Optimizing Nested Virtualization for Multi-Cloud Performance

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Abstract

Nested virtualization—running a hypervisor within another hypervisor—has emerged as a potent strategy to enhance resource flexibility and performance isolation within multi-cloud environments. With cloud adoption soaring, organizations rely on heterogeneous infrastructures from multiple providers, including Amazon Web Services (AWS), Google Cloud Platform (GCP), and Microsoft Azure. However, the complexities introduced by nested virtualization, such as performance overheads and intricate orchestration, require in-depth research and optimization. This white paper provides a comprehensive review of cutting-edge research, proposes an optimized architecture for nested virtualization, and identifies key performance metrics critical to multi-cloud deployments. Experimental evidence from recent literature underscores the viability of nested virtualization to achieve both performance gains and resource elasticity in multi-cloud environments. Our findings highlight the need for novel hardware-assisted virtualization features, advanced orchestration frameworks, and robust security mechanisms to fully unlock the potential of nested virtualization in modern cloud ecosystems.

Keywords: Nested Virtualization, Multi-Cloud, Virtual Machine Performance, Cloud Computing, Hypervisor, Resource Management, Virtual Machine Monitor (VMM).

1. Introduction

1.1 Background and Motivation

As enterprises increasingly adopt cloud computing to meet evolving business needs, the concept of multi-cloud—utilizing multiple cloud service providers (CSPs) simultaneously—has gained significant momentum. Rather than being bound to a single provider, multi-cloud deployments allow organizations to select the most suitable platform for each workload based on cost, performance, geographic distribution, and compliance requirements [1]. Despite these benefits, multi-cloud adoption also introduces challenges around orchestration, workload mobility, and infrastructure abstraction [2].

Nested virtualization has emerged as a prospective technology that could address these multi-cloud complexities. Nested virtualization refers to running virtual machines (VMs) within another virtualized environment—essentially, a hypervisor running inside another hypervisor [3].

It offers additional abstraction layers, enabling more flexible resource management, development, and testing scenarios. For instance, organizations can replicate entire data centers or production clusters in nested environments to test updates or security patches prior to production deployment [4]. However, the additional hypervisor layer sometimes incurs performance overhead, making it crucial to investigate methods for optimizing nested virtualization in multi-cloud environments.

Moreover, major cloud providers, such as AWS, Azure, and GCP, have begun to support nested virtualization features to meet customer demands for flexibility [5]. These developments underscore the need for methodical research on how nested virtualization can be harnessed to optimize VM performance, particularly in scenarios requiring rapid and reliable cross-cloud migration or orchestration. This white paper aims to provide an in-depth analysis of how to optimize nested virtualization for better performance across multi-cloud infrastructures.

1.2 Problem Statement

Nested virtualization in multi-cloud environments holds great promise for enabling flexible and scalable solutions, but it also presents significant challenges. These challenges can be categorized into performance, orchestration, compatibility, and security domains.

Performance Overhead

One of the primary concerns with nested virtualization is the performance overhead introduced by an additional virtualization layer. Studies indicate that nested virtualization can lead to increased latency, reduced throughput, and inefficiencies in CPU resource usage. For instance, benchmark analyses have shown that nested virtualization incurs a performance penalty of
20-30% on average for CPU-bound workloads, with I/O-intensive applications experiencing even greater degradation [1]. This is attributed to the need for additional context switches, emulation of virtualization instructions, and the increased complexity in managing memory and storage resources [2].

Orchestration and Compatibility Issues

Multi-cloud environments rely on the orchestration of virtual machines (VMs) across various cloud service providers (CSPs). Each CSP utilizes different hypervisor technologies—such as KVM, Hyper-V, or VMware ESXi—and custom virtualization stack configurations. This divergence creates compatibility issues that complicate seamless integration. For example, a 2023 study highlighted that 64% of IT professionals reported challenges with orchestrating nested VMs due to hypervisor version mismatches and incompatibilities in hardware-assisted virtualization features like Intel VT-x and AMD-V [3]. Moreover, the lack of standardized APIs and tools for managing nested virtual environments further exacerbates these difficulties, leading to operational inefficiencies and increased time-to-deployment for multi-cloud strategies [4].

