This domain constitutes a network of a given customer. It transports the application traffic of a given customer. Ordinary users can access this network.

Customer management zone This domain is the management network of a given customer. It is used for provisioning of virtual machines, monitoring machines, and management of application zones of this customer. Administrators of each customer can access the corresponding management zone.

Datacenter management zone This network is used by the datacenter administrators to manage the overall datacenter. This includes setting up new domains, assigning resources, or removing domains. This domain is also used for management communication between the different domains.

Demilitarized Zone The DMZ allows customers to connect to the Internet and allows outsiders to establish connections to a TVD. The former is done by establishing gateway machines that connect to the internal zone and DMZ. The latter is achieved by TVD proxy factories connecting to the DMZ.

Storage Area Network The storage area network provides virtual storage to all physical hosts in a datacenter. The management components can then connect selected storage unites to given virtual machines.

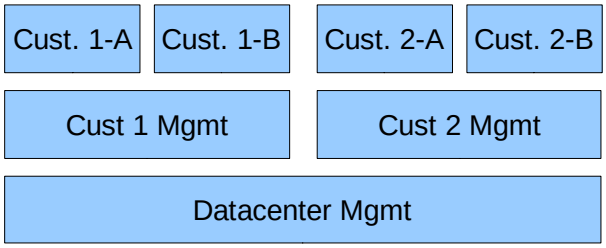


Figure 2.1: Trusted Virtual Domains of a Virtual Datacenter

These network allows clear isolation of different customers while providing a backbone management network for the TVDC infrastructure to communicate.

Figure 2.2 depicts the details of the networking for a single user-level TVD. It is important to note that the datacenter hosts are booted from the network using the Preboot eXecution Environment (PXE). This allows the administrators to seamlessly add and remove physical hosts.

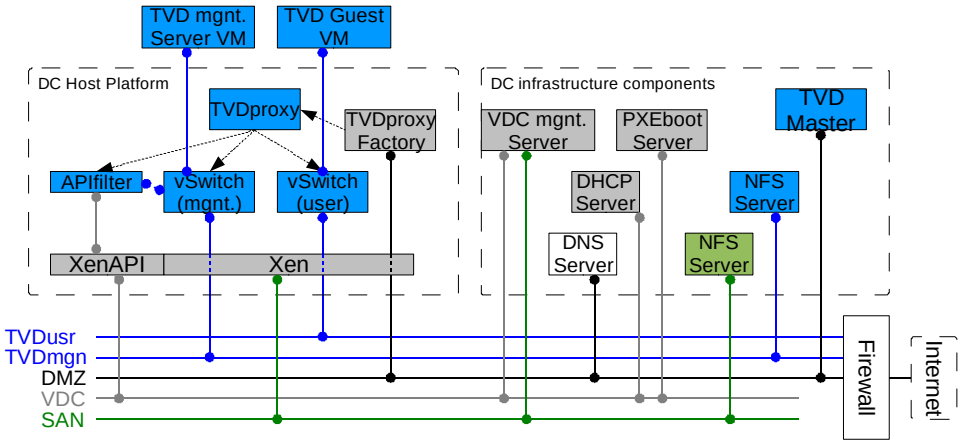


Figure 2.2: Networking Details of a Virtual Datacenter

2.2.2 Multi-Tenant Management

An important goal of our prototype is to enable heterogeneous management. This means that each customer should be able to use arbitrary existing management tools to manage their domains: While the datacenter operator uses given software to assign resources quotas to each customer, the respective customer can then use his existing management tools to use these resources to build virtual machines on assigned hosts.

We implement this multi-tenant concept by providing filtered instances of the XenAPI to individual customers while providing the complete XenAPIs only to the datacenter operator.

This is depicted in Figure 2.3: For each customer, a XenAPI filter component is providing the corresponding filtered XenAPI service to the management network of the given customer. The basic idea is that the filter obtains the list of VMs that belong to a given customer and strips all other machines from the returned information. Similarly, other elements (storage/network) that do not belong to this customer are stripped.

The XenAPI filter then forwards commands to the internal XenAPI provider. This provider in turn forwards non-security commands to the existing XenAPI provided by `xend` while forwarding security extensions to the OpenTC compartment manager.

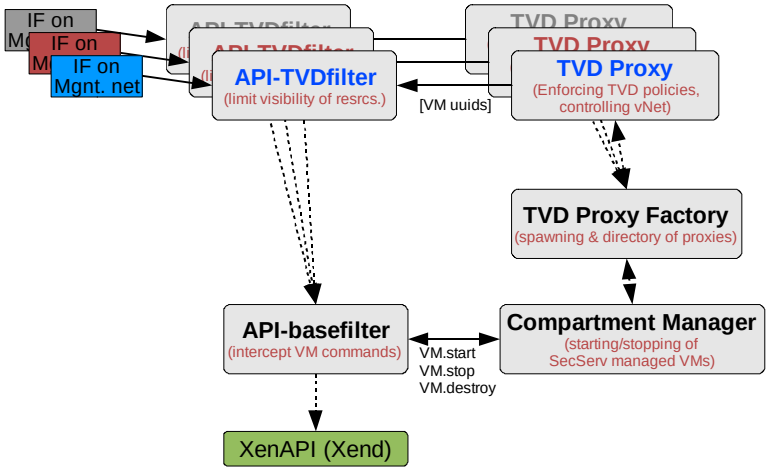


Figure 2.3: Enabling Multi-Tenant by Filtering the XenAPI

Overall this approach allows customers to run any XenAPI-based management software. By using the XenAPI-based CIM[1] provider from `http://wiki.xensource.com/xenwiki/XenCim`, customers can furthermore use any existing CIM-based management tool to manage their domains.

Similarly, the datacenter operator can directly access the underlying XenAPI to manage the overall datacenter.

[1]This refers to the DMTF System Virtualization, Partitioning, and Clustering Working Group (SVPC WG). See `www.dmtf.org`.

Chapter 3

Policy Enforcement for Virtual Datacenters

Serdar Cabuk, Chris I. Dalton, Dirk Kuhlmann (HP) Konrad Eriksson,
HariGovind V. Ramasamy, Matthias Schunter (IBM), Gianluca Ramunno (POL),
Ahmad-Reza Sadeghi, Christian Stüble(RUB)

In this chapter wee describe a security management framework that helps realize the abstraction of TVDs by guaranteeing reliable isolation and flow control between domain boundaries.

After introducing the key concepts such as Trusted Virtual Domains, we explain the security policies that are enforced in a virtual datacenter in Section 3.1. The key idea is that the datacenter management can declare a inter-TVD policy that defines how customers are isolated. Each customer (or domain of a customer) can then define a intra-TVD security policy that defines how its internal security is handled. Both policies hold for all resources and can subsequently be refined. In Section 3.2 we then discuss how these policies are enforced. For enforcement we focus on the two most important resources that are potentially shared. The key idea is to provide virtual networks and storage that is assigned to a given domain and where access by other domains is restricted.

3.1 Security Policies for Virtual Data Centers

Data centers provide computing and storage services to multiple customers. Customers are ideally given dedicated resources such as storage and physical machines. Resources such as the Internet connection, however, may be shared between multiple customers. Each customer has a set of security requirements and may often specify which security mechanisms must be used to satisfy these requirements. For example, different customers may specify different anti-virus software to be used for their VMs and different virus scanning intervals.

To model and implement these heterogeneous requirements, we introduce a domain-based security model for enforcing unified security policies in virtualized

data centers. We focus on isolation policies that mimic physical separation of data center customers. Our goal is to logically separate customer networks, storage, VMs, users, and other virtual devices. The core idea is to use this isolation as a foundation for guaranteeing desired security properties within each virtual domain while managing shared services under mutually agreed policies.

3.1.1 High-level Policy Model

Our security model is based on TVDs [BGJ+05], which isolate their resources from resources of other TVDs. In the following, we distinguish between the following resource types:

Virtual Processing Elements: Virtual Processing Elements (VPE) are active elements (subjects), such as physical or virtual machines, that can be member of one or more TVDs.

Virtual Infrastructure Elements: Virtual Infrastructure Elements (VIE) are passive elements (objects), such as physical or virtual disks, that can be member of one or more TVDs.

Note that computing platforms that host VMs but are not directly member of a TVD are not considered as VPEs. Moreover, the security model includes two high-level policies defining the security objectives that must be provided by the underlying infrastructure:

Inter-TVD Policy: By default, each TVD is isolated from the "rest of the world". The high-level information-exchange policy defines whether and how information can be exchanged with other TVDs. If no information exchange with other TVDs is permitted, no resources can be shared unless the data-center operator can guarantee that these resources guarantee isolation. If flow is in principle allowed, sub-policies further qualify the exact flow control policy for the individual resources.

Intra-TVD Policy: Domain policies allow domain owners (e.g., customers) to define the security objectives within their own TVDs. Examples of such policies include how the internal communication is to be protected and under what conditions resources (e.g., storage, machines) can join a particular TVD.

3.1.2 Security Objectives and Policy Enforcement Points

Policies are enforced across different resources in the TVD infrastructure (see Figure 3.1). The basis of all policies is isolation at the boundary of each TVD.

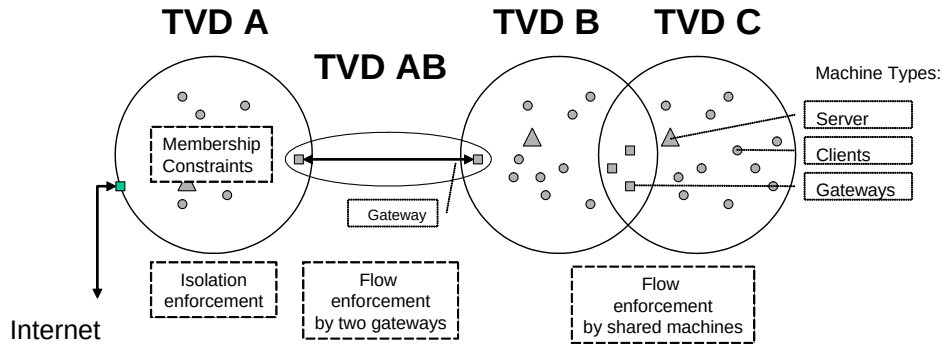


Figure 3.1: Types of TVD Policy Enforcement.

By default, each resource is associated with a single domain. This achieves a basic level of isolation. If an information flow between TVDs is allowed, resources can also be member of different TVDs. For example, a TVD can allow certain types of resources on certain hosts to provide services also to other domains. Each TVD defines rules regarding in-bound and out-bound information flow for restricting communication with the outside world. The underlying policy-enforcement infrastructure then has to ensure that only resources trusted by all TVDs are shared.

Architecturally, there are two ways of enforcing such rules, depending on the trust between the TVDs. The first method involves two shared resources connected by an intermediate domain. In this method, each TVD enforces its side of the flow control by means of its own shared resource. An example of this type of connection is the one that exists between *TVD A* and *TVD B* in Figure 3.1. This method is used when the trust level between *TVD A* and *TVD B* is low, and the two cannot agree on a shared resource that is mutually trusted. The shared resource in *TVD A* will enforce *TVD A*'s policies regarding in-bound traffic from *TVD B*, even if the shared resource in *TVD B* does not enforce *TVD B*'s policies regarding out-bound traffic. The shared resources can be thought of being a part of a "neutral" TVD (*TVD AB*) with its own set of membership requirements. The second method that requires shared trust is to establish one or more shared resources that are accessed from both TVDs while allowing controlled information flow. This mechanism is used between *TVD B* and *TVD C* in Figure 3.1.

Security within a domain is finally obtained by defining and enforcing *membership requirements* that resources have to satisfy prior to being admitted to the TVD and for retaining the membership. This may also include special requirements for different machine types: Because, for example, shared resources play a key role in restricting information flow between TVDs, the software on those machines may be subject to additional integrity verification as compared to the software on regular VPEs.

Flow control policies define the allowed traffic flow between two domains and how the domains should be protected. Membership policies define domain-internal

Table 3.1: High-level Directed Flow Control Matrix for Internet D_I, DMZ D_D, and Intranet D_i (1 allows information flow, whereas 0 denies it).

From / to	D_I	D_D	D_i
D_I	**1**	1	0
D_D	0	**1**	1
D_i	0	1	**1**

security objectives as well as the prerequisites for becoming a member of a domain.

Isolation and Permitted Flows in Data Centers

Proper customer separation in a virtualized environment requires the logical separation of all resources that belong to one TVD from those of another TVD. As mentioned above, this can either be achieved by assigning each resource only to a single domain or by enforcing flow control to limit the information flow through shared resources that belong to multiple TVDs.

By default, a VPE and its local memory belong to a single TVD. If VPEs are assigned to two or more TVDs they act as a gateway allowing controlled information flow between TVDs. This includes their system image and swap-files. To consistently enforce flow control between domains, we need to control the data flow in shared VPEs, storage, and other devices.

Allowed information flows can be represented by a simple flow control matrix as depicted in Table 3.1. Note that this matrix is directional, i.e., it might allow flows in one direction but not in the opposite direction. If flow policies between two TVDs are asymmetric, only shared resources that can enforce these policies are permitted. Device-specific policies (network, storage) can then refine these basic rules. If an information flow is not permitted, then also shared resources are not permitted between these TVDs.

Membership Requirements

Membership requirements define under what conditions resources may join a domain. From a high-level policy perspective, several criteria can be applied to decide whether an entity is allowed to join a domain, for example:

- *Certificates*: An authority defined by the TVD policy can certify a resource to be member of a TVD.
- *Attestation Credentials*: A resource may prove its right to join a TVD using integrity credentials, e.g., by means of Trusted Computing functionality, such as remote attestation.
- *White-listing*: Only entities that are listed on a white-list can join.

In general, a resource may need to show proper credentials to prove that it fulfills certain properties [SS05] before allowing the resource to join the TVD. The validations of these properties are usually done on a per-type basis. This means that, e.g., the requirements for a shared resource are usually stronger than the requirements for a TVD-internal resource.

One way of formalizing the network membership requirements is to define a function $M : T \rightarrow 2^P$, where $(P, \leq)$ is a lattice of security properties. A machine m with a set p_m of security properties may be permitted to join the TVD t if and only if $\forall p \in M(t) : \exists p' \in p_m$ such that $p' \geq p$. In other words, m is permitted to join t if and only if there is at least one property of m that satisfies each security requirement of t.

3.1.3 Example Policy Refinements for Protected Resources

Policies alone are not sufficient to enforce customer separation. Ultimately, one needs to transform these policies into data-center configurations and security mechanisms specific to each resource (e.g., VLAN configuration). To do so, we introduce a policy management scheme that accepts high-level domain policies and transforms them into resource-specific low-level policies and configurations.

Refinement Model

The high-level policy defines the basic flow control, protection, and admission requirements. We aim at enforcing these high-level objectives throughout all resources in the data center.

In the high-level model, flow control is specified by a simple matrix that defines whether flows are permitted. This however is not sufficiently fine-grained for specific resources. TVDs, for example, want to restrict their flow across boundaries by means of firewall rules. As a consequence, we need to introduce a notion of policy refinement [Wes01], because as translation moves towards lower levels of abstraction, it will require additional information (e.g., physical arrangement of the data center, "subjective" trust information) to be correctly and coherently executed.

Our notion of policy refinement mandates the enforcement of "no flow" objectives while allowing each resource to refine what it means so that flows are permitted and how exactly unauthorized flows shall be prevented. Similarly, we do not allow resources to deviate from the confidentiality/integrity objectives; however, certain resources can be declared trusted so that they may enforce these objectives without additional security mechanisms such as encryption or authentication.

Similarly, the fact that admission is restricted is then refined by specific admission control policies that are enforced by the underlying infrastructure.

Note that conflict detection and resolution [Wes01, LS99] can later be used to extend this simple notion of refinement. However, we currently stay on the safe

Table 3.2: Example Network Flow Control Policy Matrix for Three TVDs.

Enforced by/flow to	D_I	D_D	D_i
D_I	**1**	P_{ID}	0
D_D	0	**1**	P_{Di}
D_i	0	P_{Di}	**1**

side: connections are only possible if both TVDs allow them. Similarly, if one domain requires confidentiality, information flows are only allowed to TVDs that also require confidentiality. Other schemes for more elaborate flow control have been proposed in [EASH05, CBL07, N. 01, FWH$^+$01].

Network Security Policies

We now survey the policy model of [CDRS07] and show how it related to the corresponding high-level policy. Similar to our high-level policies, there are two types of policies governing security in the network. The first limits flow between networks, whereas the second defines membership requirements to each network.

Network Security Policies across TVDs A policy covers isolation and flow control between TVDs as well as integrity and confidentiality against outsiders. These basic security requirements are then mapped to appropriate policies for each resource. For example, from a networking perspective, isolation refers to the requirement that, unless the inter-TVD policies explicitly allow such an information flow, a dishonest VPE in one TVD cannot (1) send messages to a dishonest VPE in another TVD (information flow), (2) read messages sent on another TVD (confidentiality), (3) alter messages transmitted on another TVD (data integrity), and (4) become a member of another TVD network (access control).

TVDs often constitute independent organizational units that may not trust each other. If this is the case, a communication using another TVD can be established (see the communication between TVD A and B in Figure 3.1).

The advantage of such a decentralized enforcement approach is that each TVD is shielded from security failures in other TVDs. For networks, the main inter-TVD security objectives are information flow control among the TVDs as well as integrity and confidentiality protection of the channel.

An information flow control matrix is a simple way of formalizing these system-wide flow control objectives. Table 3.2 shows a sample matrix for the three example TVDs introduced earlier. Each matrix element represents a policy specifying both permitted in-bound and out-bound flows between a pair of TVDs, as enforced by one of the TVDs. The **1** elements along the matrix diagonal convey the fact that there is free information flow within each TVD. The **0** elements in the

matrix are used to specify that there should be no direct information flow between two TVDs, e.g., between the Internet D_I and the intranet D_i. Care must be taken to ensure that the pairwise TVD policies specified in the information flow control matrix do not accidentally contradict each other or allow undesired indirect flow. In our practical realization these network flow policies are implemented by firewall rules.

Intra-TVD Network Security Policy Within a TVD, all VPEs can freely communicate with each other while observing TVD-specific integrity and confidentiality requirements. For this purpose, the underlying infrastructure may ensure that intra-TVD communication only takes place over an authenticated and encrypted channel (e.g., IPSec), or alternatively, a trusted network[1].

Towards Storage Security Policies

Virtual disks attached to VPEs must retain the advantages offered by storage virtualization while at the same time enforcing TVD security policies. Advantages of storage virtualization include improved storage utilization, simplified storage administration, and the flexibility to accommodate heterogeneous physical storage devices.

Different groups of virtual disks may exist for different purposes. For example, the disk images that can be mounted for web-server VMs would be different from those for database-server VMs. A virtual disk may be attached to multiple VMs

Inter-TVD Storage Security A virtual disk has a single label corresponding to the TVD it belongs to. Whenever a virtual machine operates on virtual storage, the global flow matrix described in Section 3.1 needs to be satisfied. This is guaranteed by the following policy refinement rules that define the allowed interactions:

1. A machine in domain TVD_A can write to a disk of domain TVD_B iff flow from domain TVD_A to domain TVD_B is permitted.

2. A machine in domain TVD_A can read from a disk of domain TVD_B iff flow from domain TVD_B to domain TVD_A is permitted.

Table 3.3 shows the resulting disk flow control policy. Note that as flow within a domain is always allowed, this implies that disks of the same domain as the machine may always be mounted read/write.

By default, we consider the content of a disk to be confidential. That is, if a given domain does not declare a given storage medium as trusted, we deploy whole-disk encryption using a key that is maintained by the TVD. Another aspect reflected in the disk policies is the fact that we have a notion of blank disks. Once

[1] A network is called *trusted* with respect to a TVD security objective if it is trusted to enforce the given objective transparently. For example, a server-internal Ethernet can often be assumed to provide confidentiality without any need for encryption.

Table 3.3: Example of a Refined Disk Policy Matrix for Three TVDs.

Disk/VPE	D_I	D_D	D_i
D_I	r/w	w	0
D_D	r	r/w	r/w
D_i	0	r/w	r/w
Blank	$r/$ $w \rightarrow D_I$	$r/$ $w \rightarrow D_D$	$r/$ $w \rightarrow D_i$

they are written by another domain, they change color, and are then associated with this other domain.

Intra-TVD Storage Security For protecting the data in a particular TVD, virtual storage may in addition specify whether the disk is encrypted, which conditions on the system must be satisfied before a disk may be *re-mounted* by a VPE that has previously unmounted the disk, and whether shared mounting by multiple systems is allowed. To be compatible with a high-level policy, a disk either has to be trusted or else confidentiality requires encryption while integrity requires hash-trees protecting the disk. Similarly, membership restrictions require bookkeeping of disks and management of access of VPEs to disks.

3.2 Unified Policy Enforcement for Virtual Data Centers

In this section, we introduce a TVD-based policy enforcement framework that orchestrates the deployment and enforcement of the type of policies we presented in Section 3.1 across the data center. Existing storage and network virtualization technologies as well as existing Trusted Computing components (in software and hardware) are the building blocks of our solution. Our framework (1) combines these technologies to realize TVDs and (2) orchestrates them using the TVD infrastructure, which provisions the appropriate security mechanisms.

3.2.1 TVD Infrastructure

The TVD infrastructure consists of a management layer and an enforcement layer. The TVD management layer includes TVD masters, proxies, and factories, whereas the TVD enforcement layer consists of various security services. Each TVD is identified by a unique *TVD master* that orchestrates TVD deployment and configuration. The TVD master can be implemented as a centralized entity or have a distributed fault-tolerant implementation. The TVD master contains a repository of high-level TVD policies and credentials (e.g., VPN keys). The master also exposes a TVD management API through which the TVD owner can specify those policies and credentials. In the deployment phase, the TVD master first verifies the

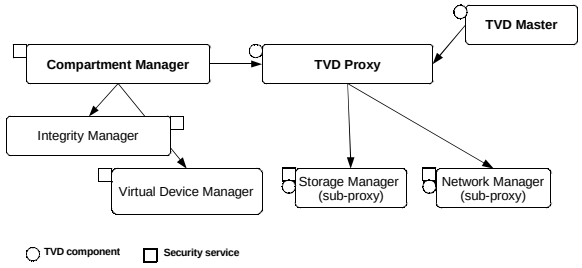


Figure 3.2: TVD Components and Security Services.

suitability and capability of the physical host (which we refer to as pre-admission control). It then uses a generic *TVD factory* service to spawn a *TVD proxy*, which acts as the local delegate of the TVD master dedicated to that particular host. The TVD proxy is responsible for (1) translation of high-level TVD policies into low-level platform-specific configurations, (2) configuration of the host and security services with respect to the translated policies, and (3) interaction with the security services in TVD admission and flow control.

