Building a Future-Proof Cloud Infrastructure

A Unified Architecture for Network, Security, and Storage Services

SILVANO GAI

With Contributions by

Roger Andersson, Diego Crupnicoff, and **Vipin Jain**

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Addison-Wesley

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To the women in my family: Antonella, Eleonora,
Evelina, and Carola;
and to Jacopo

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Preface

The Motivation for Writing this Book

I decided to write this book after the success of the *Cisco Unified Computing System (UCS) Data Center* book, which I wrote with Roger Andersson and Tommi Salli.

I attribute the excellent response to that book to the significant amount of material that we included on protocols, technologies, and system evolution. We discussed several significant changes that were happening in data centers, from the blade server architecture to the dominance of Ethernet, to the trend toward I/O consolidation. We also made some predictions on the long-term evolution, some of which turned out to be right, while others didn't.

In the eight years that followed, the pace of changes has dramatically increased, and I thought it was time to provide an updated view of the technology trends as independently as possible from actual products.

This book focuses on core services like segment routing, NAT, firewall, microsegmentation, load balancing, SSL/TLS termination, VPNs, RDMA, storage, and storage services such as compression and encryption. These services are vital components whenever multiple users share any cloud architecture, be it private, public, or hybrid. In particular, this book is about distributed services platforms that can be implemented with multiple service modules located in different hardware components, such as NICs, appliances, or switches. Distributing these service modules as closely as possible to the final applications enables very high performance, low latency, low jitter, deep observability, and rapid troubleshooting.

Who Should Read This Book

This book targets all IT professionals who want to learn about the evolution of service architectures. In particular, this book is helpful to:

- Network engineers, for the L2, L3 forwarding, Clos networks, VLAN, VXLAN, VPN, and network services
- Cloud engineers, for multi-tenancy, overlay networks, virtual switching, and GFT
- Security experts, for firewalls, encryption, key management, and zero trust
- Application engineers, for load balancing, virtualization, and microservice architecture
- High-performance computing engineers, for RDMA applications
- Storage engineers, for NVMe and NVMe-oF, compression, deduplication, and encryption in motion and at rest

After reading this book, the reader will comprehend the problems with the current reality of discrete centralized appliances and will understand the need to migrate services as closely as possible to the applications. They will then have the right knowledge to evaluate different commercial solutions, compare them by asking pertinent questions, and make the right selection for her/his business.

Chapter Organization

Chapter 1, "Introduction to Distributed Platform," introduces the need for a Distributed Services Platform that offers superior security, cloudlike scale, hardware performance, and low latency and yet be software programmable. A platform that is easy to manage, operate, troubleshoot, and works for bare metal, virtual machine, and container workloads. The chapter explores the need for domain-specific hardware, programmable through a domain-specific language for network, security, and storage services, to satisfy the insatiable demand for processing, as Moore's law hits the limits of physics.

Chapter 2, "Network Design," presents standard network designs for clouds and enterprise data centers, reviewing L2/L3 forwarding algorithms used both in classical switch routers and in hypervisors, the requirements posed by Clos networks with their leaf and spine architecture, the role of overlays and how to secure them, segment routing, and the need for "tromboning" in the presence of discrete appliances.

Chapter 3, "Virtualization," is about the trend in public, private, and hybrid clouds and virtualization; it covers the differences between bare metal, virtual machines, and containers. It describes virtualization solutions like VMware and KVM, with particular emphasis on their network and service implications. It introduces the microservice architecture and container technologies as a possible implementation, with examples on Docker and Kubernetes. It concludes with examples of OpenStack and NFV.

Chapter 4, "Network Virtualization Services," introduces networking virtualization services, starting with SDN and OpenFlow trends and more recent efforts like gRIBI. It discusses DPDK, virtual switches and OVS, offloading techniques like tc-flower, DPDK RTE flow, eBPF, and VPP and tries to provide a taxonomy of these many efforts. Popular services like load balancing and NAT are also presented. The chapter ends with a discussion about telemetry.

Chapter 5, "Security Services," introduces security services. Starting with popular services like firewall, the discussion evolves into microsegmentation, followed by a deep dive on security with symmetric and asymmetric encryption, key storage, unique key generation, digital certificates, hashing, TLS/TCP implementations, and VPNs.

