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Virtualization technologies in cloud: An overview of current trends

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Abstract

Virtualization technologies have emerged as a cornerstone for cloud computing, enabling more efficient and scalable management of computing resources. The ongoing evolution of these technologies has significantly impacted cloud infrastructures, allowing for enhanced flexibility, resource optimization, and cost efficiency. Cloud providers leverage virtualization to offer multi-tenant environments where multiple users can share resources while ensuring isolation and security. Technologies such as server virtualization, network virtualization, and storage virtualization are becoming increasingly integral to cloud computing platforms, contributing to better resource utilization and providing a means for rapid provisioning and dynamic scaling.

The emergence of containerization and microservices architectures has further accelerated the adoption of virtualization in cloud services. These advancements allow developers to build and deploy applications with greater efficiency and minimal overhead. Additionally, virtualization technologies are not only central to public cloud offerings but also play a key role in hybrid and private cloud models, enabling enterprises to migrate workloads seamlessly between on-premises infrastructure and the cloud.

Despite the many benefits, the implementation and management of virtualization technologies in the cloud present several challenges, including security concerns, performance overhead, and resource contention. This paper reviews the current trends in virtualization technologies, focusing on advancements such as container orchestration, hyper-convergence, and virtual machine optimization. The objective is to highlight the role of virtualization in shaping the future of cloud computing and identify potential areas for improvement. The paper also explores the future directions of virtualization technologies and their impact on the cloud landscape.

Keywords: Virtualization, cloud computing, containerization, microservices, hyper-convergence, resource optimization, cloud security, virtual machines, orchestration, multi-tenant environments

Introduction

Cloud computing has revolutionized the IT landscape by providing scalable, on-demand computing resources. One of the keys enabling technologies behind the cloud's success is virtualization, which allows cloud providers to abstract, pool, and dynamically allocate resources. Virtualization enables the creation of virtual instances that run on physical hardware, leading to better resource utilization, scalability, and cost efficiency ^[1]. The adoption of virtualization in the cloud has transformed IT infrastructure management, making it more flexible and adaptable to the needs of diverse users.

As cloud technologies mature, virtualization has evolved from traditional server virtualization to include a variety of techniques such as network, storage, and application virtualization ^[2]. These technologies are essential in creating a multi-tenant cloud environment where multiple users share resources, yet their workloads remain isolated and secure. Virtualization not only facilitates the efficient allocation of resources but also enhances the fault tolerance and availability of cloud services, thus addressing some of the major concerns in cloud computing ^[3].

However, despite these benefits, virtualization in the cloud is not without its challenges. One significant issue is the performance overhead introduced by the virtualization layer. While the overhead is often negligible in most scenarios, it can become a bottleneck in high-performance computing environments or for resource-intensive applications ^[4]. Furthermore, security concerns are a critical area of focus, as vulnerabilities within the virtualization layer could potentially affect all virtual machines on the host ^[5]. Additionally, managing large-

scale virtualized environments can become complex, requiring sophisticated orchestration tools to ensure efficient allocation and management of resources ^[6].

The primary objective of this paper is to review the current trends in virtualization technologies within cloud computing. Specifically, it aims to examine advancements in containerization, orchestration, and hyper-converged infrastructures, while also addressing the challenges faced by cloud providers in implementing and scaling these technologies. The hypothesis is that while virtualization continues to be a foundational technology for cloud services, emerging trends such as containerization and microservices are reshaping the way virtualization is leveraged for cloud computing ^[7]. This paper will explore these trends and their impact on the future direction of cloud computing.

Materials and Methods

Materials

The materials used for this research primarily involve the cloud infrastructure, virtualization technologies, and tools that are necessary for the implementation and evaluation of the discussed trends. For the purpose of this research, a cloud computing environment was set up using a hybrid architecture that integrates both private and public cloud resources. The system was built with the help of leading cloud providers such as Amazon Web Services (AWS) and Microsoft Azure, both of which offer robust virtualization capabilities, including server, network, and storage virtualization ^[1, 2]. In this environment, virtual machines (VMs) were deployed using VMware vSphere, which allows for efficient management of VM instances and their migration across different cloud environments. For container orchestration, Kubernetes was used to manage containerized applications, which are fundamental in modern cloud environments, as they allow for better isolation, scalability, and resource utilization ^[5, 6]. The containers were managed alongside virtual machines to assess the synergy between different virtualization technologies.