Security services implement the security enforcement layer of our TVD infrastructure. They run in a trusted execution environment on each physical host (e.g., Domain-0 in Xen) and (1) manage the security configuration of the hypervisor, (2) provide secure virtualization of resources (e.g., virtual devices) to the VMs, and (3) provide support to TVD proxies in enforcing flow and access control policies within and across TVD boundaries. Figure 3.2 shows a high-level list of security services and their interaction with the TVD components. Most importantly, the *compartment manager* service manages the life-cycle of VMs in both para-virtualized and fully virtualized modes. This service works in collaboration with the TVD proxy to admit VMs into TVDs. The *integrity manager* service implements Trusted Computing extensions and assists the TVD proxy in host pre-admission and VM admission control. The *virtual network manager* and *virtual storage manager* services are invoked by the TVD proxy. They implement resource virtualization technologies and enforce parts of the high-level TVD policies that are relevant to their operation. Lastly, the *virtual device manager* service handles the secure resource allocation and setup of virtual devices assigned to each VM.

Our TVD infrastructure is geared towards automated deployment and enforcement of security policies specified by the TVD master. Automated refinement and translation of high-level policies into low-level configurations are of particular interest. For example, for information flow between two hosts in a trusted data-center environment, other mechanisms need to be in place than for a flow between two hosts at opposite ends of an untrusted WAN link. In the latter case, the hosts should be configured to allow communication between them only through a VPN tunnel.

Another important consideration is policy conflict detection and resolution [Wes01, LS99]. In fact, conflicting high-level policies (e.g., a connection being

allowed in the inter-TVD policy but disallowed in the intra-TVD policy) can potentially result in an incorrect configuration of the underlying infrastructure. We cannot solely rely on the TVD owner to specify conflict-free policies. It is important to detect policy conflicts and provide feedback to the owner in case one is detected. In the present prototype, policy refinement is performed manually. The result is a set of configuration files that we use for configuring the security services at the policy enforcement layer (e.g., the virtual networking infrastructure). In future work, we will investigate the automation of this step using, for example, the IETF policy model [RYG00] and various graph-based mechanisms from the literature. We will also investigate different techniques for resolving conflicting policies [EASH05, CBL07, N. 01, FWH+01].

3.2.2 Virtual Networking Infrastructure

Virtual networking (VNET) technologies enable the seamless interconnection of VMs that reside on different physical hosts as if they were running on the same machine. In our TVD framework, we employ multiple technologies, including virtual switches, Ethernet encapsulation, VLAN tagging, and VPNs, to virtualize the underlying network and securely group VMs that belong to the same TVD. A single private virtual network is dedicated to each TVD, and network separation is ensured by connecting the VMs at the Ethernet level. Logically speaking, we provide a separate "virtual infrastructure" for each TVD in which we control and limit the sharing of network resources (such as routers, switches) between TVDs. This also provides the TVD owner with the freedom to deploy a wide range of networking solutions on top of the TVD network infrastructure. Network address allocations, transport protocols, and other services are then fully customizable by the TVD owner and work transparently as if the VMs were in an isolated physical network. To maintain secrecy and confidentiality of network data (where necessary), network communication is established over encrypted VPN tunnels. This enables the transparent use of untrusted networks between physical hosts that contain VMs within the same TVD to provide a seamless view of the TVD network.

In this section, we introduce the technologies we use to implement a security-enhanced VNET infrastructure for TVD owners. The concept of virtual switching is central to our architecture, which is then protected by existing VPN technologies that provide data confidentiality and integrity where needed. The VNET infrastructure acts as the local enforcer of VNET policies. As described in Section 3.1.3, these policies are based on the high-level TVD policies and translated into network configurations by the TVD proxy. The proxy then deploys the whole VNET infrastructure with respect to the translated configuration.

Virtual Switching

The *virtual switch* (vSwitch) is the central component of the virtual networking infrastructure and operates similarly to a physical switch. It is responsible for

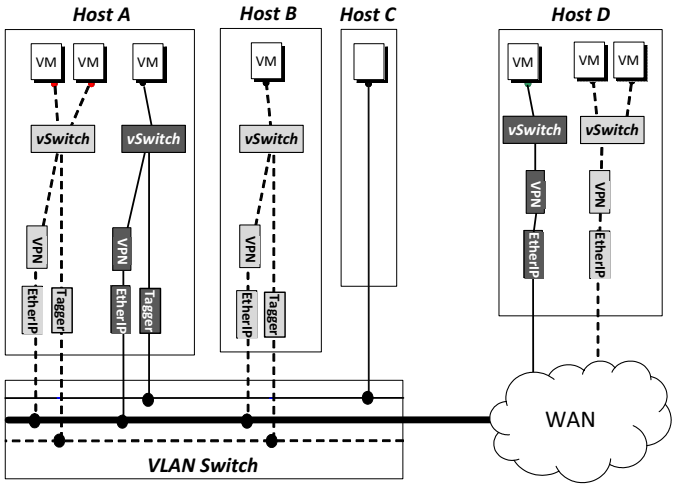


Figure 3.3: General vSwitch Architecture.

network virtualization and isolation, and enables a virtual network to span multiple physical hosts. To do so, the vSwitch uses EtherIP [IET02] and VLAN tagging [IEE98] to insert VLAN membership information into every network packet. The vSwitch also implements the necessary address-mapping techniques to direct packets only to those machines that host member VMs. Virtual switches provide the primitives for implementing higher-level security policies for networking and are configured by the higher-level TVD management layer.

Figure 3.3 illustrates an example architecture in which physical machines host multiple VMs with different TVD memberships (the light and dark shades indicate different TVDs). Hosts A, B, and D are virtualized machines, whereas Host C is non-virtualized. Furthermore, Hosts A, B, and C reside on the same LAN, and thus can communicate directly using the trusted physical infrastructure without further protection (e.g., traffic encryption). For example, the *light* VMs hosted on Hosts A and B are inter-connected using the local VLAN-enabled physical switch. In this case, the physical switch separates the TVD traffic from other traffic passing through the switch using VLAN tags. Similarly, the *dark* VMs hosted on Host A and the non-virtualized Host C are seamlessly inter-connected using the local switch. In contrast, connections that require IP connectivity are routed over the WAN link. The WAN cloud in Figure 3.3 represents the physical network infrastructure able to deal with TVD-enabled virtual networks; it can include LANs with devices capable of VLAN tagging and gateways to connect the LANs to each other over (possibly insecure) WAN links. For connections that traverse untrusted medium, we employ EtherIP encapsulation to denote TVD membership and additional security measures (such as encryption) to ensure compliance with the confidentiality and integrity requirements.

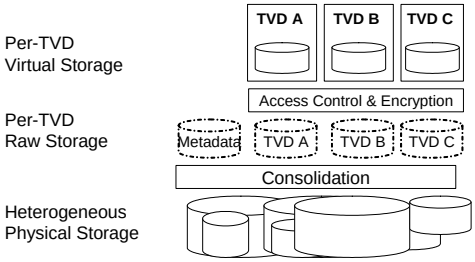


Figure 3.4: Security Enforcement for Virtualized Storage.

Virtual Private Networking

In Figure 3.3, VMs hosted on Host D are connected to the other machines over a WAN link. A practical setting in which such a connection might exist would be an outsourced remote resource connected to the local data center through the Internet. As an example, lightly shaded VMs on Host D connect to the lone VM on Host B over this untrusted link. In this setting, we use a combination of EtherIP encapsulation and VPN technology to ensure the confidentiality and integrity of the communication. To do so, we use point-to-point VPN tunnels with OpenVPN that are configured via the TVD proxy from the TVD policies. This enables reconfiguration of the topology and the involved VPNs within a TVD from a single administration point, the TVD Master.

TVD policies distributed from the TVD master to the TVD proxy also include the secret key for the VPN along with other VPN-specific settings. On a physical host, the VPN's endpoint is represented as a local virtual network interface (vif) that is plugged into the appropriate vSwitch controlled by the TVD proxy. The vSwitch then decides whether to tunnel the communication between VMs, and if so, uses the VPN module to establish the tunnel and access the VPN secret for traffic encryption and decryption.

3.2.3 Virtual Storage Infrastructure

We focus on a simplified security management of virtualized storage. Broadly speaking, storage virtualization abstracts away the physical storage resource(s). It is desirable to allow a storage resource to be shared by multiple host computers, and also to provide a single storage device abstraction to a computer irrespective of the underlying physical storage, which may be a single hard disk, a set of hard disks, a Storage Area Network (SAN), etc. To satisfy both requirements, storage virtualization is typically done at two levels. The first level of virtualization involves aggregating all the (potentially heterogeneous) physical storage devices into one or more virtual storage pools. The aggregation allows more centralized and convenient data management. The second level of virtualization concerns the unified granularity (i.e., blocks or files) at which data in each pool is presented to the higher-level entities (operating systems, applications, or VMs).

Figure 3.4 shows our storage security enforcement architecture, in which existing heterogeneous physical storage devices are consolidated into a joint pool. This virtual storage pool is then subdivided into raw storage for each TVD. Each raw storage volume has an owner TVD (indicated by the labels TVD A, TVD B, and TVD C at the per-TVD raw storage layer in the figure). In addition, when a volume may have to be shared among multiple TVDS, there is also a set of member TVDs associated with it. The access control and encryption layer helps enforce the owner TVD's storage-sharing policies, e.g., enforcing read, write, create, and update access permissions for the member TVDs. This layer is a logical layer that in reality consists of the virtual storage managers (part of the security services) located on each physical platform containing the owner TVD's VPEs. The owner TVD's virtual storage manager on each physical platform is responsible for enforcing the owner TVD's storage security policies (see Section 3.1.3) on these volumes. If a certain intra-TVD security policy requires confidentiality and does not declare the medium as trusted, the disk is encrypted using a key belonging to the owner TVD.[2] If conditions for (re-)mounting a disk have been defined, the disk is also encrypted and the key is sealed against the TCB while including these conditions into the unsealing instructions. The policy and meta-data are held on a separate raw volume that is only accessible by the data-center infrastructure.

An administrator of a domain may request that a disk be mounted to a particular VM in a particular mode (read/write). In Xen, the disk is usually mounted in the management machine Domain-0 as a *back-end device* and then accessed by a guest domain via a *front-end* device. The virtual storage manager on the platform validates the mount request against the policies of both the TVD the VM is part of and the owner TVD for the disk. Once mounted, appropriate read-write permissions are granted based on the flow control policy for the two TVDs, e.g., read access is granted only if the policies specified in the disk policy matrix allow the VM's TVD such an access to the disk belonging to the owner TVD.

3.2.4 TVD Admission Control

When a VM is about to join a TVD, different properties will be verified by the local TVD proxy to ensure that policies of all the TVDs that the VM is currently a member of as well as of the TVD that it wants to join are not violated. If the verification is successful, then the VM will be connected to that TVD. The TVD admission control protocol is the procedure by which the VM gets connected to the TVD. In the case of a VM joining multiple TVDs, the admission control protocol is executed for each of those TVDs. We now describe the steps of the protocol.

We assume that the computing platform that executes the VM provides mechanisms that allow remote parties to convince themselves about its trustworthiness. Example mechanisms include trusted (authenticated) boot and the remote attestation protocol based on TPM technology.

[2] For efficiency reasons, we currently do not provide integrity protection.

TVD Proxy Initialization Phase: To allow a VM to join a TVD, the platform hosting the VM needs access to the TVD policy, and upon successful admission, to TVD secrets, such as the VPN key. For this purpose, TVD proxy services are started on the platform for each TVD whose VPEs may be hosted . The TVD proxy can be started at boot time of the underlying hypervisor, by a system service, or by the VM itself, as long as the TVD proxy is strongly isolated from the VM.

Pre-Admission Phase: When a VPE belonging to the TVD is going to be hosted on the platform for the first time, the TVD master has to establish a trust relation with the platform running the VM, specifically with the TVD proxy. We call this step the *pre-admission* phase, and it involves the establishment of a trusted channel between the TVD master and the TVD proxy. The trusted channel allows the TVD master to verify the integrity of the TVD proxy and the underlying platform. After the trusted channel is established and the correct configuration of proxy verified, the TVD master can send the TVD policies and credentials (such as VPN key) to the TVD proxy.

Admission Control Phase: The Compartment Manager (part of the platform security services shown in Figure 3.2) is responsible for starting new VMs. The Compartment Manager loads the VM configuration and enforces the security directives with the help of the Integrity Manager (also part of the platform security services shown in Figure 3.2). The security directives may include gathering the VM state information, such as the VM configuration, kernel, and disk(s) that are going to be attached to the VM.

If the VM configuration states that the VM should join one or more TVDs, then the Compartment Manager interacts with the corresponding TVD proxy and invokes TPM functions to attest the state of the VM. The TVD proxy verifies certain properties before allowing the VM to join the TVD. More concretely, the TVD proxy has to ensure that

- the VM fulfills the integrity requirements of the TVD;
- the information flow policies of all TVDs the VM will be a member of will not be violated;
- the VM enforces specific information flow rules between TVDs if such rules are required by the TVD policy, and that
- the underlying platform (e.g., the hypervisor and attached devices) fulfills the security requirements of the TVD.

Platform verification involves matching the security requirements with the platform's capabilities and mechanisms instantiated on top of these capabilities. For example, suppose that data confidentiality is a TVD requirement. Then, if hard disks or network connections are not trusted, additional mechanisms, such as block encryption or VPN (respectively), need to be instantiated to satisfy the requirement.

TVD Join Phase: If the VM and the provided infrastructure fulfill all TVD requirements, a new network stack is created and configured as described in Section 3.2.2. Once the Compartment Manager has started the VM, it sends an attach request to the corresponding TVD vSwitch. Once the VM is connected to the vSwitch, it is a member of the TVD.

Part II

Building Blocks and Future Directions

Chapter 4

Automated Provisioning of Secure Virtual Networks

S. Cabuk, C. Dalton (HPL), H. Ramasamy, M. Schunter (IBM)

4.1 Introduction to Secure Virtual Networking

Virtualization allows the abstraction of the real hardware configuration of a computer system. A particular challenge of virtualization is isolation between potentially distrusting virtual machines and their resources. The machine virtualization alone provides reasonable isolation of computing resources such as memory and CPU between guest domains. However, the network remains to be a shared resource as all traffic from guests eventually pass through a shared network resource (e.g., a physical switch) and end up on the shared physical medium. Today's VMM virtual networking implementations provide simple mechanisms to bridge all VM traffic through the actual physical network card of the physical machine. This level of isolation can be sufficient for individual and small enterprise purposes. However, a large-scale infrastructure (e.g., a virtualized data center) that hosts services belonging to multiple customers require further guarantees on customer separation, e.g., to avoid accidental or malicious data leakage.

Outline Our focus is on security-enhanced network virtualization, which (1) allows groups of related VMs running on separate physical machines to be connected together as though they were on their own separate network fabric, and (2) enforces cross-group security requirements such as isolation, authentication, confidentiality, integrity, and information flow control. The goal is to group related VMs (e.g., VMs belonging to the same customer in a data center) distributed across several physical machines into *virtual enclave networks*, so that each group of VMs has the same protection as if the VMs were hosted on a separate physical LAN. Our solution for achieving this goal also takes advantage (whenever possible) of the

fact that some VMs in a group may be co-hosted on the same hardware; it is not necessary to involve the physical network during information flow between two such VMs.

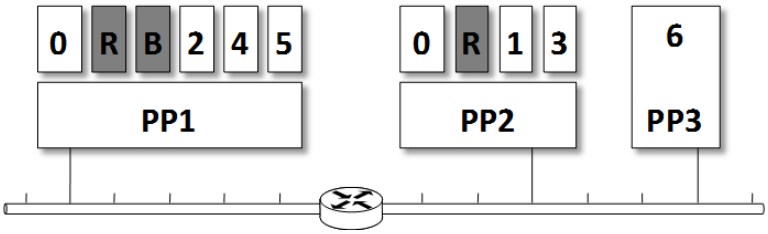
The concept of Trusted Virtual Domains or TVDs was put forth by Bussani et al. [BGJ+05] to provide quantifiable security and operational management for business and IT services, and to simplify overall containment and trust management in large distributed systems. Informally speaking, TVDs can be thought of as security-enhanced variants of virtualized network zones, in which specified security policies can be automatically enforced. We describe the first practical realization of TVDs using a secure network virtualization framework that guarantees reliable isolation and flow control requirements between TVD boundaries. The requirements are specified by TVD policies, which are enforced dynamically despite changing TVD membership, policies, and properties of the member VMs. The framework is based on existing and well-established network virtualization technologies such as Ethernet encapsulation, VLAN tagging, virtual private networks (VPNs), and network access control (NAC) for configuration validation.

Our main contributions are (1) combining standard network virtualization technologies to realize TVDs, and (2) orchestrating them through a management framework that is oriented towards automation. In particular, our solution aims at automatically instantiating and deploying the appropriate security mechanisms and network virtualization technologies based on an input security model, which specifies the required level of isolation and permitted network flows.

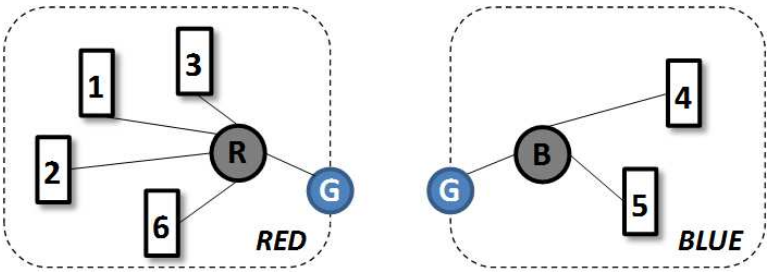
The remainder of the chapter is organized as follows. In Section 4.2, we provide an overview of our security objectives and describe the high-level framework to achieve the objectives. We introduce the networking components required for our framework in Section 4.3 and describe how they can be orchestrated to enforce TVD policies. In Section 4.4, we present the TVD security model and the components constituting the TVD infrastructure. In Section 4.5, we cover the dynamic aspects of TVD deployment including TVD establishment, population, and admission control. In Section 4.6, we describe a Xen-based prototype implementation of our secure virtual networking framework and report our performance results in Section 4.7. Finally, we conclude and discuss future extensions in Section 4.8.

4.2 Design Overview

At a high level, our secure network virtualization framework consists of a *networking infrastructure* and a *TVD infrastructure*. The networking infrastructure enables the mapping from physical to logical network topologies that we use to separate customer networks. The TVD infrastructure configures the network devices and instantiates the appropriate set of mechanisms to realize the TVD security objectives. Figure 4.1 illustrates an example mapping. Figure 4.1(a) shows the actual layout of the physical infrastructure that includes virtualized and non-virtualized platforms and networking devices. Figure 4.1(b) shows the logical layout as seen



(a) Physical view.



(b) Logical view.

Figure 4.1: An example TVD-based virtual network mapping. R and B provide switching for *red* and *blue* TVDs, respectively. G is a virtual gateway that controls inter-TVD communication (not shown in (a) for clarity).

by each TVD owner (i.e., red and blue). In this section, we provide an overview of the mechanisms that enable this mapping while enforcing TVD policies within and across domains.

4.2.1 High-level Objectives

We are specifically interested in virtualized data centers that host multiple customers with potentially conflicting interests. In this setting, the TVD-based networking framework has the following functional and security objectives:

Virtual Networking The framework should support arbitrary logical network topologies that involve virtualized and non-virtualized platforms alike.

Customer Separation The framework should provide sufficient isolation guarantees to customers, i.e., information leakage should be minimized between customer domains[1].

Unified Policy Enforcement The framework should enforce domain policies within and across domains in a seamless manner. The policies define integrity, confidentiality, and isolation requirements for each domain, and information flow control requirements between any two domains.

[1] In this chapter, we do not address indirect communication channels (e.g., covert channels).

Autonomous Management The framework should deploy and maintain customer TVDs in an automated manner, and provide customers the tools to manage their TVDs with no direct or side effect on other customer TVDs.

4.2.2 Overview of Networking Infrastructure

Virtual network extensions enable groups of related VMs running on separate physical machines to be connected together as though they were on their own separate network fabric. This allows the creation of arbitrary virtual LAN (VLAN) topologies independent of the particular underlying physical network topology. It also provides a level of isolation between VLAN segments.

A virtual network is comprised of virtual and physical network entities. The central VLAN component is a virtual switch. There is a single virtual switch per VLAN segment. A VM appears on a particular VLAN segment if one of its virtual network interface cards (Venice) is "plugged" into one of the switch ports on the virtual switch forming that segment. The virtual switch behaves like a normal physical switch and coordinates traffic to and from member VMs. Figure 4.1(b) shows two virtual switches R and B that coordinate the traffic for *red* and *blue* segments. In the foregoing arrangement, each virtual switch resides in a small VM of its own as shown in Figure 4.1(a). Additional VPN and NAC modules can be employed to strengthen security properties on untrusted communication lines and to authenticate VMs prior to VLAN admission, respectively.

4.2.3 Overview of TVD Infrastructure

A TVD is represented by a set of distributed virtual processing elements (VPE) (e.g., virtual machines and virtual switches) and a communication medium interconnecting the VPEs. The TVD provides a policy and containment boundary around those VPEs. At a high level, the TVD policy has three aspects: (1) membership requirements for the TVD, (2) interaction among VPEs of that TVD, and (3) interaction of the TVD with other TVDs and the outside world. VPEs within each TVD can usually communicate freely and securely with each other. At the same time, they are sufficiently isolated from outside VPEs, including those belonging to other TVDs. From a networking perspective, isolation loosely refers to the requirement that a dishonest VPE in one TVD cannot send messages to a dishonest VPE in another TVD, unless the inter-TVD policies explicitly allow such an information flow.

Each TVD has an associated *infrastructure* whose purpose is to provide a unified level of security to member VPEs, while restricting the interaction with VPEs outside the TVD to pre-specified, well-defined means only. Unified security within a domain is obtained by defining and enforcing *membership and communication requirements* that the VPEs and networks have to satisfy before being admitted to the TVD and for retaining the membership. Unified security across domains is obtained by defining and enforcing *flow requirements* that the VPEs have to sat-

isfy to be able to interact with VPEs in other TVDs. To do so, each TVD defines rules regarding in-bound and out-bound network traffic. Their purpose is to restrict communication with the outside world.

The central element in the TVD infrastructure is the TVD master which keeps track of high-level TVD policies and secrets. TVD masters maintain control over member VPEs using TVD proxies. There is a single TVD master per TVD and a single TVD proxy per physical platform. A VPE appears on a particular TVD if it complies with the membership requirements enforced by the TVD proxy controlling that domain on that physical platform. VPEs communicate freely within a TVD. Communication across TVDs is controlled by entities configured by TVD proxies.