Chapter 6, "Distributed Storage and RDMA Services," presents RDMA and storage services. RDMA was born in the world of high-performance computing, but it is now used also in enterprise and cloud networks. NVMe is the new storage standard that replaces SCSI for high-performance storage

drives. NVMe is also overlaid on RDMA to provide networkwide access to storage resources in an arrangement called NVMe over Fabrics (NVMe-oF). NVMe-oF can also use TCP as an alternative to RDMA. This chapter describes this landscape with the addition of essential storage services such as encryption of data at rest, compression, and data deduplication.

Chapter 7, "CPUs and Domain-Specific Hardware," discusses servers used in clouds and data centers, looking in particular to the dramatic reduction in performance growth in recent years that calls for domain-specific hardware to take over service functions. Moore's law, Dennard scaling, Amdahl's law, and 42 years of microprocessor data are analyzed to understand the economics of the server better and to help the reader decide how to partition the server functions.

Chapter 8, "NIC Evolution," describes the evolution of network interface cards (NICs) from simple devices in charge of sending and receiving one packet at a time, to more complex and sophisticated entities capable of effectively supporting multicore CPUs, multiple types of traffic, stateless offloads, SR-IOV, and advanced parsing/classification capabilities. The term SmartNICs has recently appeared to indicate NICs that incorporate even more processing power to enable offload of networking processing from the host CPU. Understanding this evolution is essential because the NIC represents one of the possible footprints for a distributed services platform.

Chapter 9, "Implementing a DS Platform," introduces distributed services platforms, outlining their goals, constraints, and implementation. Obtaining a standard set of functionalities with a granular distribution is key to scaling the architecture to a vast number of users while creating scalability and maintaining low latency, low jitter, and minimum CPU load. The chapter compares possible implementations and trade-offs in greenfield and brownfield deployment scenarios.

Chapter 10, "DSN Hardware Architectures," describes possible hardware implementations of these Distributed Services Platforms, considering three main approaches: sea of processors, field programmable gate arrays (FPGAs), and application-specific integrated circuits (ASICs). It compares the advantages and disadvantages of each approach and draws some conclusions.

Chapter 11, "The P4 Domain-Specific Language," presents the P4 architecture that makes it possible to implement ASICs that are data plane–programmable at runtime, an important feature that marries the programmability of devices like FPGAs with the performance and power-saving capability of ASICs. The chapter ends with an analysis of future directions to make P4 more usable and flexible.

Chapter 12, "Management Architectures for DS Platforms," discusses the architectural components and design choices to build a modern management infrastructure, leveraging the concepts of distributed systems, stateless microservices, and API-driven software. It presents design trade-offs for building secure, highly available, high performance, and scalable software. It further discusses the practical aspects of a management system, like ease of deployment, troubleshooting, diagnosing, and integration with existing software ecosystems. Finally, the chapter touches upon federating the declarative intent across multiple clusters.

Help Improve This Book

If you uncover any remaining resilient bugs, please contact the authors by email at dsplatforms@ip6.com. We welcome general comments to the text and invite you to send them by email also.

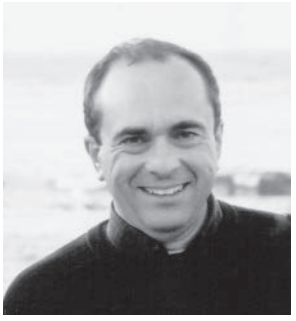
I hope this book provides useful information that you can apply to your daily activity.

—Silvano Gai

With Contributions by

- Diego Crupnicoff contributed all of Chapter 6, "Distributed Storage and RDMA Services" and helped review the book.
- Vipin Jain and Roger Andersson contributed Chapter 12, "Management Architectures for DS Platforms" and helped review the book.
- Francis Matus provided part of Chapter 7, "CPUs and Domain-Specific Hardware" on the historical evolution of processors as well as data for Chapter 10, "DSN Hardware Architectures."

