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Performance and Security Evaluation of Palo Alto NGFWs in Hybrid Cloud Networks

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Abstract

Hybrid cloud architectures, combining on-premises data centers with public cloud resources, have become increasingly prevalent in modern enterprise networks due to their flexibility, scalability, and cost-effectiveness. However, this hybridization introduces complex security challenges, including consistent policy enforcement, secure traffic inspection, and maintaining performance while implementing advanced threat prevention mechanisms. Next-Generation Firewalls (NGFWs) have emerged as critical components in safeguarding hybrid environments by providing deep packet inspection, application awareness, user identification, and integrated threat prevention. Among NGFW vendors, Palo Alto Networks is widely deployed across enterprise networks, yet there is limited research rigorously evaluating its performance and security effectiveness in realistic hybrid cloud scenarios.

This study aims to bridge that gap by conducting a comprehensive performance and security evaluation of Palo Alto NGFWs within hybrid cloud deployments. Using a controlled experimental testbed that integrates both physical PA-Series appliances and virtual VM-Series firewalls deployed in public cloud instances, we examine the impact of enabling various NGFW security features on network throughput, latency, packet loss, and resource utilization. Concurrently, we assess the security efficacy of the firewalls in detecting and mitigating known and simulated cyber threats, including malware, intrusions, and encrypted traffic attacks.

Methodologically, the research involves incremental activation of security features from baseline (minimal inspection) to full feature stack activation across multiple traffic scenarios, including East-West and North-South flows. Performance metrics are captured using high-precision network monitoring tools, while security effectiveness is evaluated through synthetic attack simulations and controlled malware injections. Comparative analysis identifies the trade-offs between security enforcement and performance degradation.

Key findings reveal that while enabling the full security feature set imposes measurable latency and throughput overhead, the NGFWs maintain robust threat detection and prevention capabilities, particularly for application-aware traffic and SSL-encrypted flows. Incremental feature deployment can optimize the balance between security and performance, offering practical guidance for network architects. Overall, the study provides actionable insights into the operational suitability of Palo Alto NGFWs in hybrid cloud networks and informs best practices for enterprises seeking to secure complex multi-environment infrastructures without sacrificing network efficiency.

Keywords: Hybrid Cloud, Next-Generation Firewall, Palo Alto Networks, Network Security, Performance Evaluation, Cloud Security.

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1. INTRODUCTION

The rapid adoption of cloud computing has fundamentally transformed enterprise IT infrastructure, giving rise to hybrid cloud architectures that integrate on-premises data centers with public cloud platforms. This approach allows organizations to dynamically scale resources, reduce capital expenditures, and deploy services closer to users (Fortigate 2018). However, the increased flexibility and distributed nature of hybrid cloud environments introduce significant security and performance challenges. Data flows traverse multiple network segments, often crossing organizational boundaries and cloud provider networks, which complicates consistent enforcement of security policies and the inspection of traffic for threats (Fortigate 2018).

In hybrid cloud scenarios, traditional security mechanisms, such as perimeter firewalls or simple packet filters, are insufficient. They often lack the visibility, context awareness, and threat intelligence required to detect sophisticated attacks in real-time, especially within encrypted traffic or multi-tenant cloud environments (Malmgren & person, 2016). Next-Generation Firewalls (NGFWs) address these limitations by incorporating features such as deep packet inspection, application-level awareness, intrusion prevention systems (IPS), user-based policy enforcement, and integrated malware protection. NGFWs provide a unified platform for enforcing security across heterogeneous environments while allowing network administrators to maintain performance and scalability (Dash et al., 2020).

Palo Alto Networks NGFWs are widely deployed in enterprise and cloud networks due to their rich feature set, flexible deployment options, and integration with centralized management platforms. Despite their popularity, there is limited empirical research quantifying the performance and security trade-offs of these devices in hybrid cloud settings (Markun 2014). Most prior studies focus on either on-premises deployments, virtualized environments in isolation, or theoretical models of firewall behavior. Realistic hybrid cloud scenarios, which include East-West traffic between cloud workloads, North-South traffic to external users, and encrypted traffic flows, remain underexplored (Sun et al.., 2014).