4.2.4 Overview of TVD-based Virtual Networking

Virtual networking and TVD infrastructures play complementary roles in meeting the objectives listed earlier. In essence, the VNET infrastructure provides the tools and mechanisms to enable secure virtual networking in a data center. The TVD infrastructure defines unified domain policies, and automatically configures and manages these mechanisms inline with the policy. It also provides customers the necessary tools to manage their TVDs. Any action by the customer is then seamlessly reflected on the underlying networking infrastructure. This two-layer architecture has many advantages:

1. The policy (TVD) and enforcement (VNET) layers are clearly separated from each other, which yields a modular framework. As a result, other technologies (e.g., VNET) can be easily deployed in place of the current offering.

2. The policy layer is not restricted to network-type policies. Thus, same policies can be used to configure and manage, for example, mechanisms to enforce storage isolation.

3. The policy layer provides a high-level abstraction to customers so that they can manage their TVDs without worrying about the specifics of the underlying enforcement mechanisms.

4. Automated deployment, configuration, and management of customer TVDs are desirable capabilities in a virtualized data center that can effectively reduce operational costs and leverage virtualization to the fullest extent.

4.3 Networking Infrastructure

In this section, we present the network virtualization layer that enables the creation of arbitrary virtual topologies on top of the underlying physical network. This layer also provides the basic mechanisms to help enforce TVD admission and flow policies at a higher level.

4.3.1 Aims and Security Requirements

The main aim of our network virtualization extensions is to allow groups of related VMs running on separate physical machines to be connected together as though they were on their own separate network fabric. In particular, we would like to create arbitrary virtual network topologies independently of the underlying physical network topology. For example, a group of related VMs may have to be connected directly together on the same VLAN segment even though, in reality, they may be at opposite ends of a WAN link separated by many physical LAN segments. Further, multiple segmented virtual networks may have to be established on a single physical network segment to achieve improved security properties such as network isolation. Our network virtualization extensions are required to inter-operate with existing non-virtualized entities (e.g., standard client machines on the Internet) and allow our virtual networks to connect to real networks.

Virtual networking extensions must also adhere to security requirements such as isolation and confidentiality. In particular, our extensions must isolate the virtual resources used by different VLAN segments as well as the traffic generated by each. Network connections can be established between VMs that belong to the same VLAN segment and VMs that belong to different VLAN segments (i.e., TVDs). These connections must be secured to meet the security requirements whenever they are established over untrusted physical infrastructures. Additionally, all entities (virtual or physical) that seek membership to a network segment must be properly authenticated prior to being admitted to the network.

4.3.2 Network Virtualization

One option for virtual networking is to virtualize at the IP level. However, to avoid problems regarding the support for non-IP protocols and IP support services (such as ARP) that sit directly on top of the Ethernet protocol, we have chosen to virtualize at the Ethernet level.

Our network virtualization extensions allow multiple VMs belonging to different VLAN segments to be securely hosted on one or more physical machine. The framework provides isolation among various segments using a combination of VLANs and virtual private networks (VPNs). Each VLAN segment is an Ethernet broadcast domain and there is one *internal* VLAN for each security domain (i.e., TVD)[2]. An *external* VLAN may be used for communication with other TVDs and TVD-external entities. In the absence of a trusted physical network, each VLAN segment can employ an optional VPN layer to provide authentication, integrity, and confidentiality.

The virtual networking framework is comprised of a mixture of physical and virtual networking components. Physical components include physical hosts and standard physical networking devices such as VLAN-enabled switches and routers. Virtual entities include VMs, vNICs, virtual switches, virtual routers, and virtual

[2] In this chapter, we use both *VLAN segment* and *TVD* to denote a security domain.

gateways. Each VM has a number of vNICs where each can be associated with at most one VLAN segment. Each VLAN segment is represented by a virtual switch or a *vSwitch*. A VM appears on a particular VLAN if one of its vNICs is "plugged" into one of the switch ports on the vSwitch forming that segment. The vSwitch behaves like a normal physical switch. Ethernet broadcast traffic generated by a VM connected to the vSwitch is passed to all VMs connected to that vSwitch. Like a real switch, the vSwitch also builds up a forwarding table based on observed traffic so that non-broadcast Ethernet traffic can be delivered in a point-to-point fashion to improve bandwidth efficiency.

The vSwitch is designed to operate in a distributed fashion. The VMM on each physical machine hosting a VM connected to a particular VLAN segment hosts part of the vSwitch forming that VLAN segment. A component of the VMM captures the Ethernet frames coming out of a VM's vNIC. This component is configured to know which vSwitch the VM is supposed to be connected to. We describe the vSwitch implementation in detail in Section 4.6.

To enable network virtualization, VM Ethernet frames can be encapsulated in IP packets or tagged with VLAN identifiers using EtherIP [IET02] and IEEE 802.1Q standards [IEE98], respectively. Virtual switches employ both schemes to encapsulate or tag each outgoing packet to insert the corresponding VLAN identifier. The choice of which scheme depends on the destination host plus the configuration dictated by the higher-level TVD management layer. The actual encapsulation or tagging of the packet is done by an EtherIP or a VLAN tagging module on request by the vSwitch.

4.3.3 Virtual Switch and EtherIP

EtherIP is a standard protocol for tunneling Ethernet and 802.3 packets via IP datagrams and can be employed to expand a LAN over a Wide or Metropolitan Area Network [IET02]. We employ EtherIP encapsulation as the standard mechanism to insert VLAN membership information into Ethernet/802.3 frames. To do so, each tunnel endpoint uses a special network device provided by the operating system that encapsulates outgoing Ethernet/802.3 packets in new IP packets. We insert VLAN membership information (i.e., the VLAN identifier) into the EtherIP header of each encapsulated packet. The encapsulated packets are then transmitted to the other side of the tunnel where the embedded Ethernet/802.3 packets are extracted and transmitted to the destination host that belongs to the same VLAN segment.

Address Mapping

The virtual switch component on a VMM maps the Ethernet address of the encapsulated Ethernet frame to an appropriate IP address. This way, the encapsulated Ethernet frame can be transmitted over the underlying physical network to physical machines hosting other VMs connected to the same LAN segment that would have seen that Ethernet traffic had the VMs actually been on a real LAN together.

The IP address chosen to route the encapsulated Ethernet frames over the underlying physical network depends upon whether the encapsulated Ethernet frame is an Ethernet broadcast frame or not and also whether the virtual switch has built up a table of the locations of the physical machines hosting other VMs on a particular LAN segment based on observing traffic on that LAN.

IP packets encapsulating broadcast Ethernet frames are given a multicast IP address and sent out over the physical network. Each virtual LAN segment has an IP multicast address associated with it. All the physical machines hosting VMs on a particular virtual LAN segment are members of the multicast group for that virtual LAN segment. This mechanism ensures that all VMs on a particular virtual LAN segment receive all broadcast Ethernet frames from other VMs on that segment. Encapsulated Ethernet frames that contain a directed Ethernet address destination are either flooded to all the VMs on a particular LAN segment (using the IP multicast address as in the broadcast case) or sent to a specific physical machine IP address. This depends upon whether the virtual switch component on the encapsulating VM has learned the location of the physical machine hosting the VM with the given Ethernet destination address based on traffic observation through the virtual switch.

Requirements Revisited

EtherIP can be used over arbitrary Layer 3 networks. The decision to encapsulate Ethernet frames from VMs within IP packets allow us to connect different VMs to the same virtual LAN segment as long as the physical machines hosting those VMs have some form of IP based connectivity between them, even a WAN link. There are no restrictions on the topology of that physical network.

To allow routing within virtual networks, a router within a virtual network is provided by the use of a virtual machine with multiple virtual network interface cards. The interface cards are plugged into ports on the different virtual switches that it is required to route between. Standard routing software is then configured and run on the virtual machine to provide the desired routing services between the connected LAN segments.

To allow for communication with systems that live in the non-virtualized world, we provide a virtual gateway that simply is a virtual machine with two vNICs. One of the cards is plugged into a port on a virtual switch. The other virtual network card is bridged directly on to the physical network. The gateway has two main roles: (1) It advertises routing information about the virtual network behind it so that hosts in the non-virtualized world can locate the virtual machines residing on a virtual network, and (2) it converts packets to and from the encapsulated format required of our virtual networks.

4.3.4 Virtual Switch and VLAN Tagging

VLAN tagging is a well-established network virtualization standard that provides isolation of VLAN segments on physical network equipment [IEE98]. We employ VLAN tagging as an alternative to Ethernet encapsulation for efficiency purposes. For example, in a virtualized datacenter a VLAN-enabled switch may be used that yield increased performance over EtherIP encapsulation.

Each VLAN segment employs its own VLAN tagging module to tag its Ethernet frames. This module resides within the host OS or privileged domain that facilitates the networking capabilities, captures packets coming from VMs and tags those with the ID of the VM's VLAN before sending them onto the physical wire. On the receiving side, the module removes the VLAN tag and passes the packets untagged into the destination VM(s). Packets are only tagged when the have to be transmitted over the physical network. VMs are unaware of the VLAN tagging and send/receive packets without any VLAN information.

To handle VLAN tagged packets, the physical network equipment needs to support IEEE 802.1Q and be configured accordingly. As an example, if a machine hosts a VM that is part of VLAN 42, then the switch port that is used by that machine needs to be assigned to that specific VLAN 42. Of course, a machine might host multiple VMs which can be on different VLANs, and therefore a switch port might be assigned to multiple VLANs (which creates a `VLAN trunk` between the host and the switch port). Whenever a host deploys a new VM or removes a VM, the switch port might need to be reconfigured. Ideally, this can be done in a dynamic and automated fashion, e.g., through network management protocols. As the physical switches only pass packets between machines within the same VLAN, those provide an additional isolation mechanism to our VLAN-capable virtual switch that is deployed on all of the hosts.

Address Mapping

VLAN tagging does not require any extra address mapping mechanism. VMs discover address information of other VMs using standard discovery protocols as in a non-virtualized environments. However, the virtual switch module that runs on each physical machine learns Ethernet addresses attached to the virtual switch ports by inspecting packets (in the same way as physical switches do) and builds up lookup tables (one table per virtual switch / VLAN) that store information about the location of VMs based on their Ethernet addresses. The virtual switch uses this table to decide if a packet has to be passed to a local VM or onto the physical network to be delivered to a remote machine.

There is no explicit mapping of broadcast / multicast addresses as in the case of EtherIP encapsulation. Instead, physical switches that manage the underlying network infrastructure ensure that broadcast and multicast traffic never crosses VLAN boundaries. Broadcast and multicast packets that are tagged with a VLAN ID are passed to all switch ports that are associated with that particular VLAN, but no

other ports. When those packets enter the physical machine that runs our virtual switch module, the packets are only passed into VMs that are attached to virtual switch ports that are assigned to the VLAN matching the ID in the packets.

Requirements Revisited

VLAN tagging can be used over arbitrary Layer 3 networks. However, unlike EtherIP, a solution based on pure VLAN tagging is limited to a LAN environment and cannot be deployed over WAN links. VLAN tagging highly depends on support from the physical network equipment that is managing the underlying infrastructure. E.g., switches need to support the VLAN tagging standard that we use when tagging our packets in our virtual switch module (IEEE 802.1Q) and need to be configured to handle tagged packets in order to provide appropriate isolation between VLANs.

A VLAN is a logical network segment and by default network traffic such as broadcast messages or ARP communication is limited to a single VLAN. However, it is also possible to allow communication between (virtual) machines of different VLANs through `Inter-VLAN routing`. There are multiple well-known and standardized solutions to allow this. For example, most of today's network switches facilitate fast Layer 3 routing between multiple VLANs. This solution offers high performance, but requires that routing policies can be configured on the physical network devices – ideally in an automated fashion. As an alternative, we can also deploy specific VMs that have multiple network interfaces in multiple VLANs and route packets between those – as in the EtherIP encapsulation approach.

VLAN tagging inherently supports communciation with non-virtualized systems. This is because VLAN tagging is a widely used standard that is deployed within infrastructures where physical machines do not run any (network) virtualization software. There is no need for a gateway VM as in the EtherIP case. Instead, physical switches can be configured to remove VLAN tags from packets when transmitting on a port where the connected endpoint is not VLAN-capable, and add tags whenever packets are received on that specific port. In that case those endpoints are completely unaware of VLANs, and receive and transmit packets without any VLAN information.

4.3.5 Virtual Switch and Secure Networking

In addition to EtherIP and VLAN tagging modules, virtual switches employ a network access module for admission control and an optional VPN module for packet tunneling. Network access control or NAC is an IEEE 802.1X standard for port-based access control [IEE04]. NAC can be implemented by various network devices which in turn force a host (supplicant) go through an authentication process prior to using services provided by the device (e.g., being admitted to the network). All network traffic originating from the supplicant is blocked prior to admission ex-

cept the NAC traffic itself. NAC requests are received by an access point (authenticator) and forwarded to an authentication server (AS) (e.g., a RADIUS server). The AS runs a choice of authentication protocol specified by the extensible authentication protocol (EAP). It returns the verdict to the authenticator with respect to which access is granted to the supplicant or denied. The NAC module is incorporated into the vSwitch admission process during which the requesting VM is authenticated prior to TVD admission. The choice of which authentication method depends is dictated by the high-level TVD policies.

Encapsulation and tagging alone do not provide any guarantees on the confidentiality and integrity of the packets / frames that are transmitted on the wire. Without a proper VPN layer, these schemes are only suitable for routed and controlled networks in which the underlying physical infrastructure is trusted, e.g., a virtualized data center. In cases no such guarantees can be given (e.g., a WAN link), we employ an implementation of IPSec [KS05] to tunnel VLAN communication in a confidential and an integrity-preserving way. To do so, the VPN module employs the Encapsulating Security Payload (ESP) of IPSec that encapsulates IP packets and applies block encryption to provide confidentiality and integrity. This adds an additional layer of packet encapsulation on top of EtherIP. The optional VPN module is incorporated into the virtual switch. We provide further details on NAC and VPN implementations in Section 4.6.

4.3.6 Composition of Secure Virtual Networks

Figure 3.3 on Page 23 illustrates how the networking components can be composed into a secure networking infrastructure that provides isolation among different TVDs, where each TVD is represented by a different color (red (solid), green (dashed), or blue (double) line). A non-virtualized physical host, such as Host-3, is directly connected to a VLAN-enabled physical switch without employing a vSwitch. Further, a VM can be connected to multiple VLAN segments using a different vNIC for each VLAN segment; hence, the VM can be a member of multiple TVDs simultaneously. For example, the lone VM in Host-2 of Figure 3.3 is part of two VLAN segments, each represented by a vSwitch with a different color; hence, the VM is a member of both the blue and green TVDs.

Abstractly speaking, it is as if our secure virtual networking framework provides colored networks (in which a different color means a different TVD) with security guarantees (such as confidentiality, integrity, and isolation) to higher layers of the virtual infrastructure. Internally, the framework provides the security guarantees through admission control and the appropriate composition and configuration of VLANs, VPNs, gateways, routers, and other networking elements.

Ethernet frames originating from the source node are handled differently depending on whether the source node is virtualized and whether the destination node resides in the same LAN. We illustrate frame-processing alternatives for different scenarios in Figure 3.3 on Page 23. For a virtualized domain (e.g., Host-1), each frame is tagged using the VLAN tagging module. If the destination of the Ether-

net frame is a VM on another host that is connected to the same VLAN-capable switch (e.g., another physical domain in a datacenter), this tag indicates the VLAN segment to which the VM belongs. If the destination is a host that resides outside the LAN domain (e.g., Host-4), the VLAN tag forces the switch to bridge the connection to an outgoing WAN line (indicated by the black (thick) line in the VLAN-enabled physical switch of Figure 3.3) that is connected to a router for further packet routing. In this case, the VM Ethernet frames are encapsulated in IP packets to indicate the VLAN segment membership. Lastly, if a non-virtualized physical host is directly connected to the VLAN switch (e.g., Host-3), no tagging is required for the outgoing connection from the host's domain. We provide more details on each processing step in Section 4.6, where we describe our Xen-based prototype implementation.

4.4 TVD Infrastructure

4.4.1 Security Objectives and Policies

Security within a TVD Within a TVD, all VPEs can freely communicate with each other while observing TVD-specific integrity and confidentiality requirements. For this purpose, intra-TVD communication may take place only over an authenticated and encrypted channel (e.g., using IPsec), or alternatively, a trusted network[3]. The trusted network alternative may be reasonable in some situations, e.g., within a data center.

TVD security requirements may have multiple facets: internal protection, membership requirements, etc. Given a set T of trusted virtual domains, one way of formalizing internal protection is to define a domain-protection function $P : T \rightarrow 2^{\{c,i,s\}}$, which describes the subset of security objectives (confidentiality, integrity protection, and isolation) assigned to a particular TVD. Informally, integrity means that a VPE cannot inject "bad" messages and pretend they are from another VPE. Confidentiality refers to the requirement that two honest VPEs (in the same TVD or different TVDs) can communicate with each other without an eavesdropper learning the content of the communication. Lastly, isolation refers to the requirement that resources used by two VPEs are logically separated and there is no unintended direct information flow[4].

Admission control and membership management are important aspects of TVDs. A TVD should be able to restrict its membership to machines that satisfy a given set of conditions. For example, a TVD may require certificates stating that the platform will satisfy certain properties [SS05] before allowing the platform to join the TVD. One way of formalizing the membership requirements is to define

[3] A network is called *trusted* with respect to a TVD security objective if it is trusted to enforce the given objective transparently. For example, a server-internal Ethernet can often be assumed to provide confidentiality without any need for encryption.

[4] Addressing covert channels that utilise indirect information flow would exceed the scope of this report.

Table 4.1: Example TVD Policy Specification for Three TVDs

Flow Control				Co-Location	Multi-TVD
from/to	TVD_α	TVD_β	TVD_γ		
TVD_α	$\mathbf{1}^*$	$\mathbf{0}^*$	$P_{\alpha\gamma}$	TVD_β	TVD_γ
TVD_β	$\mathbf{0}^*$	$\mathbf{1}^*$	$\mathbf{0}$	TVD_α	**none**
TVD_γ	$P_{\gamma\alpha}$	$P_{\gamma\beta}$	$\mathbf{1}$	**all**	TVD_α

a function $M : T \rightarrow 2^P$, where $(P, \leq)$ is a lattice of security properties. A machine m with a set p_m of security properties may be permitted to join the TVD t iff $\forall p \in M(t) : \exists p' \in p_m$ such that $p' \geq p$. In other words, m is permitted to join t iff there is at least one property of m that satisfies each security requirement of t.

Member VPEs may be required to prove their eligibility on a continual basis either periodically or on-demand. For example, members may be required to possess certain credentials such as certificates or may be required to prove that they satisfy some integrity properties (property-based attestation [SS05]). The conditions may vary for different types of VPEs. For example, servers and workstations may have different TVD membership requirements. Some VPEs may be part of more than one TVDs, in which case they would have to satisfy the membership requirements of all the TVDs they are part of. For a VPE to simultaneously be a member of multiple TVDs, the individual TVD membership requirements must be conflict-free.

Security across TVDs Inter-TVD security objectives are independently enforced by each of the individual TVDs involved. To facilitate such independent enforcement, global security objectives are decomposed into per-TVD security policies. The advantage of such a decentralized enforcement approach is that each TVD is shielded from security failures in other TVDs. Security objectives may take different forms; here, we focus on information flow control among the TVDs, multi-TVD memberships, and co-hosting restrictions.

An information flow control matrix is a simple way of formalizing the system-wide flow control objectives. Figure 4.1 shows a sample matrix for three TVDs: TVD_α, TVD_β, and TVD_γ. Each matrix element represents a policy specifying both permitted inbound and outbound flows between a pair of TVDs, as enforced by one of the TVDs. The **1** elements along the matrix diagonal convey the fact that there is free information flow within each TVD. The **0** elements in the matrix are used to specify that there should be no information flow between two TVDs, e.g., between TVD_α and TVD_β.

Information flow control from one TVD to another is specified by two policies, with each TVD independently enforcing one. For example, $P_{\alpha\beta}$, which represents the information flow policy from TVD_α to TVD_β, would consist of two sub-policies: (1) $P^{\text{in}}_{\alpha\beta}$, which would be enforced by the recipient TVD, TVD_β, and is concerned with the integrity protection of TVD_β, and (2) $P^{\text{out}}_{\alpha\beta}$, which would

be enforced by the sender TVD, TVD_α, and is concerned with the confidentiality protection of TVD_α. The distribution of policy enforcement to both TVDs means that the recipient TVD does not have to rely solely on elements of the sender TVD to enforce rules regarding its inbound traffic.

Care must be taken to ensure that the pair-wise TVD policies specified in the information flow control matrix do not accidentally contradict each other or allow undesired indirect flow. E.g., if $P_{\alpha\beta} = \mathbf{0}$ in Figure 4.1, then $P_{\alpha\gamma}$ and $P_{\gamma\beta}$ should not be inadvertedly $\mathbf{1}$. Otherwise, indirect information flow from TVD_α to TVD_β would be unconstrained, which would contradict with $P_{\alpha\beta}$.

Part of the TVD policy is the *co-location policy*, which specifies which TVD VPEs are allowed to share the same physical platform. There may be three types of co-location policies: **none**, **specific**, or **all**. In the first type (i.e., **none**), a VPE belonging to the TVD cannot be co-located on a platform hosting VPEs belonging to other TVDs, e.g., a top secret TVD in a MLS military infrastructure. In the second case (i.e., **specific**), the policy specifies a set of *allowed TVDs*. A VPE generally cannot be co-located on a platform hosting VPEs belonging to other TVDs, unless the only TVDs on the platform are those in the allowed set. For example, the policies in Figure 4.1 specify that the allowed set for TVD_α includes TVD_β, and vice versa; hence, VPEs belonging to TVD_α and TVD_β can be co-located. In the third type (i.e., **all**), there are no co-location restrictions; a VPE belonging to a TVD can be co-located with VPEs of any other TVD.

The TVD policy also includes *multi-TVD membership policy*, which specifies whether a VPE can hold multiple TVD memberships simultaneously. Like co-location policies, there may be three types of multi-TVD membership policies: **none**, **specific**, or **all**. In the first type (i.e., **none**), a VPE belonging to the TVD cannot simultaneously be a member of any other TVD, e.g., TVD_α and TVD_β in Figure 4.1. In the second type (i.e., **specific**), the policy specifies a set of *allowed TVDs*. A VPE belonging to the TVD generally cannot simultaneously be a member of any other TVD, except for TVDs in the allowed set. In the third type (i.e. **all**), a VPE belonging to the TVD can simultaneously be a member of any other TVD.

At the time of TVD policy specification, it is important to ensure that there is no conflict between the various policy forms, e.g., if the information flow control policy specifies that there should be no information flow between TVD_α and TVD_β, then the multi-TVD membership restrictions cannot allow any VM to simultaneously be a member of TVD_α and TVD_β.