About the Authors



Silvano Gai, who grew up in a small village near Asti, Italy, has more than 35 years of experience in computer engineering and computer networks. He is the author of several books and technical publications on computer networking as well as multiple Internet Drafts and RFCs. He is responsible for 50 issued patents. His background includes seven years as a full professor of Computer Engineering, tenure track, at Politecnico di Torino, Italy, and seven years as a researcher at the CNR (Italian National Council for Scientific Research). For the past 20 years, he has been in Silicon Valley where, in the position of Cisco Fellow, he was an architect of the Cisco Catalyst family of network switches, of the Cisco MDS family of storage networking switches, of the Nexus family of data center switches, and the Cisco Unified Computing System (UCS). Silvano is currently a Fellow with Pensando Systems.

Roger Andersson has spent more than 28 years in the computer and storage industry with work experience that spans across EMC/Data General, Pure Storage, Veritas/Symantec and Nuova Systems/Cisco UCS, focusing on software automation, OS provisioning, and policy-driven management at scale. Roger's roles started in hardware engineering, moved to software engineering, and for the past 16 years has been in technical product management roles. Roger is currently working at Pensando as a Technical Product Manager focusing on Distributed Service Management at scale. Roger was born in Stockholm, Sweden.

Diego Crupnicoff has been a Fellow at Pensando Systems since May 2017. Prior to that, Diego served as VP Architecture at Mellanox Technologies where he worked since its inception in 1999, driving chip and system architectures for multiple generations of Ethernet and RDMA products. Diego has been a member of the InfiniBand Trade Association since its early days and took part in the definition of the InfiniBand RDMA Standard. Among other roles, Diego chaired the IBTA Technical Working Group for many years. He was also among the founding directors of the OpenFabrics Alliance and chaired its Technical Advisory Council for several years. Over the past two decades, Diego has participated in multiple other SDOs and Tech Committees, including the IEEE802, IETF, T11, NVME, and the ONF. Diego is an inventor in multiple patents on the areas of computer networks and system architecture. He holds a B.Sc. in Computer Engineering (Summa Cum Laude) and an M.Sc. in EE. (Summa Cum Laude), both from the Technion - Israel Institute of Technology.

Vipin Jain is a passionate engineer with 20 years of industry experience. Over the years, he has contributed in the areas of switching, routing, network protocols, embedded systems, ASIC architecture, data path design, distributed systems, software-defined networking, container networking, orchestration systems, application security, open source, cloud infrastructure, and DevOps.

He holds numerous patents and has been a speaker at many conferences, author of IETF RFCs, and been a developer evangelist for his open source work. He enjoys coding for work and for fun. He also enjoys snowboarding, hiking, kayaking, and reading philosophy. He holds a bachelor's degree in Computer Science from NIT Warangal, India. He has worked in multiple successful startups in technical and management leadership roles. He is founder and CTO at Pensando Systems.

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Chapter 1

Introduction to Distributed Platforms

In the last ten years, we have observed an increasingly rapid transition from monolithic servers to virtualization. Initially, this happened inside enterprise networks, creating the need for virtual networking, but it has quickly evolved into modern cloud architectures that add the dimension of multitenancy and, with multitenancy, increased demand for security. Each user requires network services, including firewalls, load balancers, virtual private networks (VPNs), microsegmentation, encryption, and storage, and needs to be protected from other users.

This trend is very evident in cloud providers, but even larger enterprises are structuring their networks as private clouds and need to secure network users from each other.

Software-based services are often the solution. The server CPU implements a Distributed Services Architecture in software. A virtual machine or a container comprises the software that implements the service architecture. All network traffic goes through this software and, after the appropriate processing, packets are delivered to their final destinations (other virtual machines or containers). Similar processing happens on the reverse path.

A pure software solution is limited in performance, and it has high latency and jitter. Moreover, it is very problematic in bare-metal environments where the entire server is dedicated to a user or an application, and there is no place to run the services architecture.

> A distributed services platform is a set of components unified by a management control plane that implements standard network services, such as stateful firewall, load balancing, encryption, and overlay networks, in a distributed, highly scalable way with high performance, low latency, and low jitter. It has no inherent bottleneck and offers high availability. Each component should be able to implement and chain together as many services as possible, avoiding unnecessary forwarding of packets between different boxes that perform different functions. The management control plane provides role-based access to various functions and is itself implemented as a distributed software application.

We offer a new term, *distributed services node (DSN)*, to describe the entity running various network and security services. A DSN can be integrated into existing network components such as NICs (network interface cards), switches, routers, and appliances. The architecture also allows for a software implementation of the DSN, even though only hardware is capable of providing the security and performance needed by today's networks.