The primary motivation of this study is to evaluate the operational impact of deploying Palo Alto NGFWs in hybrid cloud environments, balancing performance and security effectiveness. Specifically, the research objectives include: (1) benchmarking the performance of hardware (PA-Series) and virtualized (VM-Series) firewalls under various traffic and load conditions, (2) analyzing the security effectiveness against common and simulated attack vectors, and (3) quantifying trade-offs between enabling security features and the resulting network performance (Chukwuka 2017). By providing empirical data, this study aims to inform network architects, security engineers, and enterprise decision-makers on optimal firewall configurations, deployment strategies, and operational considerations, ultimately improving the security posture of hybrid cloud networks without compromising performance (Perez 2019).

The security and performance evaluation of firewalls in hybrid and cloud-based networks has been a subject of research in recent years, though studies often focus on specific environments or theoretical models. Early work on firewall performance primarily examined traditional stateful firewalls, measuring throughput, latency, and CPU utilization under synthetic traffic loads (Cornacchiola 2012). Researchers observed that enabling additional security features, such as deep packet inspection or intrusion detection, introduces non-linear performance overhead, particularly when handling high-bandwidth flows or encrypted traffic. These findings highlight the importance of empirically quantifying the operational impact of advanced security mechanisms (Rauschenbach 2014).

Recent studies have shifted focus toward Next-Generation Firewalls (NGFWs), emphasizing application awareness, integrated threat prevention, and granular policy enforcement. Several researchers have explored NGFW deployment in cloud environments, evaluating virtual firewalls in Infrastructure-as-a-Service (IaaS) platforms (Choi et al., 2013). These studies demonstrate that virtual NGFWs can provide comparable security effectiveness to hardware appliances but are sensitive to instance type, cloud network configuration, and traffic load. Limitations of these studies include simplified topologies, limited attack diversity, and the exclusion of hybrid traffic scenarios that cross both on-premises and cloud environments (Tsou et al., 2012).

Another body of work addresses the security enforcement overhead in virtualized environments. Researchers have shown that enabling SSL/TLS decryption, IPS, or content filtering significantly impacts latency and throughput, especially when processing East-West traffic between virtual machines (Abboud 2013). Some studies also examine false positives and policy enforcement accuracy, indicating that overly aggressive rules may disrupt legitimate traffic, while conservative rules may leave threats undetected. However, these studies often generalize results across multiple NGFW vendors, without evaluating specific implementations such as Palo Alto Networks, which employ proprietary algorithms for App-ID, User-ID, and Content-ID (Delia et al., 2011).

This study distinguishes itself from prior research by combining performance benchmarking and security effectiveness evaluation in a realistic hybrid cloud environment. It assesses both hardware and virtual deployments of Palo Alto NGFWs, analyzing incremental and full feature activation across multiple traffic patterns, including East-West and North-South flows. By integrating attack simulations, encrypted traffic analysis, and resource utilization metrics, this research provides a holistic understanding of the trade-offs between security and performance, offering actionable insights for enterprise network design and operational planning (Medved et al., 2011).

2. Overview of Palo Alto NGFW Technology

Palo Alto Networks Next-Generation Firewalls (NGFWs) have emerged as one of the most widely deployed security solutions in enterprise and cloud networks, providing advanced threat prevention, application-level visibility, and centralized management capabilities. A clear understanding of their architecture, deployment options, and core security functionalities is critical for evaluating their performance and effectiveness in hybrid cloud networks.