4.4.2 TVD Components

In this section, we present the components of the TVD infrastructure, the composition of the components to form TVDs and to enforce TVD policies, and describe the management of the TVD infrastructure. Here, we focus on the static behavior of a secure network virtualization framework that is already up and running. Later, in Section 4.5, we focus on the more dynamic aspects of the framework, including establishment and deployment of the secure virtual infrastructure.

TVD networking master The TVD networking master (short TVD master) plays a central role in the management and auto-deployment of TVDs. There is one TVD master per TVD. We refer to the TVD master as a single logical entity, although its implementation may be a distributed one. The TVD master is trusted by the rest of the TVD infrastructure and the VPEs that are members of the TVD. Known techniques based on Trusted Computing [Tru03] can be used to determine the trustworthiness of the TVD master by verifying its software configuration. The TVD master can hosted on a physical machine or a virtual machine. In the case of a VM implementation, the PEV architecture proposed by Jansen et al. [JRS07] can be used to obtain policy enforcement and compliance proofs for the purpose of assessing the TVD master's trustworthiness.

The TVD policy is defined at the TVD master by the system administrator (e.g., the administrator of a data center hosting multiple TVDs, each belonging to a different customer). The TVD master has the following main responsibilities:

1. distributing the TVD policy and other TVD credentials (such as VPN key) to the TVD proxies and informing them of any updates,

2. determining the suitability of a platform to host a TVD proxy (described below), and thereafter, periodically assessing the platform's continued suitability to host VPEs belonging to the TVD.

3. maintaining an up-to-date view of the TVD membership, which includes a list of TVD proxies and the VPEs hosted on their respective platforms.

TVD networking proxy On every host that may potentially host a VM belonging to the TVD, there is a local delegate of the TVD master, called the *TVD networking proxy* (short TVD proxy). Like the TVD master, the TVD proxy is also trusted. The TVD proxy is the local enforcer of the TVD policies on a given physical platform. At the time of its creation, the TVD proxy receives the TVD policy from the TVD master. Upon an update to the TVD policy (by a system administrator), renewal of TVD credentials, or refresh of TVD VPN keys at the TVD master, the master conveys the update to the TVD proxies.

The TVD proxies on a given platform are independent. Although TVD proxies are trusted, TVD proxies on the same platform should be sufficiently isolated from each other. For example, a TVD proxy should not be able to access private TVD information (such as policies, certificates, and VPN keys) belonging to another TVD proxy. For improved isolation, each TVD proxy on the platform may be hosted in a separate *infrastructure* VM, which is different from a VM hosting regular services, called *production* VM. On a platform with the Trusted Platform Module or TPM [Tru03], isolation can further be improved by TPM virtualization [BCG+06], assigning a separate virtual TPM to each infrastructure VM, and using the virtual TPM as the basis for storing private TVD information.

A TVD proxy must only be able to interact with VMs hosted on the platform belonging to the same TVD. As we describe below, that requirement is enforced by the LCTC.

The main responsibilities of the TVD proxy are:

Configuration of the Local TVD vSwitch The TVD proxy configures the local TVD vSwitch based on TVD policy. For example, if the TVD policy specifies that information confidentiality is an objective, then the TVD proxy enables all traffic through the vSwitch to pass through the VPN module and provides the VPN key to the module.

Maintenance of Private TVD Information The TVD proxy maintains private TVD information such as policies, certificates, and VPN keys.

Status Reports to the TVD Master Upon request or periodically, the TVD proxy provides a platform status report to the TVD master. The report includes information such as the number of VMs belonging to the TVD and their unique addressable identifiers and the current vSwitch configuration. The status report also serves as an "I am alive" message to the TVD master, and helps the TVD master to keep an updated list of TVD proxies that are connected to it.

Enforcement of Admission Requirements for VMs into the TVD A VM's virtual NIC is attached to a vSwitch only after the TVD proxy checks that the VM satisfies TVD membership requirements.

Enforcement of Co-Location Restrictions The LCTC checks with each TVD proxy already existing on the platform for co-location compatibility before instantiating a new TVD proxy.

Enforcement of Multi-TVD Membership Restrictions A VM may belong to multiple TVDs simultaneously. However, approval from TVD proxies corresponding to the TVDs in which the VM holds membership is needed before the VM can join a new TVD.

Continuous Enforcement of TVD Policy The TVD proxy is responsible for continuous enforcement of TVD policy despite updates to the policy and changing configuration of the platform and member VMs. Upon receiving an update to the TVD policy from the TVD master, the TVD proxy may reconfigure the vSwitch, and re-assess member VMs' membership to reflect the updated policy. Even without any policy update, the TVD proxy may be required by TVD policy to periodically do such re-configuration and reassessment.

Local Common TVD Coordinator (LCTC) The Local Common TVD Coordinator or LCTC is present on every platform (hence, the word *local* in the name)

on which a TVD element has to be hosted. The LCTC itself does not belong to any single TVD (hence, the word *common* in the name). The LCTC is part of the minimal TCB[5] on every TVD-enabled platform.

The LCTC is the entity that a TVD master or a system administrator contacts to create a new TVD proxy on the platform. For this purpose, the LCTC must be made publicly addressable and knowledgeable about the identities of the entities that may potentially request the creation.

The LCTC has three main responsibilities, namely (1) creation of new TVD proxies on the local platform, (2) determining whether a new TVD proxy can be co-hosted along with TVD proxies already existing on the platform, and (3) restricting access of TVD proxies only to VMs belonging to their respective TVDs. The LCTC maintains a list of VMs currently hosted on the platform, a list of TVD proxies currently hosted on the platform, and a mapping between the VMs and the TVDs they belong to.

The actual creation of the TVD proxy is preceded by a *prepare phase*, which involves

1. Mutual authentication and authorization between the LCTC and the entity (e.g., the TVD master or system administrator) requesting the creation of the TVD proxy,

2. Determining the suitability of the platform for hosting the new TVD proxy, from the point of view of both the requesting TVD master and the TVDs already hosted on the platform.

The second step above involves determining whether a new TVD proxy can be co-hosted along with TVD proxies already existing on the platform. The LCTC is a thin implementation; it simply asks each TVD proxy whether a new TVD proxy can be co-hosted on the platform. Based on their internal security policies, the individual TVD proxies simply return a “yes” or “no” answer. The LCTC replies positively to the requesting TVD master only if all TVD proxies said “yes”; otherwise, it returns a negative reply to the requesting TVD master. The LCTC includes a list of existing TVD proxies with a positive response. Additionally, if required, the LCTC may include the attestation of the platform characteristics along with a positive response. The prepare phase concludes with the response from the LCTC. Based on the response, the requesting TVD master can determine whether its own policies allow co-hosting with the list of existing TVD proxies on the platform and whether the platform configuration is in accordance with the TVD requirements. If that is the case, then the TVD master sends a request to the LCTC to start the TVD proxy along with its own URL. In this way, the conflict manager helps ensure that a new TVD proxy is hosted on the platform only if it is compatible with the policies of TVDs already hosted on the platform as well as with those of the new TVD.

[5] On a Xen-based platform, the minimal TCB consists of the LCTC, Xen Dom0, the Xen hypervisor, and the underlying hardware.

The LCTC does the actual creation of the TVD proxy, and initializes the proxy with the TVD master's URL. Thereafter, the TVD proxy contacts the TVD master and establishes a direct secure, authenticated communication channel (using standard techniques) with the TVD master bypassing the LCTC. The TVD proxy obtains the TVD policy and other credentials from the TVD master through the channel, and configures the networking components according to TVD policy.

4.4.3 Establishment of the TVD Infrastructure

Overview

When the set of TVDs have been identified, the next step is to actually establish them. The initial step for establishing a TVD is to create the TVD master (step 0 in Figure 4.4) and initialize the master with the TVD requirements (as formalized above) and the policy model. The step involves the derivation of a comprehensive set of TVD policies, which are maintained at the TVD master. The output of the step is a TVD object that contains the TVD's unique identifier, i.e., the TVD master's URL.

Once the TVD master has been initialized, the TVD is ready for being populated with member entities, such as VMs. A VM becomes admitted to a TVD after the successful completion of a multi-step protocol (steps 1 and 2 in Figure 4.4).

1. A local representative of the TVD, called *TVD proxy*, is created by the LCTC and initialized with the URL of the TVD master.

2. The TVD proxy sets up a secure, authenticated channel with the TVD master using standard techniques.

3. The TVD proxy indicates the security and functional capabilities of the physical machine. Using the capability model, the TVD master determines which additional mechanisms must be provided at the level of the virtual infrastructure. For example, if a TVD requirements specification includes isolation and the physical infrastructure does not have that capability, then special (VLAN tagging or VPN) modules must be instantiated within the Dom0 of physical machines hosting VMs that are part of the TVD.

4. The TVD master then replies to the TVD proxy with the TVD security policy (such as flow control policies between VMs belonging to different TVDs hosted on the same physical machine) and additional mechanisms that must be provided at the virtualization level.

5. The TVD proxy then instantiates and configures the required TVD-specific modules (e.g., vSwitch, VLAN tagging module, encapsulation module, VPN module, policy engine, etc.) according to the TVD policy. After this step, the physical machine is ready to host a VM belonging to the TVD.

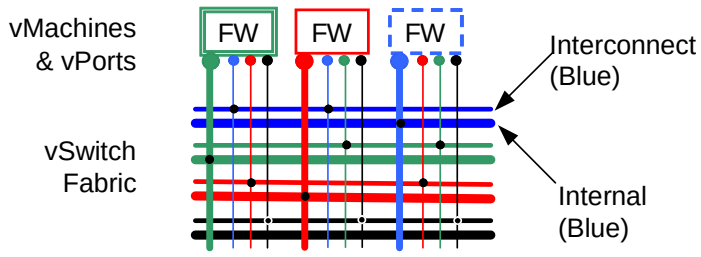


Figure 4.2: Internal- and Inter-connections for each TVD Type.

6. As shown by step 2 in Figure 4.4, a command is issued at the VM to join the TVD (active membership model[6]). This results in the VM contacting the TVD proxy. Based on the TVD security policies, the TVD proxy may carry out an assurance assessment of the VM (e.g., whether the VM has all required software properly configured). Once the required verification of the VM is successful, the TVD proxy may connect the vNICs of the VM to the appropriate TVD vSwitch. At this point, the VM is part of the TVD.

4.5 Auto-deployment of Trusted Virtual Domains)

Figure 4.3 shows the steps involved in automatic deployment of secure virtual infrastructures as TVD configurations. Figure 4.4 shows the steps involved in the establishment and management of a single TVD.

First, the virtual infrastructure topology must be decomposed into constituent TVDs, along with associated security requirements and policy model. Second, a *capability model* of the physical infrastructure must be developed. Capability modeling is essentially the step of taking stock of existing mechanisms that can be directly used to satisfy the TVD security requirements. In this chapter, we consider the case where both steps are done manually in an offline manner; future extensions will focus on automating them and on dynamically changing the capability models based on actual changes to the capabilities.

4.5.1 Capability Modeling of the Physical Infrastructure

Capability modeling of the physical infrastructure considers both functional and security capabilities. The functional capabilities of a host may be modeled using a function $C : H \rightarrow \{VLAN, Ethernet, IP\}$, to describe whether a host has VLAN, Ethernet, or IP support. Modeling of security capabilities includes two

[6] Alternatively, if the passive membership model (Section 4.5.4) is used, the command to join the TVD can be issued by the VM manager component that instantiates the VM.

orthogonal aspects: the set of security properties and the assurance that these properties are actually provided. Table 4.2 lists some examples of security properties and Table 4.3 gives examples of the types of evidence that can be used to support security property claims.

4.5.2 Instantiation of the Right Networking Modules

The TVD proxy uses the instructions given to it by the TVD master to determine the right protection mechanisms to instantiate on the local platform for the TVD network traffic, and accordingly configures the local TVD vSwitch.

Suppose that isolation of TVD traffic is a requirement. Then, VLAN tagging alone would suffice provided the TVD spans only the LAN and the physical switches on the LAN are VLAN-enabled (i.e., it must support IEEE 802.1Q and must be appropriately configured); in that case, a VLAN tagging module would be created and connected to the vSwitch. If the TVD spans beyond a LAN, then VLAN tagging must be used in conjunction with EtherIP encapsulation. In this case, the VLAN tagged packet is encapsulated in a new IP packet and tunneled to the other side, where the original VLAN tagged packet is extracted and transmitted on the VLAN. If VLAN-enabled switches are not available, then EtherIP alone would suffice for isolation.

By itself, EtherIP does not provide integrity or confidentiality of the packets. Hence, when those properties are required, EtherIP is suitable only on routed and trusted networks, e.g., EtherIP would be suitable for traffic between two vSwitches hosted on different physical platforms that are not connected to the same VLAN switch in a datacenter or corporate environment.

If integrity or confidentiality are required properties and the underlying network is not trusted, then IPsec is used in conjunction with EtherIP and VLAN. In that case, the TVD proxy will create the VPN module, initialize it with the VPN key obtained from the master, and connect it to the vSwitch. Since IPsec only operates on IP packets and not Ethernet or VLAN ones, double encapsulation is needed: EtherIP is used to first encapsulate the Ethernet or VLAN packets, followed by IPsec encapsulation and encryption (using the VPN key).

4.5.3 Inter-TVD Management

Separation of flow control and transport. Transport part is based on today's connection between autonomous systems based on BGP. Flow control is based on firewalls. Flow control part figures out whether a packet can get out to the other TVD and what protection mechanism is needed (e.g., encryption). After flow control, border gateway takes care of routing the packet to the border gateway at other end. Contact master for obtaining capability of the other side gateway. Master-master communication for generating shared key for encryption for inter-TVD traffic.

One firewall for each other TVD, or new rules for another new TVD on the same firewall?

Inter-TVD management deals with the *interchange fabric* for communication between TVDs, enforcement of inter-TVD flow control policies, external zones (IP versus Ethernet), approval of admission requests by TVD-external entities (such as a new VM) to join the TVD, and linking such entities with the appropriate TVD master.

Information flow control between TVDs has two aspects: physical topology and policies. Physically, each TVD is implemented by at least two VLANs (Figure 4.2): an external VLAN and an internal VLAN. The external VLAN (shown in Figure 4.2 by thin lines) serves as a backbone to send/receive information to/from other TVDs. It is through the external VLAN that a TVD proxy communicates with the TVD master before becoming a member of the TVD. The internal VLAN (shown in Figure 4.2 by thick lines) connects machines that are part of a TVD. Inter-TVD policies specify conditions under which VLANs belonging to different TVDs are allowed to exchange information. The policies may be conveniently represented by information flow control matrices, such as the one shown in Figure 4.1. For a given TVD, the policies are stored at the TVD master, which then enforces them in a distributed fashion through admission control and appropriate configuration of firewalls and TVD proxies.

Having separate VLANs for TVD-internal and TVD-external communication facilitates unrestricted communication within a TVD and the complete isolation of a TVD from another TVD if the inter-TVD policy specified allows no information flow between the TVDs. Such is the case for TVD_α and TVD_β, according to the flow control matrix shown in Figure 4.1.

A cheaper alternative to the dual VLAN solution would be to rely solely on trusted boundary elements such as firewalls to enforce isolation. The resulting assurance may be somewhat lower than that of the dual VLAN solution, because of the possibility of mis-configuring the boundary elements.

As shown in Figure 4.1, inter-TVD communication can be broadly classified into three types: (1) *controlled* connections, represented by policy entries in the matrix, (2) *open* or unrestricted connections, represented by **1** elements in the matrix, and (3) *closed* connections, represented by **0** elements in the matrix.

Controlled connections restrict the flow between TVDs based on specified policies. The policies are enforced at TVD boundaries (at both TVDs) by appropriately configured firewalls (represented in Figure 4.2 by entities marked FW). The TVD master may push pre-checked configurations (derived from TVD policies) into the firewalls during the establishment of the TVD topology. If available, a management console at the TVD master may be used to manually set up and/or alter the configurations of the firewalls. A TVD firewall has multiple virtual network interface cards, one card for the internal VLAN that the firewall protects and one additional card for each TVD that the members of the protected TVD want to communicate with.

Open connection between two TVDs means that any two machines in either TVD can communicate freely. In such a case, the firewalls at both TVDs would have virtual network cards for the peer domain and simply serve as bridges be-

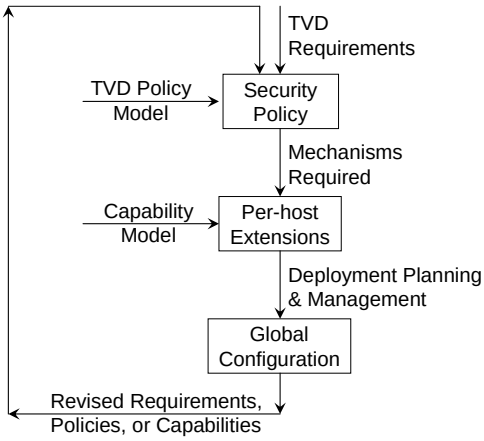


Figure 4.3: Steps in Auto-Deployment of TVDs.

tween the domains. For example, different zones in a given enterprise may form different TVDs, but may communicate freely. As another example, two TVDs may have different membership requirements, but may have an open connection between their elements. Open connection between two domains may be implemented using an unlimited number of virtual routers. In a physical machine that is hosting two VMs belonging to different TVDs with an open connection, the corresponding vSwitches may be directly connected. Communication between two TVDs, while open, may be subject to some constraints and monitoring. For example, a TVD master may permit the creation of only a few virtual routers on certain high-assurance physical machines for information flow between the TVD and another TVD with which the former has an open connection.

A closed connection between two TVDs can be seen as a special case of a controlled connection in which the firewall does not have virtual network card for the peer TVD. In addition to the firewall filtering rules, the absence of the card will prevent any communication with the peer TVD.

Special VMs (e.g., gateways) may have membership in two or more open TVDs simultaneously. Consider a VM that is first a member of TVD α. The VM has one virtual NIC that is connected to the vSwitch of TVD α. Now, suppose that the VM needs to be a member of both TVD α and TVD β simultaneously. For this purpose, the VM needs to have two virtual NICs, one connected to the vSwitch of TVD α and the other connected to that of TVD β. Any VM request to create a new virtual NIC has to be approved by the TVD proxy, which grants the approval only if TVD α is an open TVD and TVD α's policies allow such a dual membership. Initially, the new virtual NIC is connected to the default network, and the VM sends a membership request for TVD β to the local TVD proxy (if present) or a remote TVD master. If TVD β's policies allow for dual membership with TVD

α and the VM satisfies other admission requirements for TVD β, then proxy for TVD β will connect the new virtual NIC to the vSwitch of TVD β. At this point, the VM is connected to the VLANs of both TVDs.

4.5.4 Intra-TVD Management

Intra-TVD management is concerned with TVD membership (including mutual authentication), communication within a TVD, and the network fabric (i.e., internal topology) of a TVD. Prior to membership negotiation, mutual authentication requires both the TVD infrastructure (TVD proxy or the master in the absence of a proxy) and the client (i.e., the prospective member VM) to authenticate itself to each other. For TVD authentication, we employ TVD certificates that are issued and distributed for each TVD. For client authentication, we use the IEEE 802.1X standard for network access control (NAC). The latter employs a port-based authentication scheme and a third-party authenticator (e.g., a RADIUS server) to authenticate the VM. In this setting, the TVD proxy acts as the *authenticator* that forwards the request to the *authentication server* and interprets the result. We describe client authentication in detail in Sections 4.5 and 4.6.

Intra-TVD policies specify the membership requirements for each TVD, i.e., the conditions under which a VM is allowed to join the TVD. At a physical machine hosting the VM, the requirements are enforced by the machine's TVD proxy in collaboration with networking elements (such as vSwitches) based on the policies given to the TVD proxy by the TVD master. We describe TVD admission control in detail in Section 4.5.

A VLAN can be part of at most one TVD. For completeness, each VLAN that is not explicitly part of some TVD is assumed to be a member of a *dummy* TVD, TVD_{Δ}. Although a VLAN that is part of TVD_{Δ} may employ its own protection mechanisms, the TVD itself does not enforce any flow control policy and has open or unrestricted connections with other TVDs. Thus, in the information flow control matrix representation, the entries for policies, $P_{\Delta\alpha}$ and $P_{\alpha\Delta}$, would all be **1** for any TVD_{α}.

A VM that is connected to a particular VLAN segment automatically inherits the segment's TVD membership. The VM gets connected to the VLAN segment only after the TVD proxy on the VM's physical machine has checked whether the VM satisfies the TVD membership requirements. Once it has become a member, the VM can exchange information freely with all other VMs in the same VLAN segment and TVD (intra-TVD communication is typically open or unrestricted). As mentioned before, a VM can be connected to more than one VLAN (and hence, be a member of more than one TVD) through a separate vNIC for each VLAN.

A VM can become a TVD member either in an active or in a passive fashion. In the *passive membership model*, a VM can be (passively) assigned a TVD membership at the time of its creation by specifying in the VM's start-up configuration files which VLAN(s) the VM should be connected to. Alternatively, in the *active membership model*, a VM can actively request TVD membership at a later stage

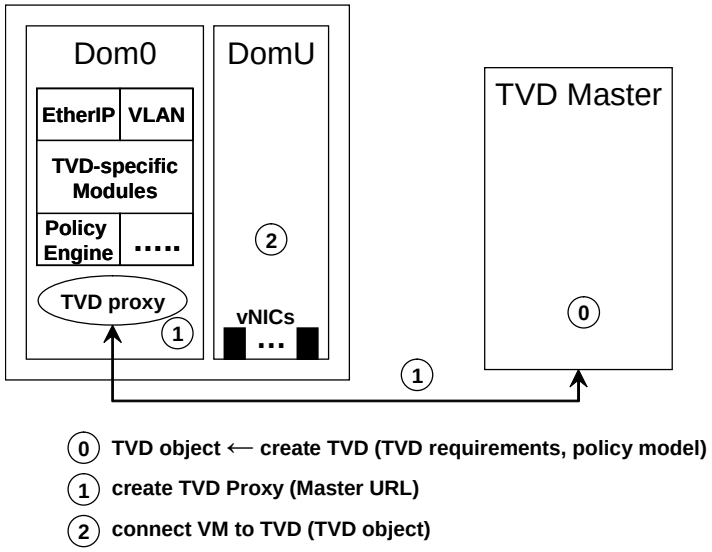


Figure 4.4: Steps in Populating a TVD.

through the corresponding TVD proxy interface or by directly contacting the TVD master if a TVD proxy is not present on the local platform. When a VM is created, it can use its default network connection to communicate with the outside world, particularly the local TVD proxy (if present) or a remote TVD master to request TVD membership. In either case, the IP address of the TVD authority must be made available to the VM.