Keeping DSNs closer to applications provides better security; however, DSNs should be ideally implemented at a layer that is immune to application, operating system, or hypervisor compromise.

Having multiple DSNs, as distributed as possible, increases scalability dramatically and effectively removes bottlenecks.

This architecture is practical only in the presence of a management system capable of distributing and monitoring service policies to all DSNs.

Figure 1-1 provides a graphical representation of a distributed services platform.

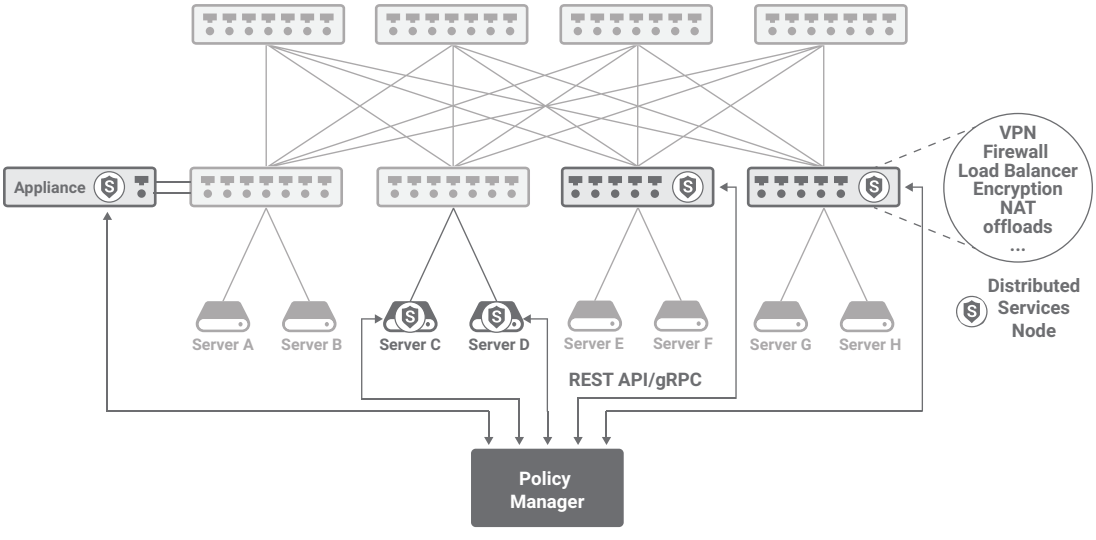

FIGURE 1-1 A Distributed Services Platform

1.1 The Need for a Distributed Services Platform

A real distributed services platform should solve not only performance issues but should also provide:

- A consistent services layer common to bare-metal servers, virtual machines, and containers
- Pervasive security without any entitlements within the perimeter; that is, decouple security from network access

- A security solution that is immune to compromised OSes or hypervisors
- Services orchestration and chaining to simplify management while enabling the delivery of different combinations of services
- Better utilization of resources, higher performance, lower latency, and latency isolation
- Tools capable of troubleshooting the network flows going through multiple services
- Built-in telemetry for edge-to-edge network troubleshooting, rather than debugging individual systems, applications and segments, to give the infrastructure the ability to proactively report potential issues and offending actors
- A comprehensive set of infrastructure services that are easy to manage and that can be used together, including features such as microsegmentation, load balancing, a firewall, encryption service, storage virtualization, and infrastructure services such as RDMA and TCP/TLS proxy
- Programmability in the management, control, and data planes so that software-defined features can be rolled out without requiring hardware swapout or extended hardware development and release cycles

1.2 The Precious CPU Cycles

In recent years, single-thread performance has only grown a few percentage points a year due to the slowdown in Moore's law as well as Dennard scaling issues (see Chapter 7, "CPUs and Domain-Specific Hardware"). Similarly, increasing the number of cores per CPU only partially helps, due to the problems pointed out in Amdahl's law on parallelization.

Another important aspect is that CPU architectures and their associated operating systems are not the best matches for implementing services at the packet level: an example is interrupt-moderation, which reduces the number of interrupts to increase throughput, but has the side effect of jitter explosion.