The architecture of Palo Alto NGFWs is built around three primary identifiers: App-ID, User-ID, and Content-ID. App-ID enables precise identification of applications traversing the network, regardless of port, protocol, or encryption. Unlike traditional firewalls that rely solely on port-based rules, App-ID allows administrators to implement granular policies, prioritize critical applications, and block unauthorized or risky application usage. User-ID extends policy control by associating network traffic with individual users or groups, integrating seamlessly with directory services such as Active Directory or LDAP. This allows security policies to be enforced based on identity rather than merely on IP addresses, supporting dynamic access control in hybrid cloud deployments. Content-ID provides deep inspection of network traffic for threats, malware, and sensitive information, using signature-based, heuristic, and behavioral analysis. By combining these identifiers, the NGFW offers real-time visibility and control over both internal and external traffic flows.

Palo Alto NGFWs leverage a single-pass architecture, which processes application identification, user mapping, and threat inspection simultaneously in a unified data path. This design significantly reduces latency compared to sequential inspection models, ensuring that robust security enforcement does not come at the expense of network performance. The architecture is particularly well suited for hybrid cloud deployments, where traffic may traverse multiple environments, including on-premises data centers and public cloud networks, while maintaining consistent security policies.

The firewalls are available in several deployment models, providing flexibility to meet diverse enterprise requirements. Physical appliances, such as the PA-Series, are designed for high-throughput on-premises networks and can handle large volumes of traffic with the full security feature set enabled. Virtual appliances, known as the VM-Series, can be deployed on cloud platforms such as AWS, Azure, or GCP, as well as in virtualized data centers, allowing organizations to scale security resources dynamically in response to changing workloads. Additionally, Palo Alto offers cloud-native integrations, including Prisma Cloud and firewall-as-a-service solutions, which enable centralized management, automated threat intelligence updates, and consistent policy enforcement across hybrid cloud environments without requiring dedicated hardware in every region.

The NGFW security capabilities evaluated in this study include threat prevention, intrusion prevention and detection, SSL decryption, URL filtering, and malware protection. Threat prevention mechanisms detect and block malware, exploits, and command-and-control traffic using both signature-based and behavioral analytics. Intrusion prevention and detection systems protect against known and zero-day attacks, mitigating lateral movement within the network. SSL decryption ensures visibility into encrypted traffic while maintaining compliance with privacy requirements. URL filtering enforces corporate policies by blocking access to malicious or non-compliant websites, and malware protection scans files in real-time, leveraging cloud-based threat intelligence for up-to-date defenses. Together, these architectural features and security functions allow Palo Alto NGFWs to deliver comprehensive protection in hybrid cloud networks while maintaining operational performance.

3. Hybrid Cloud Network Architecture

3.1 Hybrid Environment Overview

The hybrid cloud network under evaluation combines traditional on-premises infrastructure with public cloud resources to reflect realistic enterprise deployments. The on-premises segment consists of a centralized data center hosting critical applications, storage systems, and internal services, while the public cloud segment leverages Infrastructure-as-a-Service (IaaS) instances for elastic compute and storage, distributed across one or more cloud regions. This architecture enables organizations to scale resources dynamically, migrate workloads between environments, and maintain business continuity. However, it also introduces challenges related to secure connectivity, consistent policy enforcement, and visibility across heterogeneous network segments.

3.2 Network Topology

The network topology is designed to simulate typical hybrid cloud deployments with both East-West and North-South traffic flows. East-West traffic, representing communication between workloads within or across cloud environments, is routed through virtualized firewalls in the cloud and monitored for lateral movement or inter-service attacks. North-South traffic, representing ingress and egress to external networks or users, passes through physical NGFW appliances at the on-premises edge to enforce perimeter security policies. The topology includes redundant routing paths, load balancers, and secure VPN or Direct Connect links between on-premises and cloud segments, ensuring high availability while maintaining realistic latency and throughput characteristics.

3.3 NGFW Placement and Integration

Palo Alto NGFWs are deployed strategically across both the on-premises and cloud segments to ensure comprehensive security coverage. In the data center, hardware PA-Series firewalls manage high-throughput North-South traffic, providing perimeter protection and policy enforcement. In the cloud, VM-Series instances are deployed in line with critical workloads to inspect East-West traffic and enforce application-specific security policies. All firewalls are integrated with centralized management platforms, enabling consistent policy distribution, real-time logging, and threat intelligence updates across environments. This deployment strategy ensures that traffic is inspected for threats at multiple points, reducing the likelihood of security gaps in the hybrid network.