A *closed TVD* is a special TVD that has closed connections with all other TVDs. For example, in a multi-level secure (MLS) military infrastructure, a top secret military domain would be a good candidate for a closed TVD. A closed TVD is shut off from the outside world, and a VM that does not belong to the TVD is part of that outside world. Hence, the active membership model is not applicable for closed TVDs. The TVD master for closed domains maintains a list of pre-approved platforms and will create TVD proxies only on those platforms. Only the system administrator or the TVD administrator can modify the list directly at the TVD master.

Open TVDs are those that are not closed. Both active and passive membership is possible in open TVDs. If the TVD master is directly contacted by the VM, the master checks whether a TVD proxy is already present on the VM's platform. If so, the master instructs the proxy to initiate the admission protocol for the VM. If the TVD proxy is not present, then the TVD master initiates the protocol with the LCTC on the platform to create a TVD proxy.

TVD membership requirements may be checked and enforced on a one-time or on a continual basis. Membership can be a one-time operation in which the requirements are checked once and for all, and thereafter, the VM holds the TVD

membership for the duration of its life-cycle. Alternatively, membership requirements can be re-evaluated in an online fashion. The TVD proxy may regularly check whether a VM satisfies the requirements. A session-based scheme may be employed in which a VM is allowed open communication with other TVD members only until the next check (i.e., end of the session).

Policy updates at the TVD master or updates to a platform configuration may result in a platform becoming ineligible to any longer host member VPEs. In that case, the TVD master contacts the LCTC and requests it to destroy the TVD proxy. If the TVD is a closed TVD, prior to the actual destruction of the TVD proxy, members VMs are either migrated to another platform with a TVD proxy or destroyed. If the TVD is a open TVD, the VMs connected to the vSwitch are detached and re-connected to the default network connection. The LCTC sends an acknowledgment to the TVD master after the destruction of the TVD proxy. The TVD master may also rekey the TVD VPN key and distribute the new VPN key to the TVD proxies as a further security measure.

When a platform goes offline (e.g., due to maintenance or network partition), the TVD proxy gets disconnected from the TVD master. In such cases, the disconnected TVD proxy still continues to act as the local TVD authority for the VMs belonging to the TVD. However, the TVD VPEs on the platform are disconnected from the rest of the TVD. The absence of a threshold number of status reports from the TVD proxy causes the TVD master to update its list of TVD proxies. Thereafter, when the platform comes online again, the LCTC on the platform contacts the TVD master indicating that the disconnected platform is online again and contains TVD VPEs that wish to re-connect to the rest of the TVD. That is followed by a prepare phase, similar to the one that happens prior to the creation of the TVD proxy (Section 4.4.2). It is necessary to re-assess the suitability of the platform for still hosting the TVD proxy through the prepare phase, because the TVD policy and the platform state may have changed in the duration when the platform was offline. After the successful completion of the prepare phase, the TVD proxy re-establishes the secure, authenticated communication channel with the TVD master. The TVD proxy obtains the updated TVD policy and other credentials from the TVD master through the channel, and re-configures the networking components according to TVD policy.

4.6 Implementation in Xen

In this section, we describe a Xen-based [BDF+03] prototype implementation of our secure virtual networking framework. Figure 4.5 shows the implementation of two TVDs, TVD_α and TVD_β. The policy engine, also shown in the figure, implements the policies corresponding to the TVDs specified in the information flow control matrix of Figure 4.1, i.e., open connection within each TVD and closed connection between TVD_α and TVD_β.

Table 4.2: Examples of Security Properties used in Capability Modeling.

Property	Description
TVD Isolation	Flow control policies in place for a TVD.
Network	The actual topology of a virtual network in a physical machine.
Network Policy	Security policies for the network, such as firewall rules and isolation rules stating which subnets can be connected.
Storage Policy	Policies for storage security, such as whether the disks are encrypted and what VMs have permission to mount a particular disk.
Virtual Machines	The life-cycle protection mechanisms of the individual VMs, e.g., pre-conditions for execution of a VM.
Hypervisor	Binary integrity of the hypervisor.
Users	The roles and associated users of a machine, e.g., who can assume the role of administrator of the TVD master.

4.6.1 Implementation Details

Our implementation is based on Xen-unstable 3.0.4, a VMM for the IA32 platform, with the VMs running the Linux 2.6.18 operating system. Our networking extensions are implemented as kernel modules in Dom0, which also acts as driver domain for the physical NIC(s) of each physical host. A driver domain is special in the sense that it has access to portions of the host's physical hardware, such as a physical NIC.

The virtual network interface organization of Xen splits a NIC driver into two parts: a front-end driver and a back-end driver. A front-end driver is a special NIC driver that resides within the kernel of the guest OS. It is responsible for allocating a network device within the guest kernel (eth0 in Dom1 and Dom2 of hosts A and B, shown in Figure 4.5). The guest kernel layers its IP stack on top of that device as if it had a real Ethernet device driver to talk to. The back-end portion of the network driver resides within the kernel of a separate driver domain (Dom0 in our implementation) and creates a network device within the driver domain for every front-end device in a guest domain that gets created. Figure 4.5 shows two of these back-end devices, vif1.0 and vif2.0, in each of the two hosts A and B. These back-end devices correspond to the eth0 devices in Dom1 and Dom2, respectively, in each host.

Conceptually, the pair of front-end and back-end devices behaves as follows. Packets sent out by the network stack running on top of the front-end network device in the guest domain appear as packets received by the back-end network device in the driver domain. Similarly, packets sent out by the back-end network-device by the driver domain appear to the network stack running within a guest domain as packets received by the front-end network device. In its standard configuration, Xen is configured to simply bridge the driver domain back-end devices onto the real physical NIC. By this mechanism, packets generated by a guest domain find

Table 4.3: Assurance for Past, Present, and Future States used in Capability Modeling.

Past State	**Description**
Trust	A user believes that an entity has certain security properties.
Mutable Log	The entity provides log-file evidence (e.g., audits) that indicates that the platform provides certain properties.
Immutable Logs	The entity has immutable logging systems (e.g., a TPM-quote [Tru03]) for providing evidence. Since the log cannot modified by the entity itself, the resulting assurance is stronger than when mutable logs are used.
Present State	**Description**
Evaluations	Evaluation of a given state, e.g., Common Criteria evaluations [Com98].
Introspection	Introspection of a system by executing security tests, e.g., virus scanner.
Future State	**Description**
Policies	By providing policies and evidence of their enforcement, a system can justify claims about its future behavior. e.g., DRM policies and VM life-cycle protection policy.
Audit	By guaranteeing regular audits, organizations can claim that certain policies will be enforced in the future.

their way onto the physical network and packets on the physical network can be received by the guest domain.

The Xen configuration file is used to specify the particular vSwitch and the particular port in the vSwitch to which a Xen back-end device is attached. We use additional scripts to specify whether a particular vSwitch should use one or both of VLAN tagging and encapsulation mechanisms for isolating separate virtual networks.

The vSwitches for TVD_α and TVD_β are each implemented in a distributed fashion (i.e., spread across hosts A and B) by a kernel module in Dom0, which maintains a table mapping virtual network devices to ports on a particular vSwitch. Essentially, the kernel module implements EtherIP processing for packets coming out of and destined for the VMs. Each virtual switch (and hence VLAN segment) has a number identifier associated with it. The Ethernet packets sent by a VM are captured by the kernel module implementing part of the vSwitch as they are received on the corresponding back-end device in Dom0. The packets are encapsulated using EtherIP with the network identifier field set to match the identifier of the vSwitch that the VM is supposed to be plugged into. The EtherIP packet is given either a multicast or unicast IP address and simply fed into the Dom0 IP stack for routing onto the physical network. The kernel module also receives EtherIP packets destined for the physical host. The module un-encapsulates the

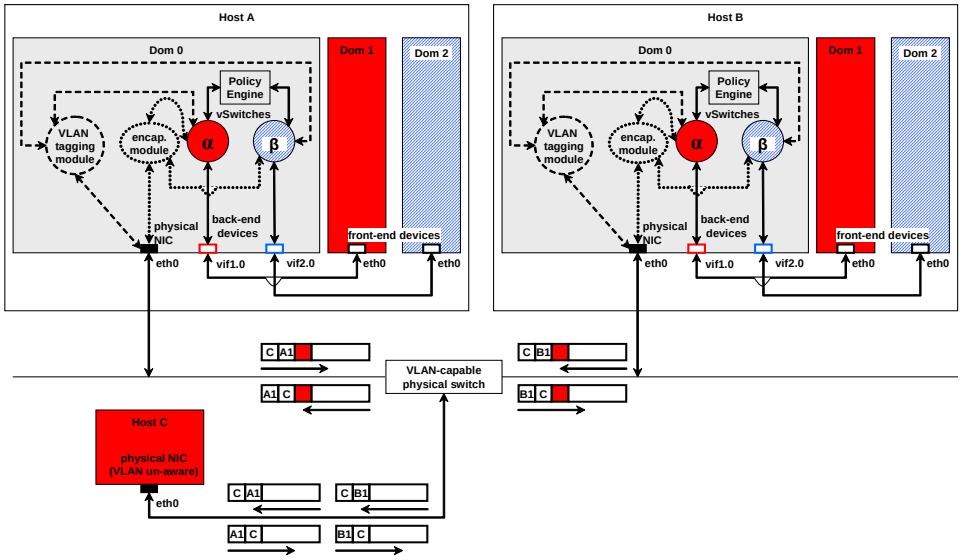


Figure 4.5: Prototype Implementation of TVDs.

Ethernet frames contained in the encapsulated EtherIP packets and transmits the raw frame over the appropriate virtual network interface so that it is received by the intended guest vNIC.

In addition to the kernel module for EtherIP processing, we have also implemented a kernel module for VLAN tagging in Dom0 of each virtualized host. Ethernet packets sent by a VM are grabbed at the same point in the Dom0 network stack as in the case of EtherIP processing. However, instead of wrapping the Ethernet packets in an IP packet, the VLAN tagging module re-transmits the packets unmodified into a pre-configured Linux VLAN device (eth0.α and eth0.β of hosts A and B, shown in Figure 4.5) matching the VLAN that the VM's vNIC is supposed to be connected to. The VLAN device[7] (provided by the standard Linux kernel VLAN support) applies the right VLAN tag to the packet before sending it out onto the physical wire through the physical NIC. The VLAN tagging module also intercepts VLAN packets arriving on the physical wire destined for a VM. The module uses the standard Linux VLAN Ethernet packet handler provided by the 8021q.ko kernel module with a slight modification: the handler removes the VLAN tags and, based on the tag, maps packets to the appropriate vSwitch (α or β) which, in turn, maps them to the corresponding back-end device (vif1.0 or vif2.0) in Dom0. The packets eventually arrive at the corresponding front-end device (eth0 in Dom1 or Dom2) as plain Ethernet packets.

[7] An alternative approach, which we will implement in the future, is to directly tag the packet and send the tagged packet straight out of the physical NIC without relying on the standard Linux VLAN devices.

4.6.2 Implementation Issues

Below are some implementation issues we had to tackle in realizing the VLAN and encapsulation approaches.

(1) Some Ethernet cards offer VLAN tag filtering and tag removal/offload capabilities. Such capabilities are useful when running just a single kernel on a physical platform, in which case there is no need to maintain the tags for making propagation decisions. However, for our virtual networking extensions, the hardware device should not strip the tags from packets on reception over the physical wire; instead, the kernel modules we have implemented should decide to which VM the packets should be forwarded. For this purpose, we modified the Linux kernel tg3.ko and forcedeth.ko network drivers so as to disable VLAN offloading.

(2) For efficiency reasons, the Xen front-end and back-end driver implementations avoid computing checksums between them for TCP/IP and UDP/IP packets. We modified the Xen code to also handle our EtherIP-encapsulated IP packets in a similar manner.

(3) The EtherIP encapsulation approach relies on mapping a virtual Ethernet broadcast domain to a IP multicast domain. While this works in a LAN environment, we encountered problems when creating VLAN segments that span WAN-separated physical machines. We resolved this issue by building uni-directional multicast tunnels between successive LAN segments.

4.7 Performance Results

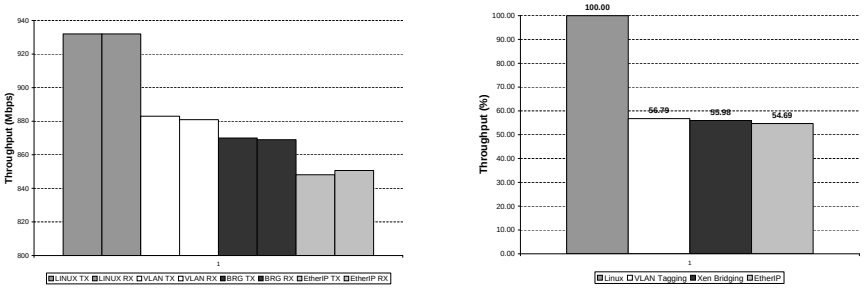
We now describe performance results for the prototype implementation of our secure virtual networking framework. We compare our results to Xen standard networking in bridging mode and also to non-virtualized systems.

4.7.1 Setup and Configuration

Our test systems run Xen 3.0.4 (release version) with a 2.6.18 Linux kernel in Domain 0. We used HP ProLiant BL25p G2 blade servers each fitted with two AMD Opteron processors running at 2 GHz, 8GB system memory and a Gigabit Ethernet card. We obtained the throughput results using the `NetPerf` network benchmark and the latency results using the `ping` tool. Using the former benchmark, we measured the Tx (outgoing) and Rx (incoming) throughput for traffic from one guest VM to another guest VM on the same physical host. To do so, we ran one instance of the benchmark on one guest VM as a server process and another instance on the second guest VM to do the actual benchmark.

4.7.2 Analysis

We report the throughput results for different networking schemes in Figure 4.6(a). The graphs show that the throughput results for both VLAN tagging and EtherIP



(a) TX/RX throughput benchmark results.

(b) Overhead of virtualization.

Figure 4.6: NetPerf Benchmark: Guest VM to Guest VM Throughput.

schemes are comparable to that of the standard Xen (bridge) configuration. Further, VLAN tagging yields the best throughput in a virtualized system that outperforms the standard Xen configuration. Both Xen bridging and VLAN tagging perform better on the **Tx path**. For EtherIP, the major cost in the Tx path is having to allocate a fresh socket buffer (`skb`) and copy the original buffer data into the fresh `skb`. When first allocating a `skb`, the Linux network stack allocates a fixed amount of headroom for the expected headers that will be added to the packet as it goes down the stack. Unfortunately, not enough space is allocated upfront to allow us to fit in the EtherIP header; so, we have to copy the data around, which is very costly. However, there is *some* spare headroom space, which is enough for the extra VLAN tag. As a result, the VLAN tagging method does not suffer from the packet copying overhead. The cost of copying data in the EtherIP case is greater than the cost of traversing two network devices (the physical Ethernet device and the Linux-provided VLAN device) for the VLAN packets. That is why the VLAN method is more efficient than the EtherIP approach for the Tx path. In a future version of our prototype, we will add a simple fix to the kernel to ensure that the initial `skb`s have enough headroom upfront for the EtherIP header.

In the Rx path, there is no packet-copying overhead for the EtherIP approach; the extra EtherIP header merely has to be removed before the packet is sent to a VM. As compared to VLAN tagging, in which packets are grabbed from the Linux network stack, EtherIP requires that packets are passed to and processed by the host OS IP stack before they are handed over to the EtherIP packet handler of the vSwitch code.

Figure 4.6(b) illustrates the overhead of virtualization technology on network performance. Table 4.4 shows the round-trip times between two guest VMs on a physical host for the bridged, VLAN, and EtherIP encapsulation cases obtained using the `ping -c 1000 host` command, i.e., 1000 packets sent. The results show that the average round-trip times for VLAN and EtherIP encapsulation are 17.8% and 36.7% higher than that of the standard Xen bridged configuration.

Table 4.4: Round-trip Times using Ping.

	Minimum	Average	Maximum	Mean Deviation
Bridged	0.136	0.180	0.294	0.024
VLAN	0.140	0.212	0.357	0.030
EtherIP	0.151	0.246	0.378	0.034

4.8 Discussion

In this chapter, we introduced a secure virtual networking model and a framework for efficient and security-enhanced network virtualization. The key drivers of our framework design were the security and management objectives of virtualized data centers, which are meant to co-host IT infrastructures belonging to multiple departments of an organization or even multiple organizations.

Our framework utilizes a combination of existing networking technologies (such as Ethernet encapsulation, VLAN tagging, VPN, and NAC) and security policy enforcement to concretely realize the abstraction of Trusted Virtual Domains, which can be thought of as security-enhanced variants of virtualized network zones. Policies are specified and enforced at the intra-TVD level (e.g., membership requirements) and inter-TVD level (e.g., information flow control).

Observing that manual configuration of virtual networks is usually error-prone, our design is oriented towards automation. To orchestrate the TVD configuration and deployment process, we introduced management entities called TVD masters. Based on the capability models of the physical infrastructure that are given as input to them, the TVD masters coordinate the set-up and population of TVDs using a well-defined protocol.

We described a Xen-based prototype that implements a subset of our secure network virtualization framework design. The performance of our virtual networking extensions is comparable to the standard Xen (bridge) configuration.

Chapter 5

Dependable and Secure Virtual Datacenters

Bernhard Jansen, HariGovind V. Ramasamy, Matthias Schunter, and Axel Tanner (IBM)

5.1 Introduction to Dependable Virtualization

In this chapter, we explore opportunities for dependability and security made available by virtualization, and provide detailed information on how virtualization affects system reliability. We make four contributions: (1) a survey of dependability and security enhancements enabled by virtualization, (2) a prototype demonstrating the effectiveness of hypervisor-based intrusion detection, (3) reliability models and analysis of the effects of virtualization, and (4) an architecture for a reliability-enhanced Xen VMM that leverages a subset of the enhancements.

We describe ways of leveraging virtualization for dependability and security enhancements, such as response to load-induced failures, administration of patches in an availability-preserving manner, enforcement of fail-safe behavior, proactive software rejuvenation, and intrusion detection and protection. We describe in detail a Xen-based implementation of a subset of these enhancements, particularly, intrusion detection and protection. The intrusion detector, called X-Spy, uses a privileged Xen VM to monitor and analyze the complete state of other VMs co-located on the same physical platform. X-Spy is close enough to the target monitored to have a high degree of visibility into the innards of the target (like host-based intrusion detection schemes). At the same time, thanks to the isolation provided by the VMM, X-Spy is far enough from the target to be unaffected even if the target becomes compromised (like network-based intrusion detection schemes). A key challenge in implementing X-Spy was the *semantic gap*, i.e., the proper interpretation of process information gathered from the VMs monitored in a completely different VM.

We provide detailed information on how virtualization affects an important dependability attribute, namely reliability. The VMM is increasingly seen as a convenient layer for implementing many services such as networking and security [GR05] that were traditionally provided by the operating system. We show why such designs should be viewed with more caution. We use combinatorial modeling to analyze multiple design choices when a single physical server is used to host multiple virtual servers and to quantify the reliability impact of virtualization. In light of the prevailing trend to shift services out of the guest OS into the virtualization layer, we show that this shift, if not done carefully, could adversely affect system reliability.

We describe a reliability-enhanced Xen VMM architecture, called *R-Xen*, that combines replication, intrusion detection, and rejuvenation. Normally, the Xen VMM consists of a relatively small hypervisor core and a full-fledged privileged VM called *Dom0* that runs a guest OS (Linux). Regular VMs running on the Xen VMM are called *user domains* or *DomUs*. Because of its size and complexity, Dom0 is the weak point in the reliability of the Xen VMM. R-Xen focuses on improving Dom0 reliability (and thereby improving the Xen VMM reliability) through three-fold replication. The three Dom0 replicas each contain X-Spy implementations to mutually monitor each other and thus detect the presence of faults and/or intrusions in the other two. If two replicas report to the hypervisor that the third is corrupted, the hypervisor terminates and rejuvenates the corrupt replica. If the replica terminated happens to be the *primary* replica that provides device virtualization for user domains, then one of the two backups becomes the new primary.

The remainder of the chapter is organized as follows. Section 5.2 describes related work in the area of virtualization-based dependability and virtualization-based intrusion detection. In Section 5.3, we describe at a high-level several dependability and security enhancements (including intrusion detection and protection) that are made possible by virtualization. Section 5.4 describes X-Spy, our Xen-based prototype implementation of intrusion detection and protection. Section 5.5 analysis the reliability impact of virtualization and highlights the importance of VMM reliability to the overall reliability of a virtualized physical node. Motivated by the conclusions of our reliability analysis and leveraging our X-Spy implementation, Section 5.6 describes an architecture for a more reliable Xen VMM.

5.2 Related Work

We now provide a sampling of related work in the area of using VMs for improving dependability. We also compare our X-Spy intrusion detection framework with previous hypervisor-based intrusion detection systems. Many of these works, including ours, implicitly trust the virtualization layer to function properly, to isolate the VMs from each other, and to control the privileged access of certain VMs to

other VMs. Such a trust can be justified by the observation that a typical hypervisor consists of some tens of thousands lines-of-code (LOC), whereas a typical operating system today is on the order of millions LOC [GR03]. This allows a much higher assurance for the code of a hypervisor.

Bressoud and Schneider [BS96] implemented a primary-backup replication protocol tolerant to benign faults at the VMM level. The protocol resolves non-determinism by logging the results of all non-deterministic actions taken by the primary and then applying the same results at the backups to maintain state consistency.

Double-Take [VMw] uses hardware-based real-time synchronous replication to replicate application data from multiple VMs to a single physical machine so that the application can automatically fail over to a spare machine by importing the replicated data in case of an outage. As the replication is done at the file system level below the VM, the technique is guest-OS-agnostic. Such a design could provide the basis for a business model in which multiple client companies outsource their disaster recovery capability to a disaster recovery hot-site that houses multiple physical backup machines, one for each client.

Douceur and Howell [DH05] describe how VMMs can be used to ensure that VMs satisfy determinism and thereby enable state machine replication at the VM level rather than the application level. Specifically, they describe how a VM's virtual disk and clock can be made deterministic with respect to the VM's execution. The design relieves the application programmer of the burden of structuring the application as a deterministic state machine. Their work is similar to Bressoud and Schneider's approach [BS96] of using a VMM to resolve non-determinism. However, the difference lies in the fact that whereas Bressoud and Schneider's approach resolves non-determinism using the results of the primary machine's computation, Douceur and Howell's design resolves non-determinism *a priori* by constraining the behavior of the computation.