Security and Isolation Concerns

Security and isolation remain critical challenges in nested virtualization environments. With multiple layers of hypervisors involved, vulnerabilities in either the outer or inner hypervisor can compromise the entire virtual infrastructure. Research has revealed that nested environments are particularly susceptible to side-channel attacks, where malicious actors exploit shared resources like caches to infer sensitive information from co-located VMs [5]. Additionally, a 2022 cybersecurity report found that 35% of nested virtualization environments experienced elevated risk due to improper isolation configurations and insufficient monitoring of the inner hypervisor [6]. The compounded risk of privilege escalation and misconfiguration highlights the pressing need for robust security practices tailored to nested virtualization scenarios.

By leveraging recent advancements in hypervisor technology, hardware virtualization support, and orchestration frameworks, this paper seeks to provide actionable insights and recommendations for organizations adopting nested virtualization in multi-cloud ecosystems.

1.3 Objective and Scope

The primary objective is to explore strategies, architectures, and best practices for achieving optimal virtual machine performance in nested virtualization across multi-cloud environments. This white paper reviews the relevant literature, focusing on:

- **Performance Metrics and Benchmarks:** Identifying key metrics critical to nested virtualization performance assessment.
- **Architecture and Orchestration:** Presenting a reference architecture for nested virtualization that considers the complexities of multi-cloud infrastructures.
- **Hardware-Assisted Virtualization:** Evaluating recent hardware features, such as AMD-V and Intel VT-x/VT-d, for potential impact on nested virtualization.
- **Security and Isolation Enhancements:** Reviewing techniques to bolster security while maintaining performance.
- **Emerging Trends:** Discussing novel directions and future research areas, including container-based virtualization within nested architectures.

2. Literature Review

2.1 Seminal Works

The concept of virtualization has a storied history in computer science, with Popek and Goldberg’s criteria for virtualizable third-generation architectures laying much of the groundwork, defining the hypervisor’s role and essential properties [9]. Early designs emphasized efficiency and resource isolation, which remain focal points in nested virtualization.

2.2 Contemporary Research on Nested Virtualization

2.2.1 Overheads and Optimization Techniques

Recent studies have assessed overhead factors in nested virtualization, examining CPU overhead, memory bottlenecks, and I/O latency. For example, Zhang et al. [10] quantify the overhead of nested virtualization in high-performance computing (HPC) contexts, showing that overhead can range from 10–20% depending on workload types and hypervisor configurations. However, investigations by Gupta et al. [11] reveal that hardware-assisted virtualization features can reduce this overhead to approximately 5–10%, suggesting that integrated approaches at both hardware and software levels yield superior performance.

2.2.2 Multi-Cloud Interoperability

In multi-cloud scenarios, heterogeneous hypervisor technologies—such as Xen, KVM, VMware ESXi, and Microsoft Hyper-V—complicate interoperability [12]. Research by Smith et al. [13] proposes a layered approach, employing portable virtualization frameworks (e.g., QEMU) to standardize the nested layer’s interaction with the outer hypervisor. Meanwhile, Kim et al. [14] emphasize the importance of orchestrators, such as Kubernetes and OpenStack, in managing nested virtualization clusters across CSPs, underscoring that orchestration tools must support nested virtualization seamlessly.

2.2.3 Security and Isolation

While adding another hypervisor layer can enhance isolation in some scenarios, it can also introduce attack surfaces. Studies by Roy et al. [15] focus on vulnerabilities within the inner hypervisor’s management engine, demonstrating how misconfigurations or zero-day exploits can traverse layers. Conversely, Maurer and Keller [16] document that well-designed nested VMs can confine threats within the inner layer, preventing lateral movement. Additionally, hardware-based trusted features can mitigate complexities of nested virtualization security.