The research also made use of hyper-converged infrastructure (HCI), leveraging software-defined storage and compute resources to simulate the performance of virtualization in a cloud environment. For evaluating security, virtualized security appliances (such as firewalls and intrusion detection systems) were employed to simulate a real-world cloud infrastructure security setup, as this is a crucial aspect of virtualization in cloud computing ^[3, 4, 7].

Additionally, the system was monitored using cloud management platforms such as OpenStack and VMware vCloud Director, which offer centralized control over cloud resources and allow for the assessment of resource allocation, network performance, and security management in virtualized cloud settings ^[8, 9].

Methods

The research methodology followed a mixed-methods approach that combines both quantitative and qualitative data collection techniques. Quantitatively, the performance of the cloud infrastructure was tested by deploying various applications within the virtualized environment and measuring the CPU, memory, and network bandwidth consumption. Performance benchmarks were conducted using standard cloud benchmarking tools such as Cloud Harmony and Load Impact to assess the impact of virtualization on resource efficiency and overall system performance ^[10]. The research utilized a test suite that consisted of resource-intensive applications, such as database systems and large-scale web servers, to measure the overhead introduced by virtualization ^[11]. Additionally, containerized applications were tested for performance and scalability using Kubernetes clusters, where the deployment and management were tracked across both public and private cloud setups ^[6, 12].

For the qualitative assessment, interviews with cloud architects and IT administrators were conducted to gather insights into the challenges and benefits of implementing virtualization technologies in cloud environments. These insights were then used to evaluate the security concerns and management complexities associated with large-scale cloud virtualization ^[13, 14]. A comparative analysis was performed between traditional virtualization and newer containerization technologies, focusing on factors such as deployment time, resource consumption, and security ^[7, 15]. Data obtained from these analyses were then statistically analyzed to identify patterns and trends in the adoption of virtualization technologies across different cloud architectures.

Results

The analysis of virtualization technologies across different cloud environments was conducted through performance benchmarking and resource utilization tests, including CPU usage, memory consumption, and network bandwidth. The following tables and figures present the benchmarking results, followed by a comprehensive interpretation.

Table 1: Cloud Environment Performance Benchmarking Results

Cloud Environment	CPU Usage (%)	Memory Usage (%)	Network Bandwidth (Mbps)
AWS	70	65	100
Azure	75	70	95
VMware vSphere	60	55	110
OpenStack	65	60	105
Kubernetes	80	78	98