Dunlap *et al.* describe ReVirt [DKC+02] for VM logging and replay. ReVirt encapsulates the OS as a VM, logs non-deterministic events that affect the VM's execution, and uses the logged data to replay the VM's execution later. Such a capability is useful to recreate the effects of non-deterministic attacks, as they show later in [JKDC05]. Their replay technique is to start from a checkpoint state and then roll forward using the log to reach the desired state.

Joshi *et al.* [JKDC05] combine VM introspection with VM replay to analyze whether a vulnerability was activated in a VM before a patch was applied. The analysis is based on vulnerability-specific predicates provided by the patch writer. After the patch has been applied, the same predicates can be used during the VM's normal execution to detect and respond to attacks.

Backtracker [KC03] can be used to identify which application running inside a VM was exploited on a given host. Backtracker consists of an online component that records OS objects (such as processes and files) and events (such as read, write, and fork), and an offline component that generates graphs depicting the possible chain of events between the point at which the exploit occurred and the point at

which the exploit was detected.

An extension of Backtracker [KMLC05] has been used to track attacks from a single host at which an infection has been detected to the originator of the attack and to other hosts that were compromised from that host. The extension is based on identifying causal relationships, and has also been used for correlating alerts from multiple intrusion detection systems.

King *et al.* [KDC05] describe the concept of time-traveling virtual machines (TTVMs), in which VM replay is used for low-overhead reverse debugging of operating systems and for providing debugging operations such as reverse break point, reverse watch point, and reverse single step. Combining efficient checkpointing techniques with ReVirt, TTVMs can be used by programmers to go to a particular point in the execution history of a given run of the OS. To recreate all relevant state for that point, TTVMs log all sources of non-determinism.

Garfinkel and Rosenblum [GR03] introduced the idea of hypervisor-based intrusion detection, and pointed out the advantages of this approach and its applicability not only for detection, but also for protection. Their Livewire system uses a modified VMware workstation as hypervisor and implements various polling-based and event-driven sensors. Compared with Livewire, our X-Spy system employs more extensive detection techniques (e.g., by checking not only processes, but also kernel modules and file systems) and protection techniques (such as prechecking and white-listing of binaries, and kernel sealing) with an explicit focus on rootkit detection. In addition, X-Spy enables easy forensic analysis.

Zhang *et al.* [ZvDJ+02] and Petroni *et al.* [NLPFMA04] use a secure coprocessor as the basis for checking the integrity of the OS kernel running on the main processor. However, as the coprocessor can only read the memory of the machine monitored, only polling-based intrusion detection is possible. In contrast, X-Spy can perform both polling-based and event-driven intrusion detection. Specifically, it can intercept and deny certain requested actions (such as suspicious system calls), and therefore has the capability to not only detect but also protect.

Laureano *et al.* [LMJ04] employ behavior-based detection of anomalous system call sequences after a learning phase in which "normal" system calls are identified. Processes with anomalous system call sequences are labeled suspicious. For these processes, certain dangerous system calls will in turn be blocked. The authors describe a prototype based on a type-II hypervisor, namely, User-Mode Linux (UML) [Dik00].

The ISIS system of Litty [Lit05] is also based on UML. ISIS runs as a process in the host operating system and detects intrusions in the guest operating system by using the `ptrace` system call for instrumenting the guest UML kernel. Unlike X-Spy, ISIS focuses mostly on intrusion detection and not protection.

Jiang *et al.* [JWX07] describe the *VMwatcher* system, in which host-based anti-malware software is used to monitor a VM from within a different VM. X-Spy and VMwatcher are similar in that both use the hypervisor as a bridge for cross-VM inspection, and both tackle the semantic gap problem. While their work focuses on bridging the semantic gap on a multitude of platforms (hypervisors and operating

systems), our work focuses on employing more extensive detection mechanisms (such as checking not only processes, but also kernel modules, network connections, and file systems) on a single hypervisor. In contrast to X-Spy, VMwatcher does not include event-driven detection methods or protection techniques.

The Strider GhostBuster system by Beck *et al.* [BVV05] is similar to X-Spy in that both use a differential view of system resources. Strider GhostBuster compares high-level information (such as information obtained by an OS command) with low-level information (e.g., kernel information) to detect malicious software trying to hide system resources from the user and administrator. However, such a comparison has limited effectiveness as detection takes place in the same (potentially compromised) OS environment. Beck *et al.* also compare the file system view obtained from a potentially compromised OS with the view obtained from an OS booted from a clean media. The disadvantage of such an approach is that it requires multiple reboots and is limited to checking only persistent data (such as file system) and not run-time data.

5.3 Using Virtualization for Dependability and Security

Commodity operating systems provide a level of dependability and security that is much lower than what is desired. This situation has not changed much in the past decade. Hence, the focus has shifted to designing dependable and secure systems around the OS problems. Thanks to the flexible manner in which VM state can be manipulated, virtualization can enable such designs. In particular, VM state, much like files, can be read, copied, modified, saved, migrated, and restored [GR05]. In this section, we give several examples of dependability and security enhancements made possible by virtualization.

Coping with Load-Induced Failures: Deploying services on VMs instead of physical machines enables a higher and more flexible resilience to load-induced failures without requiring additional hardware. Under load conditions, the VMs can be seamlessly migrated (using live migration [CFH+05]) to a lightly loaded or a more powerful physical machine. VM creation is simple and cheap, much like copying a file. In response to high-load conditions, it is much easier to dynamically provision additional VMs on under-utilized physical machines than to provision additional physical machines. This flexibility usually compensates for the additional resources (mainly memory) needed by the hypervisor.

Patch Application for High-Availability Services: Typically, patch application involves a system restart, and thus negatively affects service availability. Consider a service running inside a VM. Virtualization provides a way of removing faults and vulnerabilities at run-time without affecting system availability. For this purpose, a copy of the VM is instantiated, and the patch (be it OS-level or service-level) is applied on the copy rather than on the original VM. Then, the copy is restarted for the patch to take effect, after which the original VM is gracefully shut

down and future service requests are directed to the copy VM. To ensure that there are no undesirable side effects due to the patch application, the copy VM may be placed under special watch for a sufficiently long time while its post-patch behavior is being observed before the original VM is shut down. If the service running inside the VM is stateful, then additional techniques based on a combination of VM checkpointing (e.g., [AF02]) and VM live migration [CFH+05] may be used to retain network connections of the original VM and to bring the copy up-to-date with the last correct checkpoint.

Enforcing Fail-Safe Behavior and Virtual Patches: The average time between the point in time when a vulnerability is made public and a patch is available is still measured in months. In 2005, Microsoft took an average time of 134.5 days for issuing critical patches for Windows security problems reported to the company [Was06]. Developing patches for a software component is a time-consuming process because of the need to ensure that the patch does not introduce new flaws or affect the dependencies between the component involved and other components in the system. In many cases, a service administrator simply does not have the luxury of suspending a service immediately after a critical flaw (in the OS running the service or the service itself) becomes publicized until the patch becomes available.

Virtualization can be used to prolong the availability of the service as much as possible while at the same time ensuring that the service is fail-safe. We leverage the observation that publicizing a flaw is usually accompanied by details of possible attacks exploiting the flaw and/or symptoms of an exploited flaw. Developing an external monitor to identify attack signatures or symptoms of an exploited flaw may be done independently of patch development. The monitor may also be developed much faster than the patch itself, because the monitor may not be subject to the same stringent testing and validation requirements.

Consider a service running inside a VM rather than directly on a physical machine. Then, a VM-external monitor, running in parallel to the VM, can be used to watch for these attack signatures or detect the symptoms of exploitation of the flaw. If attack signatures are known, the VM-external monitor can be used to block the attack, e.g. by filtering the incoming network stream, to terminate interaction with the attack source, or to protect targeted structures inside the VM, e.g. the system call table. If only symptoms of exploitation are known, detection of a compromise can be used to immediately halt the VM. The monitor could be implemented at the VMM level or in a privileged VM (such as Dom0 in Xen [BDF+03]). If it is important to revert the service to its last correct state when a patch becomes available, then the above technique can be augmented with a checkpointing mechanism that periodically checkpoints the state of the service with respect to the VM (e.g., [AF02]).

Proactive Software Rejuvenation: Rebooting a machine is an easy way of rejuvenating software. The downside of machine reboot is that the service is unavailable during the reboot process. The VMM is a convenient layer for introducing hooks to proactively rejuvenate the guest OS and services running inside a VM in a performance- and availability-preserving way [RK07]. Periodically, the VMM can

be made to instantiate a *reincarnation VM* from a clean VM image. The booting of the reincarnation VM is done while the original VM continues regular operation, thereby maintaining service availability. One can view this technique as a generalization of the proactive recovery technique for fault-tolerant replication proposed by Reiser and Kapitza [RK07].

As mentioned above in the context of patch application, techniques based on VM checkpointing and live migration may be used to seamlessly transfer network connections and the service state of the original VM to the reincarnation VM. It is possible to adjust the performance impact of the rejuvenation procedure on the original VM's performance. To lower the impact, the VMM can restrict the amount of resources devoted to the booting of a reincarnation VM and compensate for the restriction in resources by allowing more time for the reboot to complete.

One can view the above type of rejuvenation as a *memory-scrubbing* technique for reclaiming leaked memory and recovering from memory errors of the original VM. More importantly, such a periodic rejuvenation offers a way to proactively recover from errors without requiring failure detection mechanisms (which are often unreliable) to trigger the recovery.

Intrusion Detection and Response: Based on the location of the intrusion detection sensors, intrusion detection system (IDS) implementations are broadly classified into host-based IDS (HIDS) and network-based IDS (NIDS) [HDW00]. A NIDS monitors network traffic from and to the target, and analyzes the individual packets for signs of intrusion. Because of its isolation from the target monitored, a NIDS decreases its susceptibility to attacks and is largely unaffected by a compromised target. However, as network traffic becomes increasingly encrypted and as the NIDS has no direct knowledge of the effects or properties of the attack targets, the usefulness of NIDS is decreased. The fact that not all intrusions may manifest their effects in the form of malicious traffic also lowers the utility of NIDS. The sensors of a HIDS are placed on the target machine itself, giving them a high degree of visibility into the internals of the target, enabling closer monitoring and analysis of the target than NIDS does. However, the location of HIDS on the same "trust compartment" as the target is also a disadvantage: after an intrusion into the target, the HIDS may no longer be trusted.

Virtualization provides a way of removing the disadvantages of HIDS and NIDS, while retaining their advantages. In our approach, the sensors are placed in a special privileged VM (called the *secure service VM* or SSVM) used for monitoring other VMs hosting regular production services (called *production VMs* or PVMs). The placement of the sensors on the same physical machine but in a different VM allows monitoring and analysis of the complete state of other VMs via the VMM, and at the same time, keeps the sensor out of reach of a potentially compromised VM and in a secure vantage position.

The twin characteristics of proximity to the target and isolation from the target also make the SSVM a convenient location for implementing intrusion response mechanisms. The secure vantage point of the SSVM allows one to implement otherwise difficult responses, e.g., even a simple response like 'shutdown a com-

promised system' may not be effectively triggered from inside the compromised system. On the other hand, it is easy and effective to suspend the operations of a compromised PVM from the SSVM. In addition, the SSVM can instruct the VMM to provision a healthy replacement PVM or block suspicious system calls that may potentially tamper with the integrity of the kernel.

For effective rejuvenation of a compromised PVM by re-provisioning a new PVM, it is not sufficient to merely boot the new PVM from a clean state. The new PVM might still possess all the vulnerabilities of the compromised one. Hence, it is important to perform a forensic analysis of the compromised PVM's state to remove as many vulnerabilities as possible. Such an analysis is facilitated by the virtualized environment hosting the SSVM. The SSVM can obtain not only modified files of a suspended PVM, but also its complete run-time state from the memory dump created at the time of suspension. The memory dump can be examined using the same techniques as the one used to observe the state of a running PVM from the SSVM for the purpose of intrusion detection.

5.4 Xen-based Implementation of Intrusion Detection and Protection

In this section, we describe the prototype implementation of a subset of the security enhancements mentioned above, namely, intrusion detection and protection for VMs. Later, in Section 5.6, we leverage the implementation for enforcing fail-safe behavior and for triggering software rejuvenation in our construction of R-Xen.

5.4.1 Intrusion Detection and Protection for Xen Virtual Machines

We have implemented an intrusion detection and protection framework called *X-Spy*. The core idea is to use a secure service VM (SSVM) that monitors one or more production VMs (PVM). The SSVM performs the following functions:

Lie Detection The SSVM accesses the memory of the PVM and compares actual critical system data (processes, mounts, etc.) against data obtained by executing normal Unix commands inside the PVM. If the comparison yields discrepancies, then that is indicative of a compromised PVM. In contrast to earlier hypervisor-based intrusion detection work, X-Spy's detection mechanisms are more comprehensive and include lie detection at the level of processes, network connections, modules, and file system mounts.

Protection We have added a system call inspector to Xen that allows the monitoring of the system calls within the PVM for the purpose of protecting relevant forensic information (like log files) and the integrity of the kernel (kernel structures, modules, and memory).

X-Spy uses the Xen [BDF+03] VMM developed by Cambridge University and guest VMs running the Linux 2.6 operating system. Nevertheless, the concepts such as system call analysis and lie detection can be applied to other operating systems such as Microsoft Windows. All X-Spy components are implemented either in the Xen hypervisor or in the SSVM. While their implementation logic depends on the guest OS, X-Spy does not require any modification to the guest OS of the PVM.

Limitations

To overcome the semantic gap, we assume some knowledge of the kernel structures of the guest operating system (specifically, Linux kernel 2.6) so that X-Spy components can be appropriately coded. If the guest operating system is upgraded to a newer version in which kernel structures are different, then the X-Spy components need to be re-coded appropriately. That fact may be an impediment to commercializing X-Spy, as it implies an ongoing commitment to develop and patch X-Spy components to keep pace with upgrades to the guest operating system.

For detecting hidden processes, X-Spy requires that the scheduler of the PVM's guest OS keep a list of processes that need to be scheduled in a standard place within a known memory structure. If an attacker is able to replace the scheduler with her own one having a different list of processes, the detection approach would be subverted. That is why it is important to protect the integrity of the kernel code (for example, using mechanisms that we describe in Section 5.4.4).

The SSVM needs read access to the memory of the PVMs for the purpose of monitoring them. In addition, it must be possible to do an SSH login to the PVM from the SSVM and execute normal Unix commands. These requirements are contrary to the isolation guarantees of the hypervisor. The SSVM itself could become a high-value attack target, and accordingly, needs stronger protection. Several measures can be taken to strongly reduce the potential of the SSVM getting compromised. For example, as the SSVM is a special-purpose VM (in contrast to PVMs), it can be hardened, its functionality reduced solely to that of monitoring the PVMs, and its access restricted through a specific administrative interface.

5.4.2 Architecture of X-Spy

The architecture of the X-Spy intrusion detection framework is shown in Figure 5.1. Our architecture consists of a PVM and a SSVM running on top of the same hardware and Xen hypervisor. In our implementation, both the SSVM and the PVM run Linux kernel 2.6. The SSVM obtains the run-time state of the PVM through the Xen hypervisor, which is at a lower level of abstraction than both the SSVM and the PVM. The SSVM has access to the raw devices of the PVMs (memory, disk, network); however, the difficulty lies in the SSVM properly interpreting

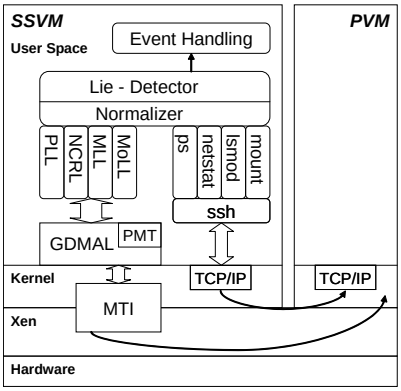


Figure 5.1: Architecture of the X-Spy Lie-Detector components.

the data because of a semantic gap [CN01]. For example, the physical memory of the host system will be made available in chunks as *pseudo-physical* memory to the VMs. In addition, the (possibly different) operating systems of the VMs use a virtual address space on top of the physical memory, leading to the problem of properly interpreting raw memory locations in a different context.

5.4.3 Intrusion Detection by means of a Lie-Detector

The basic idea of the Lie-Detector is to compare the insider and outsider views of the system to identify objects (processes, files etc.) that try to hide themselves from the operating system [BVV05]. Such behavior is typical of *rootkits*, which are then used to hide other (typically malicious) software, but is also sometimes characteristic of DRM functionality (e.g. the XCP content protection technology by Sony BMG in 2005). The Lie-Detector (Figure 5.1) consists of three major functionalities:

1. PVM Information Collection: The Lie-Detector collects information about the PVM by two different means: the *native* interface and the *frontDoor* interface.
2. PVM Information Normalization: The PVM information collected via the native interface is normalized to a format equivalent to that of commands executed through the frontDoor interface.
3. Analyze-and-Compare: The normalized information from the native and *frontDoor* interfaces is then compared to identify differences that are indicative of maliciously hidden system resources and to minimize false positives. Any findings will be reported through the *Event Handling* component.

We describe the above functionalities in detail below.

Memory Translation Interface (MTI) One of the main components of X-Spy is a Memory Translation Interface (MTI) that allows the SSVM full access to a PVM's pseudo-physical and virtual memory in a convenient fashion. The MTI has two parts:

1. An extension to the Xen hypervisor, which performs address translation and traversal of the page tables.

2. A Linux kernel device driver that runs in the SSVM kernel and provides two interfaces, namely, `/dev/mem_domX` and `/dev/kmem_domX`. These interfaces are functionally equivalent to the `/dev/mem` and the `/dev/kmem` device files, respectively, and allow the root user in the SSVM kernel access to the PVM's physical memory and kernel memory contents, respectively.

One challenge to overcome when implementing the MTI was that the SSVM cannot access a PVM's foreign memory as it corresponds to a different context. Therefore, the MTI has to emulate the memory management unit by translating the address to the right format and re-mapping it from the PVM memory space onto the memory space of the Lie-Detector process running in the SSVM. For this purpose, we have developed two user-space libraries that the MTI uses: the *Guest Domain Memory Access Library* or GDMAL and the *Process Memory Translator* or PMT. The GDMAL provides read-write access to the PVM's memory. Within the PVM's memory, the PMT allows access to the virtual address space of PVM processes. In addition, the PMT provides some helper functions to facilitate the use of the `/dev/mem_domX` and `/dev/kmem_domX` interfaces. The PMT performs the process address translation by extracting the memory management information for the process from the OS-specific task (process) description data structure. When the guest OS is Linux, as in our case, the PMT extracts the `mm_struct` data structure from the `task_struct` data structure.

The *native interface* is used to collect PVM information "from the outside" through the raw access made available by the Xen hypervisor, e.g. by accessing the PVM's memory via the MTI, and to collect host-specific data via special user-space libraries that we have developed, namely the process list library (PLL), the network connection and routing library (NCRL), and the module list library (MLL).

The second interface, called the *frontDoor interface*, is used to obtain PVM information by doing an SSH login to the PVM and executing normal Unix commands. The Lie-Detector normalizes the information collected from both interfaces, and then compares them. If the comparison yields discrepancies in the information collected from those two sources, this is strongly indicative of an intrusion. Obviously, it is not possible to obtain information through the frontDoor interface and the native interface at exactly the same time. This timing difference may lead to false positives, and we explain below how to overcome this problem. We implement comparison methods for processes, network connections, kernel modules, file system mounts and files.

The MTI provides access to the PVM's raw kernel virtual memory but lacks any semantic context. To fix this shortcoming, we manually created a *memory offset file* for each library[1]. Based on these files, the libraries such as PLL, NCRL, and MLL, implement the logic to extract all data values of interest from the raw kernel virtual memory. Each offset file stores the offset values of the start of each data item of interest from the beginning of the containing structure.

Process List The PLL acts on information provided by the MTI to generate output similar to that of the `ps` command. This is done by accessing and then traversing the doubly-linked circular task list via the MTI.

Our comparison is based on the multitude of information extractable from this `task_struct` data structure, such as PID, state, parent, open files, registers, priorities, locks, and memory management information. However, not all fields in the data structure are used. For example, the running time of a process as seen by the native interface query and the frontDoor interface query are bound to slightly differ, owing to the difference in the time of query.

This comparison will detect processes in the PVM that actively try to hide their presence or change their appearance (e.g. the owner) from queries made from within the PVM. This will identify rootkit-like behavior, as non-hiding processes can be identified by more conventional (non-hypervisor-based) malware detection tools.

Note that simply comparing the process information from the native and frontDoor interfaces results in false positives because of frequent changes to the process table. We fix this by executing a native access (outsider view) before and after the frontDoor query (insider view). If a given process disappeared in the second query but is again visible in the third, we consider it to be an intrusion. If it does not reappear, we assume that the process merely terminated.

Network Connections and Routing We obtain information about IPv4 connections, Unix socket connections, and IPv4 routing through the native and frontDoor interfaces. For the native interface queries, we have developed the NCRL library, which uses the MTI to collect information equivalent to that obtained from three commands: '`netstat -an -inet`' for IPv4 connections, '`netstat -an -unix`' for Unix Socket connections, and '`netstat -rn`' for IPv4 routing. This information can then be used to discover hidden network connections.

Similar to the timing problem in the Lie-Detector comparison of process information, we face a timing problem in the comparison of network connection information because of network connections that were terminated or started in the time interval between the native interface query and the frontDoor interface query. The solution here is again to reduce false positives by using three queries[2].

[1] With some effort, it is possible to generate the offset files automatically at kernel compilation time.

[2] Note that the frontDoor query is made through an SSH connection, which will show up only in

Module List To obtain information about the PVM's kernel modules we have developed another user-space library called the MLL for collecting information from the native interface query. The frontDoor interface query uses the `lsmod` command, which outputs the contents of `/proc/modules` displaying the kernel modules currently loaded. In addition to the native interface and frontDoor interface queries, the MLL also queries a third Xen interface for detecting hidden Linux loadable kernel modules (LKMs). LKMs are a way to link object code without interruption to the Linux kernel while it is running. Such LKMs are automatically registered at loading time, but it is possible for an LKM to un-register itself after loading. In such a case, the LKM can hide even from a native interface query (as the adore-ng rootkit indeed does; see Section 5.4.5). To address this issue, we established a *shadow module list* in the hypervisor. The hypervisor traps the `init_module` system call and analyzes the ELF header section of the object file to get the module name and stores the name in the shadow module list. The hypervisor also traps the `delete_module` system call to remove entries from the shadow module list. As the hypervisor address space cannot be accessed by the PVM, the shadow module list cannot be altered by an intruder. The Xen interface query shows the contents of the shadow module list and is taken as reference for comparison with the results of the native interface and frontDoor interface queries. If the results from the native interface and/or the frontDoor interface queries do not list an entry from the shadow module list, we conclude that the module in question is hidden.