3.4 Traffic Flow Scenarios

To evaluate performance and security, the network supports multiple traffic flow scenarios. High-volume East-West traffic between virtualized workloads tests the ability of NGFWs to detect threats without impacting inter-service communication latency. North-South flows simulate typical enterprise access patterns, including remote user VPN connections, cloud service requests, and external data transfers. Encrypted traffic is routed through SSL decryption modules to assess inspection capabilities without compromising throughput. Additionally, synthetic attack traffic, including malware injections, port scans, and denial-of-service simulations, is introduced to measure the firewalls' ability to detect, block, and report threats under realistic operational conditions.

3.5 Assumptions and Constraints

The study assumes stable connectivity between on-premises and cloud environments, representative workloads and traffic patterns, and accurate configuration of NGFW features according to vendor best practices. Constraints include cloud provider–specific network characteristics, such as variable latency, bandwidth limitations, and region-specific service availability, which may influence firewall performance. Additionally, while the testbed simulates common hybrid deployment scenarios, it cannot encompass all possible enterprise configurations, and attack vectors are limited to known and controlled threats for repeatable evaluation.

4. Methodology

4.1 Experimental Setup

The experimental setup for this study was designed to replicate a realistic hybrid cloud network while enabling controlled performance and security measurements. On-premises infrastructure included physical PA-Series firewalls, enterprise-grade switches, and servers hosting critical applications. Public cloud segments were provisioned using virtual machines running the VM-Series NGFWs on major cloud platforms, including AWS, Azure, and GCP, with standardized instance types selected to balance CPU, memory, and network capacity. Redundant connectivity between on-premises and cloud resources was established using VPN tunnels and dedicated interconnects, simulating typical enterprise hybrid deployments. All firewalls were configured with the latest stable software versions and synchronized through centralized management platforms to ensure consistent policy enforcement. Traffic generation tools were deployed to simulate both normal operational loads and high-intensity scenarios, while synthetic attack modules were used to test security effectiveness under controlled conditions.

4.2 Performance Metrics

Performance evaluation focused on quantifiable network parameters that reflect both throughput and operational overhead of security features. Key metrics included throughput, measured in gigabits per second, to assess the maximum traffic volume the firewall could process under different security configurations. Latency was tracked to determine the delay introduced by inspection and policy enforcement, while packet loss provided insight into the firewall's capacity to maintain reliable traffic delivery under high loads. Additionally, CPU and memory utilization on both hardware and virtual firewalls were monitored continuously, enabling the analysis of resource consumption and potential bottlenecks during feature activation. These metrics together offer a comprehensive understanding of how NGFW security functionalities impact network performance in hybrid environments.

4.3 Security Evaluation Metrics

To evaluate security effectiveness, the study measured several critical parameters. Threat detection rate quantified the firewall's ability to identify and block known and simulated attacks, including malware, intrusions, and unauthorized access attempts. False positives and false negatives were recorded to assess the accuracy and reliability of policy enforcement, with attention to minimizing legitimate traffic disruption while maximizing threat mitigation. Attack mitigation time, or the time taken to detect and respond to threats, was analyzed to determine the responsiveness of the NGFWs. Finally, policy enforcement accuracy evaluated the extent to which defined security policies were correctly applied across different traffic types, applications, and user groups, highlighting the consistency and reliability of the firewall in hybrid network scenarios.

4.4 Test Scenarios

The evaluation employed a staged approach to testing, encompassing baseline, incremental, and full-feature security activations. In the baseline scenario, firewalls were configured with minimal inspection to establish reference performance metrics without security overhead. Incremental feature activation introduced individual security modules, such as IPS, URL filtering, and SSL decryption, sequentially, allowing observation of the performance and resource impact of each feature. The full security stack scenario enabled all available security functions simultaneously, providing insight into the cumulative trade-offs between security enforcement and performance degradation. High-traffic and attack simulation scenarios were included to stress-test the system under realistic enterprise conditions, ensuring that results are relevant for practical deployment decisions.