As processors become more complex, processor cycles are becoming more precious every day and should be used for user applications and not for network services. A purely software-based solution might use a third of the available cores on an enterprise-class CPU to implement services; this is unacceptable in cases of high load on servers. It creates a big pushback for software-based services architectures.

1.3 The Case for Domain-Specific Hardware

Domain-specific hardware can be designed to be the best implementation for specific functions. An example of successful domain-specific hardware is the graphic processor unit (GPU).

GPUs were born to support advanced graphics interfaces by covering a well-defined domain of computing—matrix algebra—which is applicable to other workloads such as artificial intelligence (AI)

and machine learning (ML). The combination of a domain-specific architecture with a domain-specific language (for example, CUDA and its libraries) led to rapid innovation.

Another important measure that is often overlooked is power per packet. Today's cloud services are targeted at 100 Gbps, which for a reasonable packet size is equivalent to 25 Mpps. An acceptable power budget is 25 watts, which equates to 1 microwatt per packet per second. To achieve this minuscule amount of power usage, selecting the most appropriate hardware architecture is essential. For example, Field-Programmable Gate Arrays (FPGAs) have good programmability but cannot meet this stringent power requirement. You might wonder what the big deal is between 25 watts and 100 watts per server. On an average installation of 24 to 40 servers per rack, it means saving 1.8 to 3.0 kilowatts of power per rack. To give you an example, 3 kilowatts is the peak consumption of a single-family home in Europe.

When dealing with features such as encryption (both symmetric and asymmetric) and compression, dedicated hardware structures explicitly designed to solve these issues have much higher throughput and consume far less power than general-purpose processors.

This book should prove to the reader that a properly architected domain-specific hardware platform, programmable through a domain-specific language (DSL), combined with hardware offload for compression and encryption, is the best implementation for a DSN.

Although hardware is an essential aspect of a distributed services platform, a distributed services platform also uses a considerable amount of software.

The management and control planes are entirely software, and even the data plane must be software defined. The hardware is what provides the performance and lowers latency and jitter when used in conjunction with software. When we compare performance and delays, the differences can be enormous. Leading solutions exist in which the first packet of a flow incurs a 20-millisecond delay and other solutions in which the same packet is processed in 2 microseconds: a difference of four orders of magnitude.

1.4 Using Appliances

Today the most common implementation of services is through appliances, typically deployed centrally. These network devices implement services such as firewall, load balancing, and VPN termination. These are discrete boxes, and the traffic is sent to them explicitly in a technique called *tromboning* (see section 2.7). These devices become natural bottlenecks for traffic and impose a weird routing/forwarding topology. They are very high-cost, high-performance devices, and even the most capable ones have limitations in performance when compared to the amount of traffic that even a small private cloud can generate. These limitations, plus the fact that a packet must traverse the network multiple times to go through service chaining, result in reduced throughput and high latency and high jitter.

A distributed services platform avoids these large centralized appliances and relies on small high-performance distributed services nodes (DSNs) located as closely as possible to the final applications they serve. They are also multifunctional; that is, they implement multiple services and can chain them internally, in any order, without needing to traverse the network numerous times.

1.5 Attempts at Defining a Distributed Services Platform

The first question we should ask ourselves is, "Which services should this architecture support?" A precise classification is difficult, if not impossible, but Figure 1-2 is an example of some of the services typically associated with a domain-specific platform.

From 10,000 feet, we can see two groups of services: infrastructure services and value-added services.

Infrastructure services are things such as Ethernet and bridging, IP and routing, storage access through a modern protocol like NVMe, RDMA transport, TCP termination, and overlay network processing.