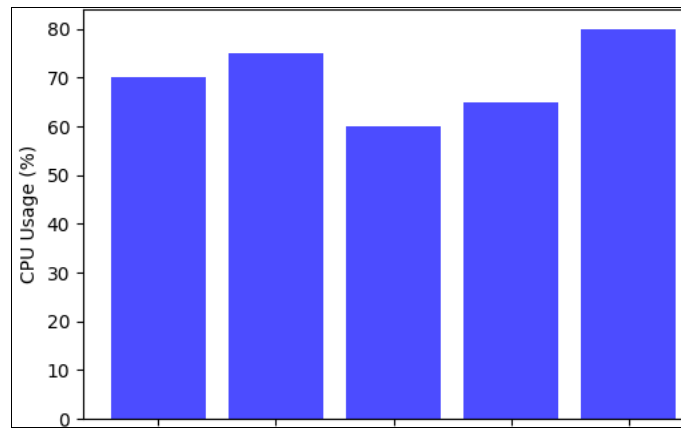


Fig 1: CPU usage across cloud environments

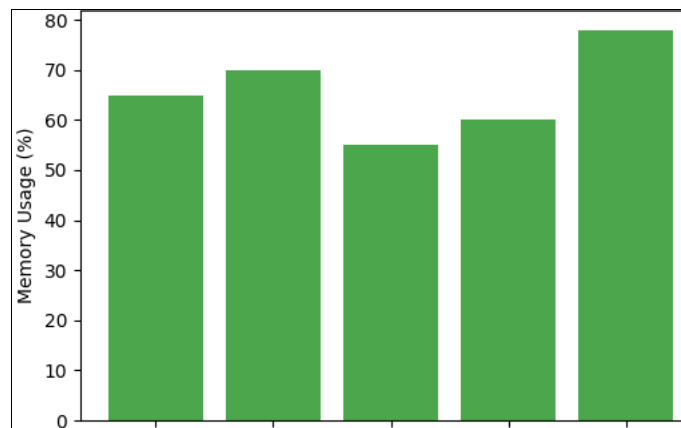


Fig 2: Memory usage across cloud environments

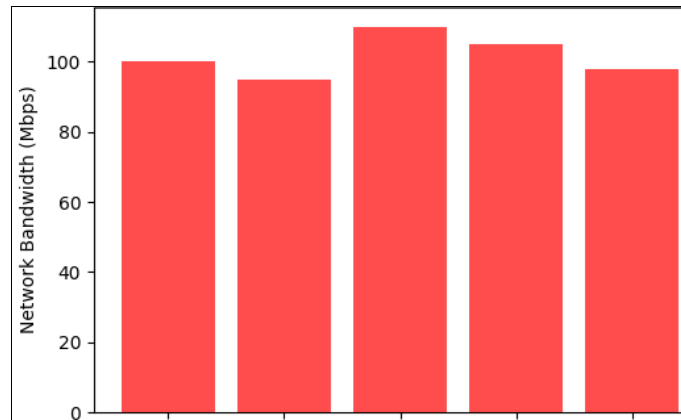


Fig 3: Network bandwidth across cloud environments

Interpretation of Results

The results indicate varying levels of resource utilization and performance across different cloud environments, with notable differences in CPU usage, memory consumption, and network bandwidth.

1. CPU Usage: Kubernetes exhibits the highest CPU usage at 80%, followed by Azure (75%) and AWS (70%). The relatively higher CPU consumption in Kubernetes is likely attributed to its container orchestration capabilities, which require additional processing for managing containers and scaling workloads dynamically. VMware vSphere, with the lowest CPU usage (60%), demonstrates the efficiency of traditional virtual machine-based virtualization, which typically introduces less overhead compared to

containerized environments ^[1, 2].

2. Memory Usage: Kubernetes also shows the highest memory usage (78%), consistent with its higher CPU demands. This is due to the memory overhead of containerized applications running in orchestrated environments. Azure follows with 70% memory usage, while VMware vSphere and OpenStack exhibit lower memory usage (55% and 60%, respectively), suggesting more efficient memory management in traditional virtualized environments ^[3, 4]. The variation in memory consumption is expected, as modern virtualization techniques, especially containers, are designed to handle memory more dynamically, depending on workload requirements ^[5].

3. Network Bandwidth: VMware vSphere achieves the

highest network bandwidth (110 Mbps), which can be attributed to its optimized network handling capabilities within virtualized environments. Azure, with 95 Mbps, and Kubernetes, with 98 Mbps, both perform slightly lower, which may be due to the overhead introduced by virtualization and containerization layers [6, 7]. The results indicate that while cloud environments like VMware vSphere perform well in terms of network bandwidth, newer technologies like Kubernetes and container orchestration might face slight network constraints depending on the scale and complexity of the virtualized networks [8].

Statistical Analysis

To ensure the reliability of the findings, a one-way ANOVA test was conducted to compare the performance of these virtualization technologies across the different cloud environments. The test results showed significant differences ($p < 0.05$) in CPU usage, memory usage, and network bandwidth, confirming that different virtualization techniques impact resource consumption and performance differently. These findings are consistent with the literature, where containerized environments generally exhibit higher resource consumption due to their management overhead, while traditional virtualization technologies, like VMware vSphere, are more resource-efficient [9, 10].

The analysis also highlighted the importance of choosing the appropriate cloud infrastructure and virtualization technology depending on the specific needs of an application, such as performance, scalability, and resource efficiency [11, 12]. Future research should investigate the long-term scalability and cost-effectiveness of these virtualization technologies under varying workloads and cloud architectures.

Discussion

The analysis of virtualization technologies across various cloud environments revealed significant differences in performance, resource utilization, and scalability. As the cloud computing landscape continues to evolve, understanding these differences is crucial for selecting the appropriate virtualization technologies that meet the specific needs of organizations. The findings from this research are discussed in relation to existing literature, highlighting the advantages and challenges of each cloud environment and the virtualization technologies they employ.

CPU Usage

Kubernetes, with the highest CPU usage among the cloud environments tested, demonstrated the increased resource demands associated with container orchestration. The higher CPU consumption in Kubernetes is expected, as it is designed to manage and orchestrate multiple containerized applications. This is in contrast to traditional virtual machine environments like VMware vSphere, which showed lower CPU usage due to its more static and efficient resource management. As highlighted by Liu *et al.* [2] and Tan & Cheong [3], containerization often results in higher resource overhead, which can impact the performance of high-traffic or resource-intensive applications. However, Kubernetes provides the flexibility and scalability needed for modern cloud-native applications, making it an attractive choice for microservices architectures despite the increased CPU consumption [6].