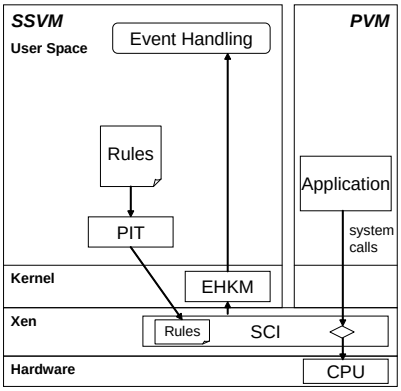
Mounts The frontDoor interface uses the `cat /proc/mounts` command, which provides a list of all mounted file systems in the PVM. An obvious alternative would have been to use the output of the `mount` command; however that alternative is less useful and secure because the command merely outputs the contents of the `/etc/mtab` file, and it is easy to mount a file system without an entry showing up in the `/etc/mtab` file by using the `mount -n` command.

The mount list library (MoLL[3]) operates on the PVM information about mounted file systems collected via the native interface query. The starting symbol for obtaining the information is the `task_struct` structure of the idle task (however, the entry for any task would be adequate), from where the MoLL gains access to the `vfsmnt` circular list. The list provides complete information about all file systems currently mounted.

The mount information gathered from the native interface query is used as the reference against which the information from the frontDoor interface is compared. If there are mounted file systems that appear in the former but not in the latter, we take this as an indication of a hidden malicious process because mount information is relatively static, and hence false positives are not a big concern.

the frontDoor query but in neither of the interface queries.

[3]The MoLL should not be confused with MLL, the module list library.



File system In the case of the file system, bridging the semantic gap in general implies the use of raw access to the physical disk and the related traffic to rebuild the file system structures of the guest operating system of the PVM in the context of the SSVM. Accessing file systems mounted by another operating system is feasible even for disparate operating systems, e.g. Microsoft Windows and Linux, as for example shown in [JWX07]. Xen can use a Linux file system existing on the Xen/Dom0 level to boot and launch guest domains. This same file system can then be mounted read-only by the SSVM. We then retrieve the file information via the frontDoor and compare it with the information of the file system mounted by the SSVM.

For efficiency and simplified forensic recording, we use a basic read-only file system and add the CoWNFS *copy-on-write* file system [KMP+04, Ros08]. This allows us to store the changes for multiple runs for later forensic analysis and protects the original state of the system from any (potentially malicious) changes. This combined file system was then used as an NFS mountable file system for booting the PVM.

5.4.4 Protection of System Integrity and Forensic Information by means of System Call Inspection

We now outline how X-Spy's System Call Inspection component is used to protect the system against intrusions.

Protection of Forensic Information

In case of a successful intrusion it is highly desirable to protect as much forensic information as possible. A smart intruder would want to hide all traces of the intrusion, e.g., by altering log-files[4] such as the `wtmp/utmp` and the `/var/log/messages` files. While these files cannot be modified by normal users, intruders with root access can. One way to address this issue would be to

[4]Note that the above protection scheme for log files can easily be extended to protect other important files, such as Xen VM configuration files, through additional rules in the rule set.

use a hardened system (e.g., SELinux). However, this protects only if the superuser is not allowed to change the SELinux rules in a running System.

In a virtualized environment as considered here, we have the possibility to protect important files by intercepting the system call sequence in the PVM through the Xen hypervisor. For this purpose, we added a module to the Xen hypervisor, the *System Call Inspector* (SCI), which can inspect all[5] system calls occurring in the PVM and either block or accept calls depending on a set of *rules*. These rules are stored and edited in the SSVM (and therefore out of reach of any activity in the PVM), and can be loaded into the SCI (in binary form) via the Policy Installation Tool (PIT).

X-Spy implements a functionality for checking and fine-tuning system calls by instrumenting the system call handling chain. An `int 0x80` instruction is intercepted by an interrupt handler located in the Xen context where checks against the previously introduced rule set are done. Only after passing the checks is the call redirected to the PVM Kernel, where the normal system call handler is invoked; otherwise, the call returns without any action being taken. In certain cases, the system call is allowed after some fine-tuning, e.g., a modification of the parameters so that the call conforms to the rule set specified. The amount of performance overhead depends on the type of checks and fine-tuning being done for a particular system call.

As the interception of the system call happens in the Xen context, the problem of semantic gap has to be overcome to determine which system calls actually merit additional checks. For our aim of protecting forensic information, system calls performing file operations are essential. We protect forensic information by preventing calls that rename, link, unlink, or delete log files. Furthermore, we limit access to log files by permitting only the append operation on them. To ensure that a malicious process cannot bypass the checking, we normalized the paths.

If the SCI finds that an application in the PVM tries to initiate a system call that is not allowed according to the rule set, it will block or modify it and send a corresponding event through an *event handling kernel module* (EHKM) in the SSVM to the high-level event handling component with information about the violated rule and the corresponding process in the PVM.

Protection of Binaries against User-Space Rootkits

The mechanism used for protecting forensic information can also be used to protect binaries from being altered by an intruder. Many user-space rootkits try to alter `ps` or `netstat` to hide their presence or to install a back door by modifying the `openssh` binary. While earlier tools, such as Tripwire, can *detect* the alteration of a binary or a library, our event-driven approach to check system calls and their arguments can actually *prevent* their alteration.

[5]Note that Xen implements a “fast trap” mechanism to enhance performance. If Xen calls are to be monitored as well, then this mechanism need to be disabled.

In addition, it is possible to restrict read/write access to an executable, but still allow its execution. Based on the corresponding rule set, the module we have implemented in the Xen hypervisor checks whether a system call is trying to change, delete, link, or rename a binary, and if so, the call is denied. As execution of a binary normally happens through the `execve` system call without actually opening the binary file, it is even possible to add a rule that forbids the opening of certain binaries completely without disallowing their execution.

Kernel Sealing

X-Spy also implements *kernel sealing*, a well-known method to protect a system or prevent intrusions. The kernel memory can be accessed directly by reading or, more dangerously, by writing to the `/dev/mem` or `/dev/kmem` device files. The rule set of the X-Spy event-driven module in the Xen hypervisor was updated to restrict access to those files, so that only read requests are allowed and write requests return an error result without performing the write operation.

Accessing the kernel memory by loading a kernel module or writing directly to /dev/(k)mem is potentially dangerous because it allows an intruder to establish its own interface to the kernel; thereafter, the intruder can easily place malicious code in the kernel and have full access to the file system and other kernel internals. X-Spy uses a technique called *white-listing* by which all kernel modules allowed to be loaded are explicitly specified along with their respective SHA-1 hash values. If the module to be loaded at run-time is not specified in the white-list or if it has an incorrect hash value, X-Spy prevents the module from being loaded by preventing the system call from reaching the PVM kernel space. Note that our X-Spy implementation does not offer protection against buffer overflows on systems calls.

Pre-Checking of Binaries

An effective way of protecting a PVM from user-space rootkits or other malicious software is to check the hash of every binary, prior to its execution, against a white-list of pre-calculated hashes and to allow its execution only if there is a match. Computing the hash of the binary has to be done out of the reach of a potential intruder in the PVM and should also not require modification of the PVM's OS. To meet these conditions, X-Spy computes the hash of the binary in the SSVM. To enable such a computation, it is necessary that the SSVM has all partitions of the PVM mounted; furthermore, the binary should not be on a RAM disk, on network file system, or on an encrypted file system that the SSVM cannot access. An alternative would be to do the computation in the hypervisor, which would require overcoming the semantic gap problem.

For computing the hash of the binary in the SSVM, we use a technique called *memory scanning*, which involves loading the complete `.text` and `.data` sections of an ELF binary into memory by setting the program counter to the next

page, asking the PVM kernel to load the page, and then hashing it while handling the page fault.

If the hash cannot be verified the hypervisor invalidates all of the memory and returns the control back to the guest domain. Because of the invalid `.text` section to which the PC points, the process will crash. Note that relying on support from the PVM's guest OS does not necessarily constitute a security gap, because a non-cooperative PVM kernel would lead to a wrong hash value and in this case, as seen above, the process will be forced to quit.

5.4.5 Evaluation

While the conceptual limitations have been discussed in Section 5.4.1, we will now evaluate the effectiveness and efficiency of our implementation.

Functional Evaluation

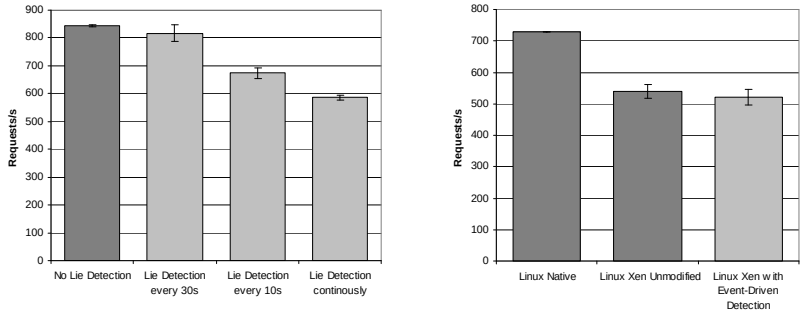
The goal of the Lie-Detector is to expose malicious code. Once all information is visible, we no longer focus on whether a particular LKM or process is hostile.

We first evaluated our implementation using a set of functional tests that implement typical rootkit functionality, such as hiding processes, kernel modules, mounts, or network connections. Our Lie-Detector correctly exposed all attempts to hide such critical information.

We then tested the system using the adore-ng rootkit [ste01]. Adore-ng is an LKM-based rootkit for Linux kernels which allows one to hide files and directories, processes, and network connections. The basic rootkit consists of the kernel module and a user-space control program. While currently this is the only widely available rootkit for the Linux kernel 2.6, other similar rootkits exist for earlier kernel versions and may be ported to the 2.6 kernel.

In a fully protected X-Spy system, the rootkit cannot even be installed as the insertion of modules is restricted through the SCI interception of the respective system calls and the white-listing of allowed modules. After explicitly allowing the rootkit to insert itself into the kernel, we used its control program to hide processes, files, and network connections. The X-Spy Lie-Detector component reported these hidden resources faithfully by comparing the responses from the native and front-Door interfaces as described in Section 5.4.3. Although the adore-ng kernel module will remove itself from the list of modules visible with `lsmod`, detection of the module by the Lie-Detector is possible with the help of the shadow module list (see discussion in Section 5.4.4).

The rule set used in X-Spy's event-driven protection mechanism contained about 110 rules, e.g. to protect forensically relevant files (e.g. `/var/log/messages` and `/var/log/wtmp`) and to prevent access to raw memory (`/dev/(k)mem`), security relevant configuration files (`/etc/ssh.config`), and operating system tools (`/bin/ls`). In addition, we specified an explicit list of allowed kernel modules (module white-listing). Once



(a) Impact of Lie-Detector (b) Impact of protective measures

Figure 5.2: Performance impact of X-Spy components: number of fulfilled requests per second in the HTTP benchmark.

the rule set was active, it either generated security events with information about the offending processes in the PVM or successfully prevented the deletion or truncation of log-files and the modification of configuration and utility files.

Performance Impact

To measure the performance impact of the Lie-Detector and the event-driven approach, we used a single machine implementing a web server scenario. The PVM hosted an Apache web server, and multiple clients were simulated using the *ab* performance benchmarking tool (see `http://httpd.apache.org/docs/2.0/programs/ab.html`). The networks were virtual and internal to this machine.

Figure 5.2(a) shows that the performance impact of the Lie-Detector depends on how often it is run. The overhead is roughly 31% when it is running continuously, 20% when it is run every 10 sec, and 4% when it is run every 30 sec.

Most practical applications will run infrequent scans. In this case, the performance impact of X-Spy is negligible, particularly when compared with the performance reduction of moving Linux into a VM.

In a real-world setting, the frequency of "Lie Detection" should be chosen based on the expected time until an intrusion occurs and the expected time until such an intrusion is detected. The latter is an important factor because it denotes the critical time window between the intrusion and its detection when the PVM is at the mercy of the intruder, who can take arbitrary actions (such as installing a fake website or copying private information onto a different system). If the PVM runs a critical service in which the critical time window should be minimized, then the Lie-Detector should be run continuously.

As seen in Figure 5.2(b), the event-driven method results in a performance loss of about 4%. Compared with the 34% overhead incurred by changing from

a service running on a non-virtualized platform to that running on a Xen-based PVM, the loss incurred by the event-driven approach is minor.

5.5 Quantifying the Impact of Virtualization on Node Reliability

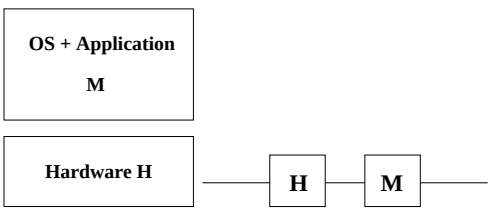
In this section, we use combinatorial modeling to perform a reliability analysis of redundant fault-tolerant designs involving virtualization on a single physical node and compare them with the non-virtualized case. The results of the analysis highlight the importance of improving the reliability of the hypervisor.

We consider a model in which multiple VMs run concurrently on the same node and offer identical service. We derive lower bounds on the VMM reliability and the number of VMs required for the virtualized node in order to have better reliability than in the non-virtualized case. We also analyze the reliability impact of moving a functionality common to all VMs out of the VMs and into the VMM. In addition, we analyze the reliability of a redundant execution scheme that can tolerate the corruption of one out of three VMs running on the same physical host, and compare it with the non-virtualized case. Our results point to the need for careful modeling and analysis before a design based on virtualization is used.

Combinatorial modeling and Markov modeling are the two main methods used for reliability assessment of fault-tolerant designs [Joh89]. We chose combinatorial modeling because its simplicity enables easy elimination of "hopeless" choices in the early stage of the design process. In combinatorial modeling, a system consists of series and parallel combinations of modules. The assumption is that module failures are independent. In a real-world setting, where module failures may not be independent, the reliability value obtained using combinatorial modeling should be taken as an upper bound on the system reliability.

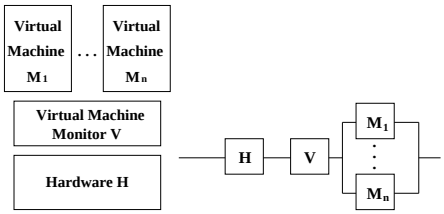
Non-Virtualized (NV) Node: For our reliability assessment, we consider a non-virtualized single physical node as the base case. We model the node using two modules: hardware (H) and the software machine (M) consisting of the operating system, middleware, and applications (Figure 5.3(a)) . Thus, the node is a simple serial system consisting of H and M, whose reliability is given by $R_{sys}^{NV} = R_H R_M$, where R_X denotes the reliability of module X (Figure 5.3(b)).

Virtualized Node with n Independent, Identical VMs: Figure 5.4(a) shows a physical node consisting of H, a type-1 VMM (V) that runs directly on the hardware (such a VMM is referred to as a *hypervisor*), and one or more VMs ($\{M_i\}, i \geq 1$). The VMs provide identical service concurrently and independently (i.e., without the need for strong synchronization). For example, each VM could be a virtual server answering client requests for static web content. Thus, the node is a series-parallel system (Figure 5.4(b)) whose overall reliability is given by $R_{sys}^{n} = R_H R_V [1 - \prod_{i=0}^{n}(1 - R_{M_i})]$. Here, we consider the reliability of the hardware to be the same as that in the non-virtualized case because the underlying hardware is the same in both cases. An obvious concern is whether the hardware in the virtualized



(a) Architecture (b) Combinatorial Model

Figure 5.3: Non-virtualized node



(a) Architecture (b) Combinatorial Model

Figure 5.4: Node with n VMs

node will register a significant drop in reliability due to load/stress compared with the non-virtualized node. However, this concern does not apply to our context of application servers in a data center, in which typical hardware utilization in a non-virtualized node is abysmally low (less than 5%) and n is typically in the low tens of VMs.

The condition for the n-replicated service to be more reliable than the non-virtualized service is given by $R_{sys}^{n} > R_{sys}^{NV}$. i.e., $R_H R_V[1 - \prod_{i=0}^{n}(1 - R_{M_i})] > R_H R_M$. For simplicity, let $R_{M_i} = R_M$ for all $1 \leq i \leq n$. This is a reasonable assumption, as each VM has the same functionality as the software machine M in the non-virtualized case. Then, the above condition becomes

$$R_V[1 - (1 - R_M)^n] > R_M. \tag{5.1}$$

Inequality (5.1) immediately yields two conclusions. First, if $n = 1$, then again the above condition does not hold ($R_V < 1$). What this means is that it is necessary to have some additional coordination mechanism or protocol built into the system to compensate for the reliability lost by the introduction of the hypervisor. In the absence of such a mechanism/protocol, simply adding a hypervisor layer to a node will only decrease node reliability. Second, if $R_V = R_M$, then it is obvious that above condition does not hold.

It is clear that the *hypervisor has to be more reliable than the individual VMs*. The interesting question is how much more reliable. Figure 5.5 shows that for a fixed R_M value, the hypervisor has to be more reliable when deploying fewer VMs. The graph also shows that, for fixed values of R_M and R_V, there exists a lower bound on n below which the virtualized node reliability will definitely be lower than that of a non-virtualized node. For example, when R_M = 0.1 and R_V = 0.3, deploying fewer than 4 VMs would only lower the node reliability. This is a useful result, as in many practical settings, R_M and R_V values may be fixed, e.g., when the hypervisor, guest OS, and application are commercial off-the-shelf (COTS) components with no source-code access.

The equation for R_{sys}^{n} also suggests that by increasing the number of VMs, the node reliability can be made as close to the hypervisor reliability as desired. Suppose we desire the node reliability to be R, where $R < R_V$. Then, $R = R_H R_V[1-(1-R_M)^n]$. Assume that the hardware is highly reliable, i.e., $R_H \simeq 1$.

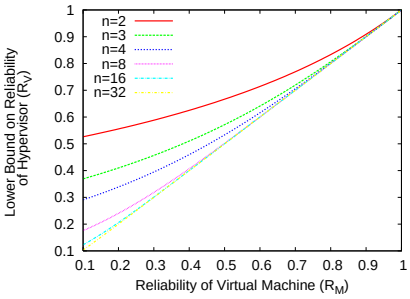


Figure 5.5: Lower bound on the hypervisor reliability for a physical node with n independent and concurrently operating VMs providing identical service.

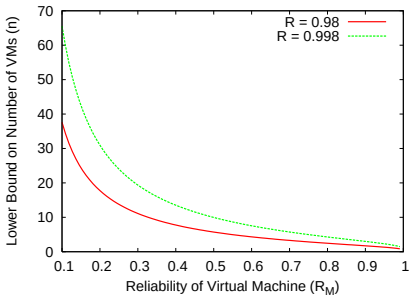


Figure 5.6: Lower bound on the number of VMs to achieve desired reliability R for a physical node with n independent and concurrently operating VMs providing identical service when $R_V = 0.999$.

Then, the above equation becomes the inequality,

$R < R_V[1 - (1 - R_M)^n]$

$\Longrightarrow (1 - R_M)^n < 1 - \frac{R}{R_V}$

$\Longrightarrow n.\log(1 - R_M) < \log(1 - \frac{R}{R_V})$

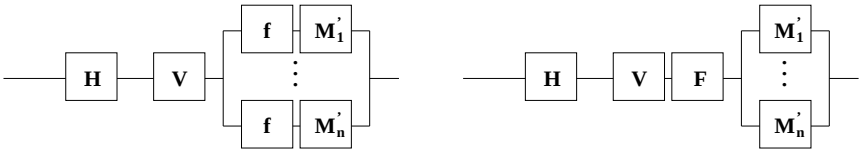
Dividing by $\log(1 - R_M)$, a negative number, we obtain,

$$n > \frac{\log(1 - \frac{R}{R_V})}{\log(1 - R_M)}. \tag{5.2}$$

Inequality (5.2) gives a lower bound on the number of VMs required for a virtualized physical node to meet a given reliability requirement. In practice, the number of VMs that can be hosted on a physical node is ultimately limited by the resources available on that node. Comparing the lower bound with the number of VMs that can possibly be co-hosted provides an easy way of eliminating certain choices early in the design process.

Figure 5.6 shows the lower bound for n for two different R values (0.98 and 0.998) as the VM reliability (R_M) is increased from roughly 0.1 to 1.0, with the hypervisor reliability fixed at 0.999. The figure shows that for fixed R_V and R_M values, a higher system reliability (up to R_V) can be obtained by increasing the number of VMs hosted. However, when n is large, one is faced with the practical difficulty of obtaining sufficient diversity to ensure that VM failures are independent.

Moving Functionality out of the VMs into the Hypervisor: We now analyze the reliability impact of moving a functionality out of the VMs and into the hypervisor. As before, our system model is one in which a physical node has $n \geq 1$ independent and concurrently operating VMs providing identical service. Consider a functionality f implemented inside each VM. Then, each VM M_i can be divided into two components, f and $M_i^{'}$, the latter representing the rest of M_i.



(a) Configuration C_1: Functionality f implemented within each VM

(b) Configuration C_2: Functionality F implemented as part of Hypervisor

Figure 5.7: Moving functionality out of the VMs into the hypervisor

Figure 5.7(a) shows the reliability model for a node containing n such VMs. Let us call this node configuration C_1. Further, suppose that the functionality f is moved out of the VMs and substituted by component F implemented as part of the hypervisor. Now, the new hypervisor consists of two components F and the old hypervisor V. Figure 5.7(b) shows the reliability model for a node with the modified hypervisor. Let us call this node configuration C_2.

We now derive the condition for C_2 to be at least as reliable as C_1. For simplicity, let us assume that $R_{M'_i} = R_{M'}$ for all $1 \leq i \leq n$. Then, the desired condition is

$R_{sys}^{C_2} \geq R_{sys}^{C_1}$

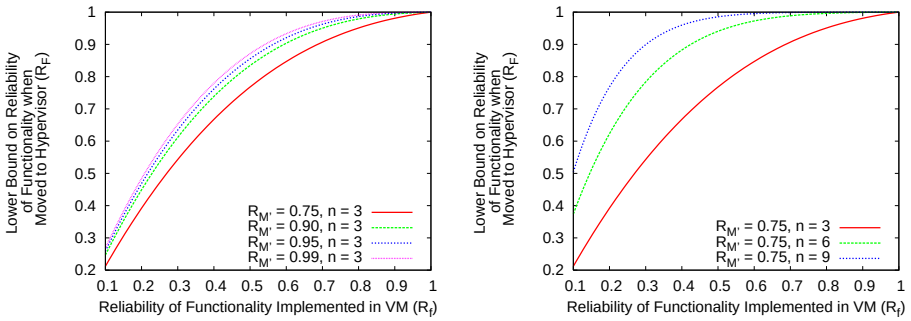
$$\implies R_H R_V R_F[1-(1-R_{M'})^n] \geq R_H R_V[1-(1-R_f R_{M'})^n]$$

$$\implies R_F \geq \frac{[1-(1-R_f R_{M'})^n]}{[1-(1-R_{M'})^n]}. \tag{5.3}$$

It is easy to see from Figure 5.7 that if there is only one VM, it does not matter whether the functionality is implemented in the hypervisor or in the VM. We can also confirm this observation by substituting $n = 1$ in inequality (5.3).