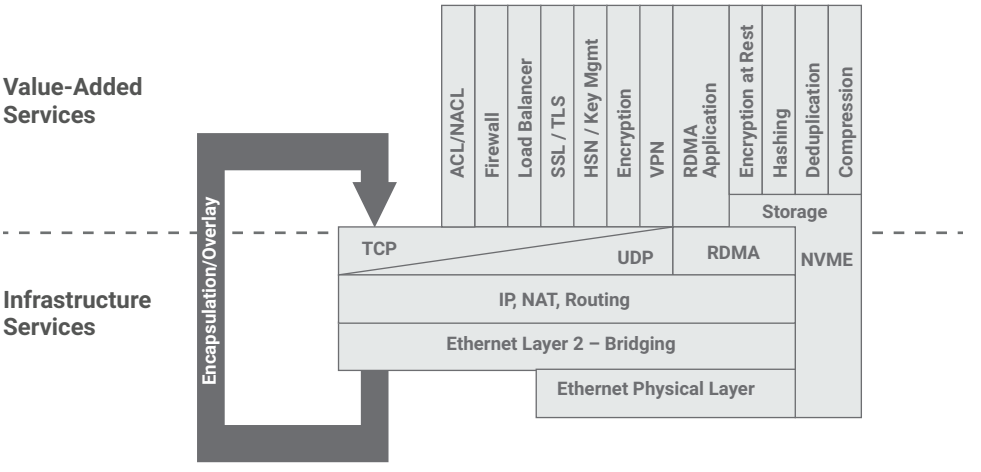

FIGURE 1-2 Services

Value-added services include a firewall, load balancer, encryption (both symmetric and asymmetric, both in flight and at rest), key management and secure storage, classical VPNs like IPsec, and more modern ones such as SSL/TLS, storage compression, and deduplication.

In this book, we will present infrastructure and value-added services together because they are deployed together in the majority of the cases.

The first attempt at a truly "distributed" network architecture can be traced back to software-defined networking (SDN). SDN is a paradigm that was introduced initially on switches and routers but was expanded to servers. It offers the capability to control and program the NIC virtual forwarding functions.

The main focus of SDNs is on infrastructure services. They do not currently address value-added services, but they create a framework where DSNs are under the central coordination of a common manager and work together toward a common goal.

There is also an open-source effort within the container community, called *service mesh*, that defines the services, such as load balancing, telemetry and security, distributed across the clusters of nodes

and combined with a management control plane. The approach uses a software proxy sitting next to an application to provide layer 4 or layer 7 load balancing features and TLS security between applications and provide telemetry for all the traffic that passes through the proxy. The management control plane provides integration with orchestration systems, such as Kubernetes, and also provides a security framework to do key management for applications and define authorization primitives that can police interapplication communication. Although the effort started for containers, the concepts and code can be leveraged for virtual machines. There are many implementations of service mesh, such as Istio, Nginx, Linkerd, and some commercial closed-source implementations.

It is definitely possible to provide a much superior service mesh with DSNs by offering better security via keeping private keys within the hardware root of trust, by improving performance by an order of magnitude, and by reducing interapplication latency, without losing the software programmability.

The distributed services platform also attempts to address a few additional elements:

- Provide immunity from host/application/hypervisor compromises; that is, the enforcer shouldn't be compromised if the enforcee is compromised
- Provide services beyond the network, for example, storage, RDMA, and so on
- Offer low latency, high throughput, and latency isolation without impacting application performance
- Exhibit cloudlike scale to handle millions of sessions

A distributed services platform may be used alongside service mesh, which is an application layer concept, as opposed to an infrastructure layer concept. For example, the distributed services platform may provide isolation, security, and telemetry at the virtualization infrastructure layer, whereas service mesh can provide application layer TLS, API routing, and so on.

1.6 Requirements for a Distributed Services Platform

A truly distributed services platform requires the availability of DSNs that are placed as closely as possible to the applications. These DSNs are the enforcement or action points and can have various embodiments; for example, they can be integrated into NICs, appliances, or switches. Having as many services nodes as possible is the key to scaling, high performance, and low delay and jitter. The closer a DSN is to applications, the lesser the amount of traffic it needs to process, and the better the power profile becomes.

Services may appear to be well defined and not changing over time, but this is not the case. For example, new encapsulations or variations of old ones or different combinations of protocols and encapsulations are introduced over time. For this reason, DSNs need to be programmable in the management, control, and data planes. The control and management planes may be complicated, but they are not data intensive and are coded as software programs on standard CPUs. Data plane programmability is a

crucial requirement because it determines the performance and the scaling of the architecture. Network devices that are data plane programmable are still pretty rare, even if there have been some attempts in the adapter space with devices that are typically called SmartNIC and in the switching/routing space using a domain-specific programming language called P4.