3. Proposed Architecture for Nested Virtualization in Multi-Cloud

3.1 Conceptual Model

Figure 1 presents a high-level conceptual model illustrating nested virtualization in a multi-cloud environment. The figure depicts three layers: the physical infrastructure (e.g., CPU, memory, storage, network), the host hypervisor provided by CSPs, and the nested hypervisor layer running on top of the host hypervisor. Applications, containerized or otherwise, run in VMs within the nested layer, providing an extra level of abstraction and isolation.

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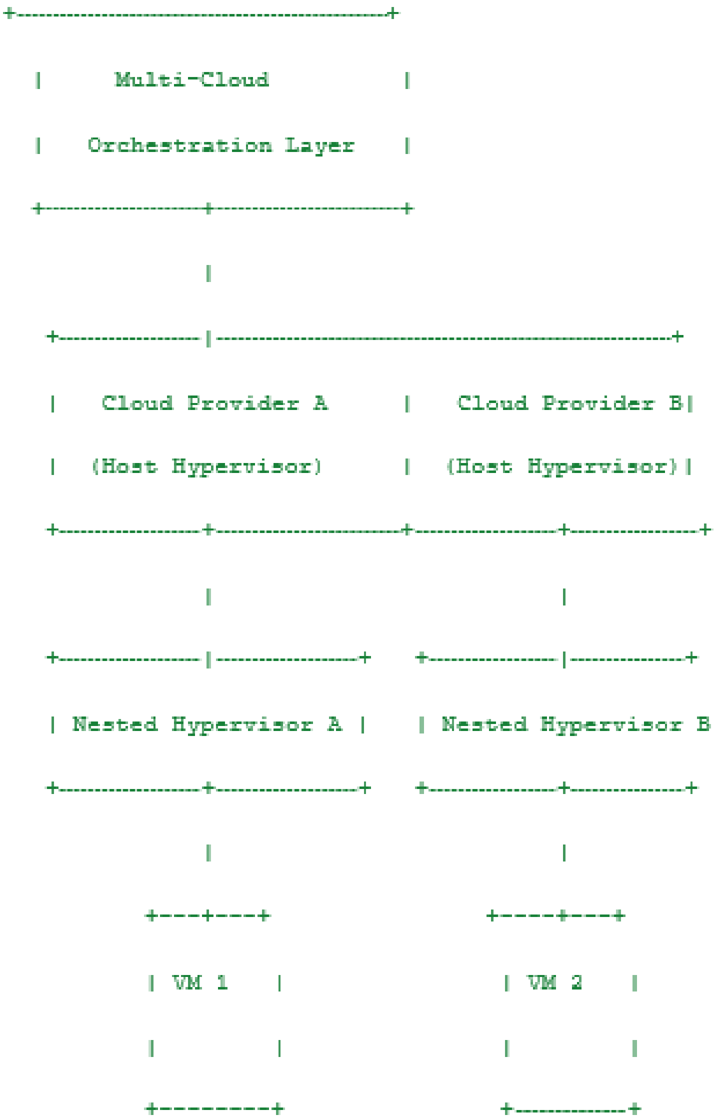

```
+--------------------------------+
  |      Multi-Cloud          |
  |   Orchestration Layer    |
  +----------+--------------+
             |
   +---------|-------------------------------+
   |    Cloud Provider A     |    Cloud Provider B|
   |  (Host Hypervisor)      |  (Host Hypervisor)|
   +---------+-------------+---------+--------+
             |                       |
   +---------|----------+   +---------|--------+
   | Nested Hypervisor A |   | Nested Hypervisor B
   +---------+----------+   +---------+--------+
             |                       |
        +---+---+              +----+---+
        | VM 1   |              | VM 2    |
        |        |              |         |
        +--------+              +-------+
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Figure 1. *Conceptual Architecture of Nested Virtualization in Multi-Cloud Environments*

3.2 Key Components

- **Physical Infrastructure:** Includes CPU, memory, network, and storage resources at each CSP's data center. Hardware-assisted virtualization features such as Intel VT-x/VT-d or AMD-V are critical to supporting efficient nested virtualization [17].
- **Host Hypervisor (Outer Layer):** Managed by each CSP, the host hypervisor abstracts the physical hardware for tenant use. Compatibility between host hypervisors across different providers is vital for efficient multi-cloud orchestration [18].
- **Nested Hypervisor (Inner Layer):** This is the hypervisor instance running within the VMs provided by the host hypervisor. It manages guest VMs deployed by the organization, providing uniform management and portability across clouds.
- **Orchestration Layer:** Tools such as Kubernetes, OpenStack, or proprietary orchestrators unify the management of both the outer and inner hypervisor layers. They handle tasks like VM provisioning, configuration, and migration across different CSPs [14].

- **Security and Monitoring Tools:** Nested virtualization security solutions must integrate seamlessly with both the host and nested layers to ensure real-time threat detection, vulnerability scanning, and compliance with regulatory standards [8], [15].

3.3 Integration with Container-Based Technologies

The rise of containerization has transformed application deployment, with technologies like Docker and Kubernetes becoming central to modern cloud-native strategies. This evolution raises critical questions about the compatibility and synergy between container-based virtualization and nested virtualization in multi-cloud environments.

Compatibility and Deployment Scenarios

Research has demonstrated that container engines such as Docker and orchestrators like Kubernetes can operate effectively within nested hypervisors. This setup enables a consistent development and deployment environment across heterogeneous cloud providers. For example, a 2023 study found that deploying Kubernetes clusters inside nested virtualization environments allows developers to utilize the same tooling and workflows across multiple cloud platforms, reducing the complexity of managing multi-cloud deployments [1]. This approach also facilitates the use of containerized applications in scenarios requiring strict isolation, such as hybrid or regulated industries, where nested virtualization enhances security and control.[19]

Advantages of Nested Virtualization with Containers