Figures 5.8(a) and (b) illustrate how R_F varies as R_f is increased from 0.1 to 1. The graphs show that for configuration C_2 to be more reliable than C_1, F has to be more reliable than f. Figure 5.8(a) shows that as $R_{M'}$ increases, the degree by which F should be more reliable than f also increases. Figure 5.8(b) shows that the degree is also considerably higher when more VMs are co-hosted on the same physical host. For example, even with modest $R_{M'}$ and R_f values of 0.75, F has to be ultra-reliable: R_F has to be more than 0.9932 and 0.9994 if $n = 6$ and $n = 9$, respectively. Thus, when more than a handful of VMs are co-hosted on the same physical node, a better system reliability is more likely to be obtained by retaining a poorly reliable functionality in the VM rather than by moving the functionality into the hypervisor.

Virtualized Node with VMM-level Voting: Consider a fault-tolerant 2-out-of-3 replication scheme in which three VMs providing identical service are co-hosted on a single physical node. The VMM layer receives client requests and forwards them to all three VMs in the same order. Assume that the service is a deterministic state machine; thus, the VM replicas yield the same result for the



(a) Fixed n, varying $R_{M'}$ (b) Fixed $R_{M'}$, varying n

Figure 5.8: Plot of $R_F \geq \dfrac{[1-(1-R_f R_{M'})^n]}{[1-(1-R_{M'})^n]}$

same request. The VMM receives the results from the VM replicas. Once the VMM has obtained replies from two replicas with identical result values for a given client request, it forwards the result value to the corresponding client. Such a scheme can tolerate the arbitrary failure of one VM replica, and is similar to the one suggested in the RESH architecture for fault-tolerant replication using virtualization [RHKSP06]. Assuming that the VMs fail independently, the system reliability is given by

$$R_{sys}^{2-\text{of}-3} = R_H R_V [R_M^3 + \binom{3}{2} R_M^2 (1-R_M)].$$

Then, $R_{sys}^{2-\text{of}-3} > R_{sys}^{NV}$ gives the condition for the 2-out-of-3 replication scheme to be more reliable than the non-virtualized service. Thus, we obtain

$$R_H R_V [R_M^3 + \binom{3}{2} R_M^2 (1-R_M)] > R_H R_M$$

$$\implies R_V > \frac{1}{3R_M - 2R_M^2}. \tag{5.4}$$

Inequality (5.4) gives a lower bound on the hypervisor reliability for the 2-out-of-3 replication scheme to have better reliability than the non-virtualized case. Figure 5.9 shows a plot of $\frac{1}{3R_M - 2R_M^2} < R_V < 1$. It is clear from the graph that there exists no R_V value that satisfies inequality (5.4) and is less than 1 when $R_M \leq 0.5$. In other words, if the VM reliability (i.e., the operating system and service reliability) is poor to begin with, then the 2-out-of-3 replication scheme will only make the node reliability worse even if the hypervisor is ultra-reliable. This result concurs with the well-known fact that any form of redundancy with majority voting is not helpful for improving overall system reliability when the overall system is composed of modules with individual reliabilities of less than 0.5 [Joh89]. The graph also shows that the higher the hypervisor reliability, the larger the range of VM reliability values for which the 2-out-of-3 replication scheme has better reliability than the non-virtualized case. For example, when $R_V = 0.98$, the range

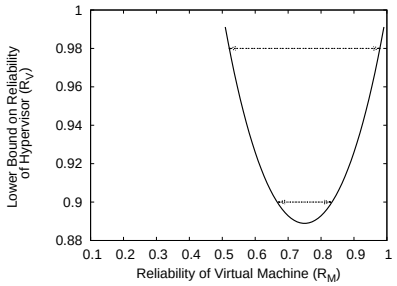


Figure 5.9: Plot of $(3R_M - 2R_M^2)^{-1} < R_V < 1$

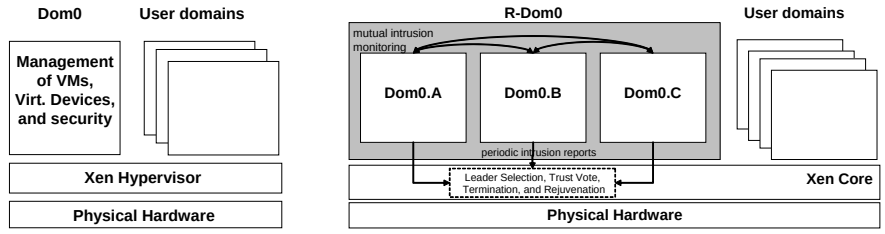
of VM reliability values that can be accommodated is greater than the range when $R_V = 0.9$.

5.6 An Architecture for a More Reliable Xen VMM

As shown by the model-based analysis in Section 5.5, it is highly desirable to make the VMM as reliable as possible to improve the overall reliability of a virtualized node. In this section, we leverage our X-Spy implementation to propose a reliability-enhanced design of the popular Xen open-source VMM [BDF+03].

The Xen VMM (Figure 5.10(a)) consists of a hypervisor core and a privileged domain (or VM) called Dom0 or domain zero. The hypervisor core is small in size and concerned with virtualizing the memory and CPU. Dom0 is a full-fledged VM running a guest OS (Linux) and virtualizes other hardware devices (such as disks and network interfaces). Dom0 is the first domain that is created, and controls all other domains, called user domains or DomUs. For any given physical device in Xen, the native device driver is part of at most one VM. If the device is to be shared with other VMs, then the VM with the native device driver makes the device available through a *back-end driver*. Any VM that wants to share the device exports a virtual device driver called the *front-end driver* to the back-end driver. Every front-end virtual device has to be connected to a corresponding back-end virtual device; only then does the front-end device become active. The mapping is one-to-one, i.e., each front-end virtual device from each user domain is mapped to a corresponding back-end virtual device. The communication between the back-end and front-end drivers takes places through shared memory and event channels. The event channel is used for sending simple lightweight notifications and the shared memory is used for sending requests and data.

As Dom0 is relatively large, we expect its reliability to be lower than that of the hypervisor core. Thus, improving the reliability of Dom0 is crucial to improving the reliability of the Xen VMM as a whole. We combine some of the technologies described in Section 5.3, namely, intrusion detection, enforcing fail-stop behavior, and intrusion response in form of software rejuvenation, to architect a more reliable Xen VMM, which we call *R-Xen*.



(a) Normal Xen Architecture (b) R-Xen Architecture

Figure 5.10: Enhancing the Reliability of the Xen VMM

In R-Xen, we enhance the reliability of Dom0 by replication (Figure 5.10(b)). Dom0 is a single logical entity that actually consists of three privileged domains, *Dom0.A*, *Dom0.B*, and *Dom0.C*, with identical privilege levels. The three replicas mutually monitor each other using the techniques we described above in our X-Spy implementation. Specifically, each Dom0 replica is simultaneously the PVM and the SSVM for the other two Dom0s. Periodically, the Dom0 replicas submit a fault detection vote to the hypervisor core that indicates whether one of its two peers is thought to be compromised. If any given Dom0 replica is labeled as being faulty by its two peer SSVMs, then the replica will be terminated and rejuvenated by the hypervisor. In this way, we enforce fail-stop behavior of the replica despite the presence of a more severe kind of fault in the replica. The hypervisor core then starts a new Dom0 replica as a replacement of the terminated one.

One of the Dom0 replicas is designated as *active* by the hypervisor core, and it is this active replica that provides the back-end drivers for the devices of the user domains. The other two replicas are designated as *passive*, and do not provide any back-end devices. As mentioned above, each of the three Dom0 replicas monitors and is being monitored by the other two. If the hypervisor gets reports from two independent replicas labeling the third replica as faulty, then the hypervisor terminates that replica and replaces it with a new Dom0 replica. If the terminated replica is a primary, then the hypervisor designates one of the backups as the new primary replica by re-connecting the front-end devices of the user domain(s) to the replica's back-end devices. The disconnection and reconnection of the user domain(s) to a different Dom0 has already been implemented in Xen and is used for live migration of domains. Therefore, the code can be reused. The hypervisor itself has to actively give permissions for doing the reconnection and re-routing the data from the old Dom0 to the new one. It also has to shutdown the old Dom0 after the reconnection process has been completed. Using a previously started backup as the new primary results in less interruption to the user domain than using the replacement replica (which has to be booted from scratch) as the new primary. It also enables the booting of the replacement replica to occur concurrently to the re-connection of the front-end devices. Like other fault-detection-based techniques, there is the drawback of *detection latency*, i.e., a time delay between the actual occurrence of the fault and its detection. I/O requests sent by the user domain(s) during this

latency period may have to be re-issued. On the positive side, our technique can be implemented in a manner that is completely transparent to the user domain(s). In other words, a DomU running on normal Xen should be able to run without modification on this type of R-Xen as well.

Part III

Conclusion

In this report, we have described the OpenTC approach towards a Trusted Virtual Datacenter. The core idea is to build a datacenter that allows for and isolates multiple customers while satisfying the security requirements of each customer.

Securing the access to data on persistent media and during transfer over the network is a serious problem in distributed virtual data-center and cloud computing scenarios. We described a framework based on TVDs and Trusted Computing for secure network and storage virtualization that includes mechanisms for verifying the integrity of the hypervisor, VMs, and security policy enforcement points.

This is achieved by means of so-called Trusted Virtual Domains that provide a virtual environment for each customer. Each trusted virtual domain exposes a standardized management interface that allows customers to run existing management software to manage their respective domains. The concept of TVDs is rigid enough to allow consistent policy enforcement across a group of domain elements, while being flexible enough to support policy-controlled interactions between different TVDs. TVD policies and configurations are 'backward-compatible' in supporting options that could be taken for granted in non-virtualized data centers. For example, co-hosting of specific customer services with those of other data-center customers on the same physical platform could be inhibited if so desired. By incorporating hardware-based Trusted Computing technology, our framework allows the creation of policy domains with attestable trust properties for each of the domain nodes.

In order to enforce the given security requirements, we deploy the security services described in Deliverable D05.4 [Ope08b] that allow verifiable security within each domain. This includes validation of the trusted computing base as well as verifiable enforcement of given per-domain policies. The inclusion of integrity measurement and management mechanisms as part of the physical platform's TCBs provides both data-center customers and administrators with a much needed view of the elements (hypervisors, VMs, etc.) that are part of their virtual infrastructure as well as information on the configurations of those elements. Our framework can be used to obtain information about the elements on a 'need-to-know' basis without having to introduce all-powerful roles of administrators with access to every aspect of a platform.

Another insight was that building a security API that is at the same time flexible, usable, and manageable has proved to be more difficult than expected. A key reason for this difficulty is the requirement that the API should be easily adaptable to other hypervisor architectures and to workstation scenarios with GUI interfaces. While addressing each of these requirements separately is feasible, their combination comes with many trade-offs.

Yet another type of trade-off concerns our aim of decomposing the Xen architecture into multiple, dedicated security services while reducing the reliance on the management domain. While such decomposition is advantageous from a security perspective, it tends to reduce flexibility. The availability of a full-fledged Linux management domain with access to all systems enables easy extensibility and rapid prototyping (scripting, adding devices, firewalls, VPNs etc), and also corresponds

to the expectations of many Xen users. In general, however, considerations of usability tend to favor design decisions that are sub-optimal from a strict security perspective.

Bibliography

[AF02] A. Agbaria and R. Friedman, *Virtual Machine Based Heterogeneous Checkpointing*, Software: Practice and Experience **32** (2002), no. 1, 1–19.

[BCG+06] Stefan Berger, Ramon Cáceres, Kenneth Goldman, Ron Perez, Rainer Sailer, and Leender van Doorn, *vTPM: Virtualizing the Trusted Platform Module*, Proc. 15th USENIX Security Symposium, August 2006, pp. 21–21.

[BDF+03] P. T. Barham, B. Dragovic, K. Fraser, S. Hand, T. L. Harris, A. Ho, R. Neugebauer, I. Pratt, and A. Warfield, *Xen and the Art of Virtualization*, Proc. 19th ACM Symposium on Operating Systems Principles (SOSP-2003), October 2003, pp. 164–177.

[BGJ+05] A. Bussani, J. L. Griffin, B. Jansen, K. Julisch, G. Karjoth, H. Maruyama, M. Nakamura, R. Perez, M. Schunter, A. Tanner, L. van Doorn, E. V. Herreweghen, M. Waidner, and S. Yoshihama, *Trusted Virtual Domains: Secure foundation for business and IT services*, Research Report RC 23792, IBM Research, November 2005.

[BS96] T. C. Bressoud and F. B. Schneider, *Hypervisor-Based Fault Tolerance*, ACM Trans. Comput. Syst. **14** (1996), no. 1, 80–107.

[BVV05] Doug Beck, Binh Vo, and Chad Verbowski, *Detecting Stealth Software with Strider GhostBuster*, DSN '05: Proceedings of the 2005 International Conference on Dependable Systems and Networks (DSN'05) (Washington, DC, USA), IEEE Computer Society, 2005, pp. 368–377.

[CBL07] A. Cappadonia C. Basile and A. Lioy, *Algebraic models to detect and solve policy conflicts*, MMM-ACNS 2007 (I. Kotenko V. Gorodetsky and V.A. Skormin, eds.), CCIS, vol. 1, Springer-Verlag, 2007, pp. 242–247.

[CDRS07] Serdar Cabuk, Chris Dalton, HariGovind V. Ramasamy, and Matthias Schunter, *Towards automated provisioning of secure virtualized networks*, Proc. 14th ACM Conference on Computer and Communications Security (CCS-2007), October 2007, pp. 235–245.

[CFH+05] C. Clark, K. Fraser, S. Hand, J. G. Hansen, E. Jul, C. Limpach, I. Pratt, and A. Warfield, *Live Migration of Virtual Machines*, Proc. 2nd Symposium on Networked Systems Design and Implementation (NSDI-2005), May 2005, pp. 273–286.

[CN01] P. M. Chen and B. D. Noble, *When Virtual is Better than Real*, Proceedings of HotOS-VIII: 8th Workshop on Hot Topics in Operating Systems, May 2001, pp. 133–138.

[Com98] Common Criteria Project Sponsoring Organisations, *Common Criteria for Information Technology Security Evaluation (version 2.0)*, dopted by ISO/IEC as Draft International Standard DIS 15408 1-3, May 1998.

[DH05] J. R. Douceur and J. Howell, *Replicated Virtual Machines*, Tech. Report MSR TR-2005-119, Microsoft Research, September 2005.

[Dik00] Jeff Dike, *A User-Mode Port of the Linux Kernel*, ALS'00: Proceedings of the 4th conference on 4th Annual Linux Showcase & Conference, Atlanta (Berkeley, CA, USA), USENIX Association, 2000, pp. 7–7.

[DKC+02] G. W. Dunlap, S. T. King, S. Cinar, M. A. Basrai, and P. M. Chen, *ReVirt: Enabling Intrusion Analysis through Virtual-Machine Logging and Replay*, SIGOPS Operating System Review **36** (2002), no. SI, 211–224.

[EASH05] H. Hamed E. Al-Shaer, R. Boutaba and M. Hasan, *Conflict classification and analysis of distributed firewall policies*, IEEE Journal on Selected Areas in Communications, IEEE **23** (Oct. 2005), no. 10, 2069–2084.

[FWH+01] Zhi Fu, Shyhtsun Felix Wu, He Huang, Kung Loh, Fengmin Gong, Ilia Baldine, and Chong Xu, *IPSec/VPN security policy: Correctness, conflict detection, and resolution*, POLICY, 2001, pp. 39–56.

[GR03] Tal Garfinkel and Mendel Rosenblum, *A Virtual Machine Introspection Based Architecture for Intrusion Detection*, Proc. Network and Distributed Systems Security Symposium, February 2003.

[GR05] T. Garfinkel and M. Rosenblum, *When Virtual is Harder than Real: Security Challenges in Virtual Machine Based Computing Environments*, Proc. 10th Workshop on Hot Topics in Operating Systems (HotOS-X), May 2005.

[HDW00] M. Dacier H. Debar and A. Wespi, *A Revised Taxonomy of Intrusion-Detection Systems*, Annales des Telecommunications **55** (2000), no. (7-8), 83–100.

[IEE98] IEEE, *Standards for local and metropolitan area networks: Virtual bridged local area networks*, Tech. Report ISBN 0-7381-3662-X, IEEE, 1998.

[IEE04] _____, *802.1x: IEEE standard for local and metropolitan networks — port-based network access control*, IEEE Standards, 2004, Revision of 802.1X-2001.

[IET02] IETF, *EtherIP: Tunneling Ethernet Frames in IP Datagrams*, 2002, RFC 3378.

[JKDC05] A. Joshi, S .T. King, G. W. Dunlap, and P. M. Chen, *Detecting Past and Present Intrusions through Vulnerability-Specific Predicates*, Proc. 20th ACM Symposium on Operating Systems Principles (SOSP-2005), 2005, pp. 91–104.

[Joh89] B. W. Johnson, *Design and Analysis of Fault-Tolerant Digital Systems*, Addison-Wesley, 1989.

[JRS07] Bernhard Jansen, HariGovind Ramasamy, and Matthias Schunter, *Compliance proofs and policy enforcement for xen virtual machines*, Submitted for Publication, 2007.

[JWX07] Xuxian Jiang, Xinyuan Wang, and Dongyan Xu, *Stealthy malware detection through vmm-based "out-of-the-box" semantic view reconstruction*, CCS '07: Proceedings of the 14th ACM conference on Computer and communications security (New York, NY, USA), ACM, 2007, pp. 128–138.

[KC03] S. T. King and P. M. Chen, *Backtracking Intrusions*, Proc. 19th ACM Symposium on Operating Systems Principles (SOSP-2003), 2003, pp. 223–236.

[KDC05] S. T. King, G. W. Dunlap, and P. M. Chen, *Debugging Operating Systems with Time-Traveling Virtual Machines*, Proc. 2005 Annual USENIX Technical Conference, April 2005, pp. 1–15.

[KMLC05] S. T. King, Z. M. Mao, D. G. Lucchetti, and P. M. Chen, *Enriching Intrusion Alerts through Multi-Host Causality*, Proc. Network and Distributed System Security Symposium (NDSS-2005), 2005.

[KMP+04] Evangelos Kotsovinos, Tim Moreton, Ian Pratt, Russ Ross, Kier Fraser, Steven Hand, and Tim Harris, *Global-scale Service Deployment in the XenoServer Platform*, Proceedings of the 1st USENIX Workshop on Real, Large Distributed Systems (WORLDS '04) (San Francisco, CA), December 2004.

[KS05] S. Kent and K. Seo, *Security Architecture for the Internet Protocol*, Internet Engineering Task Force: `http://www.ietf.org/rfc/rfc4301.txt`, December 2005, Network Working Group RFC 4346. Obsoletes: RCF2401.

[Lit05] L. Litty, *Hypervisor-Based Intrusion Detection*, Ph.D. thesis, University of Toronto, 2005.

[LMJ04] Marcos Laureano, Carlos Maziero, and Edgard Jamhour, *Intrusion Detection in Virtual Machine Environments*, EUROMICRO '04: Proceedings of the 30th EUROMICRO Conference (EUROMICRO'04) (Washington, DC, USA), IEEE Computer Society, 2004, pp. 520–525.

[LS99] Emil Lupu and Morris Sloman, *Conflicts in policy-based distributed system management*, IEEE Transaction on Software Engineering **25** (1999), no. 6, 852–869.

[N. 01] N. Dunlop, J. Indulska, K. A. Raymond, *A formal specification of conflicts in dynamic policy-based management systems*, DSTC Technical Report, CRC for Enterprise Distributed Systems, University of Queensland, Australia, August 2001.

[NLPFMA04] Jr. Nick L. Petroni, Timothy Fraser, Jesus Molina, and William A. Arbaugh, *Copilot - A Coprocessor-based Kernel Runtime Integrity Monitor*, SSYM'04: Proceedings of the 13th conference on USENIX Security Symposium (Berkeley, CA, USA), USENIX Association, 2004, pp. 13–13.

[Ope08a] Open Trusted Computing (OpenTC) Project, *The OpenTC Project Homepage*, 2008, `http://www.opentc.net/`.

[Ope08b] OpenTC Workpackage 05, *Design of the cross-domain security services*, Deliverable, The OpenTC Project `www.opentc.net`, 05/26/2008.

[RHKSP06] H. P. Reiser, F. J. Hauck, R. Kapitza, and W. Schröder-Preikschat, *Hypervisor-Based Redundant Execution on a Single Physical Host*, Proc. 6th European Dependable Computing Conference (EDCC-2006), October 2006, p. S.2.

[RK07] Hans P. Reiser and Rudiger Kapitza, *Hypervisor-Based Efficient Proactive Recovery*, SRDS '07: Proc. 26th IEEE International Symposium on Reliable Distributed Systems, IEEE Computer Society, Washington, DC, USA, 2007, pp. 83–92.

[Ros08] Russ Ross, *CoWNFS*, http://www.russross.com/CoWNFS.html, 2008.

[RYG00] D. Pendarakis R. Yavatkar and R. Guerin, *A framework for policy-based admission control*, RFC 2753, January 2000.

[SS05] A-R. Sadeghi and C. Stüble, *Property-based Attestation for Computing Platforms: Caring about Properties, not Mechanisms*, Proc. 2004 Workshop on New Security Paradigms (NSPW-2004) (New York, NY, USA), ACM Press, 2005, pp. 67–77.

[ste01] stealth, *Adore-ng v0.42*, http://packetstormsecurity.org/, 2001.

[Tru03] Trusted Computing Group, *TPM Main Specification v1.2*, November 2003, `https://www.trustedcomputinggroup.org`.

[VMw] VMware, *VMware Double-Take*, `http://www.vmware.com/pdf/vmware_doubletake.pdf`.

[Was06] Washington Post, *A Time to Patch*, 2006, `http://blog.washingtonpost.com/securityfix/2006/01/a_time_to_patch.html`.

[Wes01] Andrea Westerinen, *Terminology for policy-based management*, RFC 3198, November 2001.

[ZvDJ+02] Xiaolan Zhang, Leendert van Doorn, Trent Jaeger, Ronald Perez, and Reiner Sailer, *Secure coprocessor-based intrusion detection*, EW10: Proceedings of the 10th workshop on ACM SIGOPS European workshop (New York, NY, USA), ACM, 2002, pp. 239–242.