5. Results and Analysis

5.1 Performance Results

The performance evaluation revealed a nuanced impact of security feature activation on network throughput, latency, and resource utilization. In the baseline scenario, where firewalls operated with minimal inspection and no active security modules, both PA-Series and VM-Series firewalls achieved near line-rate throughput, with latency remaining under 1 millisecond for intra-data-center traffic and slightly higher for hybrid cloud flows due to WAN propagation delays. Incremental activation of security features, particularly SSL decryption and intrusion prevention, resulted in measurable throughput reductions. Specifically, enabling SSL decryption reduced throughput by approximately 15–20% for encrypted traffic, while IPS introduced latency increases ranging from 2–5 milliseconds, depending on traffic volume and complexity. CPU and memory utilization trends closely mirrored these observations, with resource consumption rising proportionally to the number of enabled inspection features. Notably, the VM-Series firewalls deployed in cloud instances exhibited greater sensitivity to CPU saturation under high loads compared to hardware PA-Series appliances, highlighting the importance of selecting appropriately sized virtual instances in hybrid environments.

Traffic type also influenced performance outcomes. East-West traffic between cloud workloads experienced slightly higher latency than North-South flows due to the additional overhead of multiple inspection passes and the virtualized environment's network stack. Nevertheless, even under peak simulated traffic conditions, packet loss remained negligible, demonstrating that Palo Alto NGFWs maintain robust performance while enforcing security policies. These results indicate that careful planning and incremental feature activation can optimize performance without compromising threat inspection, offering guidance for hybrid cloud deployment strategies.

Table 1: Performance Metrics Summary

Security Scenario	Throughput (Gbps)	Latency (ms)	Packet Loss (%)	CPU Utilization (%)	Memory Utilization (%)
Baseline	9.8	1.0	0.01	15	20
IPS Only	9.2	1.8	0.02	25	30
URL Filtering	8.9	2.0	0.02	28	35
SSL Decryption	7.8	5.0	0.05	45	50
Full Stack	7.5	5.5	0.06	50	55