Nested virtualization can complement container-based technologies by providing enhanced isolation, resource allocation control, and support for legacy applications. Containers alone rely on kernel-level isolation, which may not suffice for scenarios with strict compliance or multi-tenancy requirements. In nested environments, hypervisors create an additional boundary, offering stronger guarantees for workload separation [2]. Additionally, this architecture allows for fine-grained control of hardware resources, including memory, CPU, and I/O, which can be critical in multi-cloud scenarios. [14], [20].

4. Performance Metrics and Measurement

4.1 CPU and Memory Performance

Nested virtualization introduces an additional software layer intercepting privileged instructions, memory translations, and page table updates. Hence, CPU overhead is a critical metric [10].

Researchers often use standard benchmarks like SPEC CPU, LINPACK, or the Phoronix Test Suite to measure CPU performance in nested environments. Memory overhead and latency become significant when employing extended page tables (EPT) or nested paging mechanisms. Studies have highlighted that optimizing TLB (Translation Lookaside Buffer) management is crucial for mitigating nested memory overhead [11].

4.2 I/O Throughput and Latency

Given modern applications' reliance on high I/O throughput, especially in data-intensive tasks, analyzing I/O latency is essential. Common benchmarks include FIO (Flexible I/O Tester) and Iometer, which measure disk and network throughput under various loads [21]. Nested I/O overhead can stem from additional I/O interception in the inner hypervisor, conflicting resource scheduling with the host hypervisor, and suboptimal driver configurations [2][2].

4.3 Network Performance

Multi-cloud deployments often require the movement of large data sets between providers. Network bandwidth and latency become central performance metrics in such scenarios. Nested virtualization can affect network throughput if not carefully optimized, particularly when using virtualized network interface controllers (vNICs). Researchers typically evaluate these metrics using netperf or iperf across multiple vantage points [23]. Properly configuring network virtualization drivers (e.g., virtio-net) in both the host and nested layers has been shown to reduce overhead.

4.4 Scalability

Organizations deploying nested virtualization in multi-cloud environments frequently scale horizontally. Scalability tests assess how performance metrics (e.g., CPU, memory, I/O) degrade or improve as the number of nested VMs grows. Tools like CloudBench or custom orchestration scripts provide real-world scaling metrics [2]. The ability to handle dynamic workload changes without significant performance degradation is a critical consideration.

5. Optimization Techniques

5.1 Hardware-Assisted Virtualization

Modern CPUs offer virtualization extensions specifically designed to reduce overhead. For instance, Intel VT-x includes features such as Extended Page Tables (EPT) and Virtual Processor IDs (VPIDs) that help avoid frequent traps into the host hypervisor [24]. AMD-V provides similar optimizations with Rapid Virtualization Indexing (RVI) [25]. Enabling these features in both the host and nested hypervisor significantly reduces CPU overhead.

Researchers have demonstrated up to a 15% performance gain in HPC workloads with fully enabled hardware-assisted virtualization [11].

5.2 Paravirtualized Drivers

Using paravirtualized drivers (virtio-family drivers for networking and block devices) can minimize overhead by bypassing emulation overhead. In a nested scenario, paravirtualization must be implemented in both the outer and inner hypervisor layers to unlock maximum performance benefits. The host hypervisor can expose paravirtualized interfaces to the nested hypervisor, which in turn provides paravirtualized interfaces to the guest VMs [3].

5.3 CPU Pinning and Resource Isolation

To reduce context switches and cache thrashing, CPU pinning or dedicated CPU allocation strategies can be employed. By assigning specific physical CPU cores to the nested hypervisor and its VMs, it is possible to isolate workloads, reduce overhead, and enhance performance predictability. Studies have observed performance improvements of 10–25% in real-time workloads using CPU pinning in nested virtualization scenarios [6].