An excellent services platform is only as good as the monitoring and troubleshooting features that it implements. Monitoring has significantly evolved over the years, and its modern version is called *telemetry*. It is not just a name change; it is an architectural revamp on how performance is measured, collected, stored, and postprocessed. The more dynamic telemetry is and the less likely it is to introduce latency, the more useful it is. An ideal distributed services platform has "always-on telemetry" with no performance cost. Also, compliance considerations are becoming extremely important, and being able to observe, track, and correlate events is crucial.

Where do services apply? To answer this question, we need to introduce a minimum of terminology. A common way to draw a network diagram is with the network equipment on top, and the compute nodes at the bottom. If you superimpose a compass rose with the North on top, then the term North-South traffic means traffic between the public network (typically the Internet) and servers; the term East-West implies traffic between servers (see Figure 1-3).

Historically the North-South direction has been the focus of services such as firewall, SSL/TLS termination, VPN termination, and load balancing. Protecting the North-South direction is synonymous with protecting the periphery of the cloud or data center. For many years, it has been security managers' primary goal because all the attacks originated on the outside, and the inside was composed of homogeneous, trusted users.

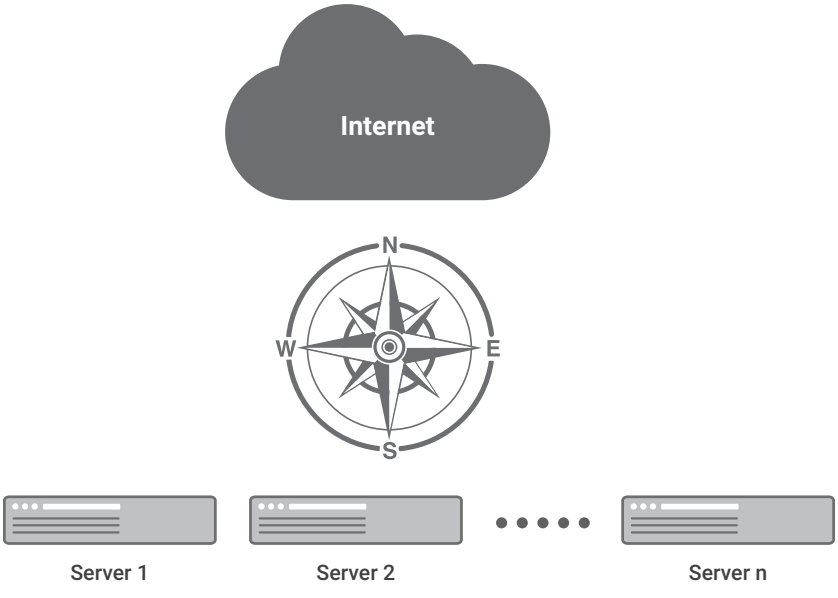

FIGURE 1-3 North-South vs. East-West

With the advent of public clouds, the change in the type of attacks, the need to compartmentalize large corporations for compliance reasons, the introduction of highly distributed microservice architectures, and remote storage, East-West traffic is now demanding the same level of services as the North-South connections.

East-West traffic requires better services performance than North-South for the following reasons:

- Usually, the North-South traffic has a geographical dimension; for example, going through the Internet creates a lower bound to the delay of milliseconds, due to propagation delays. This is not the case for East-West traffic.
- East-West traffic is easily one order of magnitude higher in bytes than North-South traffic, a phenomenon called "traffic amplification," where the size of the response and internal traffic can be much larger, that is, "amplified," compared to the inbound request. For this reason, it requires services with higher throughput.
- With the advent of solid-state disks (SSDs), the storage access time has dramatically decreased, and delays associated with processing storage packets must be minimal.
- In microservice architectures, what on the North-South direction may be a simple transaction is in reality composed of multiple interactions between microservices on the East-West direction. Any delay is critical because it is cumulative and can quickly result in performance degradation.

Institutions with sensitive data, such as banks or healthcare providers, are considering encrypting all the East-West traffic. It implies, for instance, that each communication between two microservices must be encrypted and decrypted: If the encryption service is not line-rate and low-latency, this will show up as degraded performance.

1.7 Summary

This introductory chapter delineated what a distributed services platform could be, the continuously evolving requirements of the cloud world, the rising importance of the East-West traffic, and the need for domain-specific hardware and common management.

Starting with the next chapter, we will cover all these aspects in detail.

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