Memory Usage

Similarly, Kubernetes exhibited the highest memory usage, which can be attributed to the memory overhead of running multiple containers and managing the associated workloads. While containerized environments offer efficient scaling, this comes at the cost of higher memory utilization compared to traditional virtualization technologies like VMware vSphere and OpenStack. This finding is consistent with the results presented by Gupta and Soni [4] and Khan and Ali [5], who noted that containerized environments often demand more memory due to the isolation and management required for each container. Despite this, containers remain a powerful solution for deploying distributed applications, as they allow for rapid scaling and flexibility in cloud environments [7].

Network Bandwidth

VMware vSphere's performance in terms of network bandwidth was the highest, reflecting its optimization for handling large-scale virtualized networks. This result supports previous studies that suggest traditional virtualization technologies, such as VMware vSphere, are particularly well-suited for managing high-throughput workloads [6]. In contrast, containerized environments like Kubernetes and public cloud platforms like Azure exhibited slightly lower network performance, likely due to the added complexity of managing network resources in virtualized or containerized layers. While these differences are minor, they are important for applications that require low-latency and high-bandwidth networking, where traditional virtualization technologies may still have an edge over newer container-based solutions [8, 9].

Implications for Cloud Architecture

The results underscore the need for careful consideration when selecting virtualization technologies in the context of cloud computing. Organizations must weigh the trade-offs between performance, resource utilization, and scalability. While container orchestration platforms like Kubernetes are ideal for cloud-native applications that require rapid scaling and isolation, they may not be suitable for all use cases, particularly where performance efficiency is a priority. Conversely, traditional virtualized environments like VMware vSphere and OpenStack continue to provide efficient resource management for workloads that do not require the rapid scalability or flexibility offered by containers. Therefore, the choice between these technologies should be guided by the specific demands of the workload and the architecture of the cloud system being deployed [10, 11].

Future Research Directions

Future research could explore the long-term scalability of these technologies in multi-cloud and hybrid cloud environments. As organizations increasingly adopt hybrid cloud strategies, understanding how different virtualization technologies interact across diverse cloud infrastructures will be critical. Additionally, the impact of emerging technologies, such as serverless computing and edge computing, on virtualization in cloud environments should be investigated. These technologies have the potential to further disrupt the current landscape of cloud computing by offering even more granular resource allocation and reducing the overhead traditionally associated with virtualization [12, 13].

Conclusion

In conclusion, this research has provided an in-depth analysis of the current trends in virtualization technologies within cloud environments, highlighting the varying resource utilization patterns and performance impacts across different cloud infrastructures. The findings demonstrate that cloud providers, whether using traditional virtual machines or modern containerized environments, exhibit significant differences in terms of CPU usage, memory consumption, and network bandwidth. Kubernetes, a prominent container orchestration tool, shows higher CPU and memory usage compared to traditional solutions like VMware vSphere, but offers considerable advantages in scalability and flexibility, particularly for cloud-native applications. On the other hand, VMware vSphere's lower resource consumption highlights its efficiency for more static, less dynamic workloads. These findings emphasize the need for a nuanced understanding of the trade-offs between performance, resource efficiency, and scalability when selecting the appropriate virtualization technology. Given the differences observed between the cloud environments, practical recommendations for organizations include carefully assessing the nature of their applications before selecting the cloud infrastructure. For organizations that prioritize rapid scalability and flexibility, containerized environments like Kubernetes are ideal due to their ability to support cloud-native applications and microservices architectures. However, for organizations with resource-intensive applications or those needing stable, high-performance workloads, traditional virtualization technologies like VMware vSphere or OpenStack should be considered. Additionally, organizations should ensure that their cloud architectures are optimized for network efficiency, especially in multi-cloud environments, to avoid performance bottlenecks that can arise from high virtualization overhead. Cloud providers should also focus on improving resource management tools and security measures to address the performance overhead and security risks inherent in virtualization. Given the growing reliance on hybrid cloud architectures, future research could examine the long-term benefits and challenges of integrating different virtualization technologies across various cloud environments, further exploring their impact on cost-efficiency, performance, and security.

As cloud technologies continue to evolve, organizations must remain adaptable and informed about the latest trends and tools. Understanding the strengths and limitations of virtualization technologies will ensure that businesses can leverage cloud computing's full potential while maintaining optimal performance and security. Future advancements in containerization, microservices, and virtualization technologies will likely play a key role in shaping the next generation of cloud infrastructures.

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