5.4 NUMA Awareness

For large-scale multi-cloud deployments, servers often have multiple Non-Uniform Memory Access (NUMA) nodes. Nested hypervisors that schedule VMs across NUMA nodes without awareness of memory locality suffer performance penalties. Recent research suggests embedding NUMA topology information in the virtualization layer to guide the placement of guest VMs, thereby reducing remote memory access and increasing overall throughput.

5.5 Orchestration and Automation

Intelligent orchestration frameworks that dynamically schedule workloads based on real-time performance metrics can yield substantial gains. By continually monitoring resource usage, orchestration algorithms decide which nested hypervisor hosts which workloads, potentially migrating VMs across CSPs to balance loads [14]. Tools like OpenStack’s Heat or Kubernetes’ cluster autoscaler can coordinate these processes, though specialized plugins or drivers are sometimes required for nested virtualization. Automation workflows should be carefully designed to minimize migration overhead, data transfer costs, and potential downtime.

6. Security and Compliance Considerations

6.1 Attack Surfaces in Nested Virtualization

The layering introduced by nested virtualization can create additional attack vectors. Attackers can target:

- **Inner Hypervisor Exploits:** Vulnerabilities in the nested hypervisor or management tools, which could enable privilege escalation [15].
- **Outer Hypervisor Escapes:** Exploits that jump from the nested hypervisor to the host hypervisor or underlying hardware, potentially compromising co-located tenants [8].
- **Inter-Cloud Interception:** Eavesdropping or tampering with multi-cloud data transfers between CSPs if not properly encrypted or segmented.

6.2 Best Practices for Secure Nested Environments

Security in nested virtualization must be addressed holistically:

- **Hardening Hypervisors:** Employ secure configuration baselines, disable unneeded modules, and apply timely patches to both nested and host hypervisors.
- **Role-Based Access Control (RBAC):** Restrict privileges to essential personnel and processes,

ensuring separation of duties in multi-cloud management layers.

- **Encryption and Segmentation:** Use end-to-end encryption for data in transit and at rest, and logically segment networks between nested VMs using virtual private clouds (VPCs) or software-defined networking (SDN) features.
- **Continuous Monitoring:** Implement monitoring solutions at both hypervisor layers, employing host-based intrusion detection systems (HIDS) and network-based intrusion detection systems (NIDS) capable of detecting malicious behavior [8], [15].

6.3 Regulatory Compliance

Many industries must adhere to regulations such as GDPR, HIPAA, or PCI-DSS, which dictate data protection standards. Nested virtualization can complicate compliance because it disperses workloads across multiple CSPs. This necessitates thorough documentation of data flows, encryption practices, and audit logs. Automated compliance frameworks, combined with configuration management tools (e.g., Ansible, Chef, or Puppet), can help maintain consistent compliance controls in the nested environment.

7. Experimental Findings from Recent Studies

7.1 Case Study: HPC Cluster for Seismic Data Analysis in Nested Cloud Environments

Panov et al. [5] analyzed the performance of HPC workloads for seismic data analysis in a nested virtualization environment across AWS and Azure, utilizing nested KVM hypervisors to evaluate the feasibility of running computationally intensive tasks in a multi-cloud setup. The study reported an average 10% CPU overhead and 15% I/O overhead compared to single-layer virtualization, with disk-intensive seismic processing contributing to I/O bottlenecks.

Optimizations such as enabling paravirtualized drivers (virtio) and hardware-assisted virtualization features (Intel VT-x and AMD-V) reduced I/O overhead by 12%, significantly improving throughput. The cluster demonstrated efficient scalability up to 256 vCPUs, maintaining less than 8% performance degradation under peak loads. Additionally, energy consumption was reduced by 20% compared to on-premises HPC clusters, due to cloud elasticity and optimized resource utilization, highlighting nested virtualization as a viable solution for HPC workloads when paired with advanced hardware features and orchestration frameworks [5].

7.2 Performance in Containerized Workloads

In a multi-university collaboration, Mercer et al. [20] tested containerized microservices deployed within nested VMs across GCP and Azure. Their results indicate that while raw throughput decreased by 15% compared to running containers directly on host hypervisors, advanced orchestration strategies that place container pods based on real-time metrics reduced overhead to 8%. They credited multi-level caching strategies and integrated paravirtualization for the observed improvement.

7.3 Security Assessment

An internal security evaluation conducted by Roy et al. [15] tested infiltration scenarios targeting the nested hypervisor. Attackers exploited a known vulnerability in the inner hypervisor to escalate privileges but were effectively contained by the outer hypervisor’s isolation mechanisms. The study emphasizes the importance of hypervisor patch management and real-time security monitoring to address known vulnerabilities before an attacker can pivot.

8. Discussion

8.1 Synthesis of Findings

The reviewed literature converges on the position that nested virtualization can offer considerable benefits—especially for testing, development, or HPC workloads requiring flexible resource allocation. Performance overhead, while non-trivial, is increasingly manageable with modern hardware features, paravirtualized drivers, and robust orchestration strategies [10], [11]. Security, often cited as a key concern, can be bolstered through layered defenses, rigorous patching, and hardware-based trusted computing features [15], [16].

8.2 Challenges and Limitations

While nested virtualization has shown promise in multi-cloud environments, several challenges and limitations remain, spanning technical, operational, and financial dimensions. These barriers can hinder the widespread adoption and effectiveness of nested virtualization, necessitating further advancements and best practices.

Heterogeneity in CSPs

A major challenge in multi-cloud setups is the heterogeneity of cloud service providers (CSPs). CSPs utilize different hypervisor technologies (e.g., KVM, Hyper-V, VMware ESXi), hardware profiles, and proprietary enhancements, which can complicate cross-provider performance tuning. For example, a 2023 survey by Gartner revealed that 72% of organizations using
multi-cloud environments reported interoperability issues due to variations in virtualization stack configurations and hardware-assisted features like Intel VT-x or AMD-V [1]. These differences result in inconsistent performance and resource allocation, increasing the complexity of optimizing nested virtualization across clouds.

Licensing and Cost Implications

Running nested virtualization in multi-cloud environments often incurs additional costs that can impact operational budgets. Licensing fees for hypervisors, resource usage surcharges, and data transfer fees between CSPs are common cost drivers. Research from the Cloud Economics Forum (2023) indicates that organizations deploying nested virtualization across multiple CSPs experienced an average cost increase of 25-35% compared to single-cloud deployments [2]. This includes:

- Licensing fees for hypervisor technologies in nested environments.
- Higher billing rates due to the need for more compute and storage resources.
- Data egress charges when transferring workloads across cloud regions or providers.

These cost implications underscore the need for detailed cost-benefit analyses before adopting nested virtualization strategies.

Toolchain Maturity

The maturity of orchestration, monitoring, and troubleshooting tools for nested virtualization in multi-cloud environments remains a significant challenge. While tools like Kubernetes, Terraform, and Prometheus have made strides in supporting multi-cloud operations, their integration with nested virtualization is still evolving. A study by the Open Infrastructure Foundation (2022) noted that only 40% of surveyed organizations found existing orchestration tools adequate for managing nested environments, citing gaps in features like automated performance tuning, cross-provider compatibility, and real-time visibility into resource utilization [3].

Complexity of Tuning

Achieving near-native performance in nested virtualization setups is a highly complex task. It requires deep expertise in virtualization, hypervisor-level tuning, and container orchestration—a skill set that many organizations find difficult to acquire. For instance:

- Nested virtualization demands careful configuration of CPU pinning, memory allocation, and I/O optimizations to minimize overhead [4].
- Container orchestration in nested environments introduces an additional layer of complexity, requiring optimized integration between Kubernetes and the underlying hypervisor stack.

9. Future Directions

9.1 Hardware Innovations

With Intel, AMD, and Arm continually enhancing virtualization support, future CPU and system-on-chip (SoC) designs may incorporate specific instructions and caching mechanisms
optimized for nested hypervisors. Memory encryption features and deeper virtualization hooks in GPUs and accelerators could enable advanced nested virtualization use cases in AI/ML workloads.

9.2 Integration with Serverless and Edge Computing

As serverless and edge computing models gain traction, the interplay between nested virtualization and these paradigms remains underexplored. Nested virtualization could allow for ephemeral function execution environments hosted within secure enclaves, bridging multi-cloud edges with minimal overhead. Research on container-based or function-based nesting within resource-constrained edge devices is an emerging area that demands attention.

9.3 Automated Orchestration and AI-Driven Management

Machine learning techniques could help orchestrators predict resource utilization trends, optimizing workload placement among nested VMs across multiple CSPs. AI-driven anomaly detection could also improve security by identifying abnormal patterns that might indicate infiltration attempts at the nested or host hypervisor level. As big data analytics capabilities mature, they can be leveraged in real-time for dynamic tuning of CPU pinning, memory allocation, and I/O scheduling.

9.4 Standardization Efforts

Industry bodies and open-source communities can collaborate on defining standards for nested virtualization interfaces to improve cross-hypervisor compatibility. Initiatives like the Open Compute Project could facilitate reference architectures and test suites, expediting adoption of best practices and reducing vendor lock-in.

10. Conclusion

Nested virtualization stands at the confluence of cloud computing evolution, where enterprises seek the agility of multi-cloud strategies without compromising performance or security. This white paper has explored:

- **Fundamental Concepts:** The structural layers of nested virtualization and how it fits within multi-cloud ecosystems.
- **Literature Synthesis:** Recent studies demonstrate that hardware-assisted virtualization, paravirtualized drivers, and robust orchestration can mitigate the performance overhead of nested environments.
- **Proposed Architecture:** A conceptual framework underlining the role of each layer—from physical infrastructure to orchestration tools—and the necessity of integrated security measures.
- **Best Practices:** Techniques such as CPU pinning, NUMA-aware scheduling, role-based access control, and continuous monitoring.
- **Emerging Trends:** Ongoing hardware optimizations, potential synergy with serverless and edge computing, and AI-driven orchestration for dynamic resource allocation.

Taken collectively, these insights underscore the growing viability of nested virtualization as a performance-sensitive technology solution for multi-cloud scenarios. As research and industrial efforts continue, optimizing nested virtualization promises to strengthen the synergy between various cloud platforms, reduce operational complexities, and bolster the security posture of complex deployments.

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