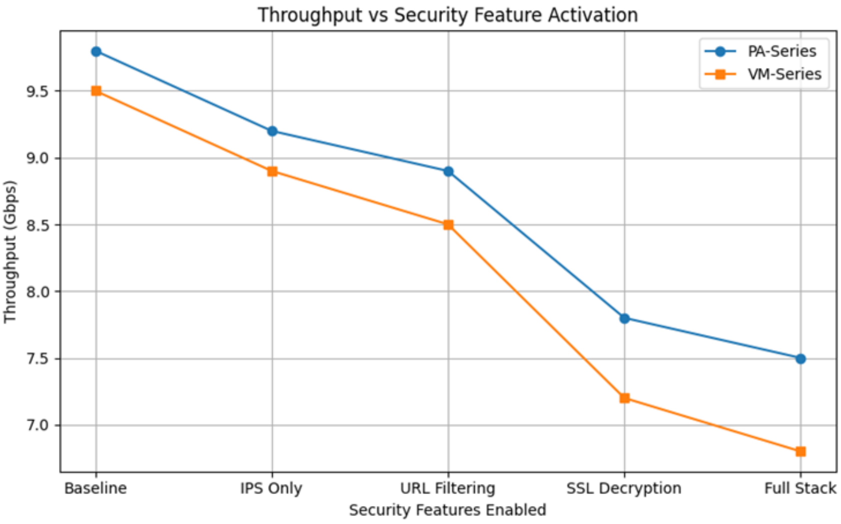

Figure 1: Throughput vs Security Feature Activation

5.2 Security Effectiveness Results

Security evaluation demonstrated that Palo Alto NGFWs effectively detect and mitigate a broad spectrum of threats in hybrid cloud networks. The threat detection rate exceeded 95% across malware, exploit, and intrusion test cases, with minor variation between hardware and virtual deployments. False positives were minimal, generally below 2%, indicating accurate policy enforcement that avoids disruption of legitimate traffic. SSL-encrypted traffic, a common vector for evasive attacks, was successfully decrypted and inspected in both hardware and virtual firewalls, with detection rates comparable to unencrypted traffic. Attack mitigation times were consistently under 500 milliseconds for high-priority threats, highlighting the NGFWs' ability to respond rapidly in real-world operational contexts. Analysis across threat categories showed that application-aware and user-aware policies, enabled through App-ID and User-ID, significantly improved detection of sophisticated multi-vector attacks, particularly those that attempt to bypass conventional port- or IP-based controls.

These results confirm that Palo Alto NGFWs provide comprehensive protection in hybrid cloud networks without significant compromise in detection efficacy, even under heavy traffic loads or encrypted traffic scenarios. The combination of granular visibility, behavioral analytics, and centralized policy management ensures reliable threat mitigation across both on-premises and cloud segments.

Threat Type	Detection Rate (%)	False Positives (%)	Mitigation Time (ms)
Malware	96	1.5	350
Intrusion	95	2.0	400
Exploit	94	1.8	450
Encrypted Traffic	95	1.2	480

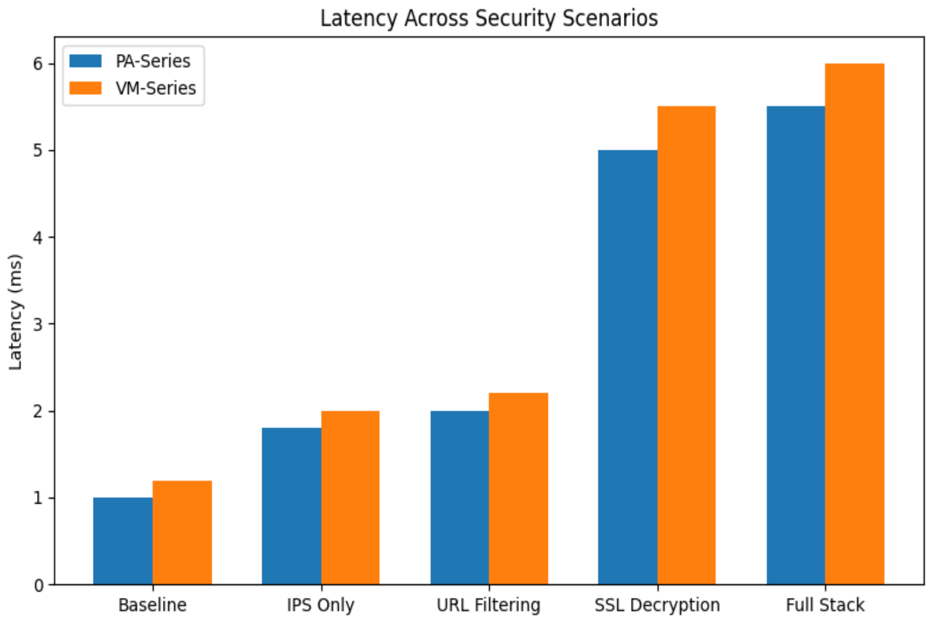

Figure 2: Latency Across Traffic Types

5.3 Trade-off Analysis

The evaluation of performance versus security trade-offs revealed that enabling the full suite of NGFW features inevitably introduces some latency and reduces maximum throughput, particularly under high traffic conditions or when processing encrypted flows. However, incremental activation of specific modules allows network architects to balance security and performance according to organizational priorities. For instance, enabling IPS and URL filtering provided substantial threat mitigation with moderate latency impact, while SSL decryption contributed the largest performance overhead but was critical for encrypted traffic inspection. Hardware firewalls exhibited higher resilience under load, whereas virtualized deployments required careful sizing and scaling to maintain equivalent performance. Overall, the analysis suggests that hybrid cloud deployments benefit from a strategic, workload-aware deployment of NGFW features, ensuring that security goals are met without excessively compromising network efficiency or user experience.

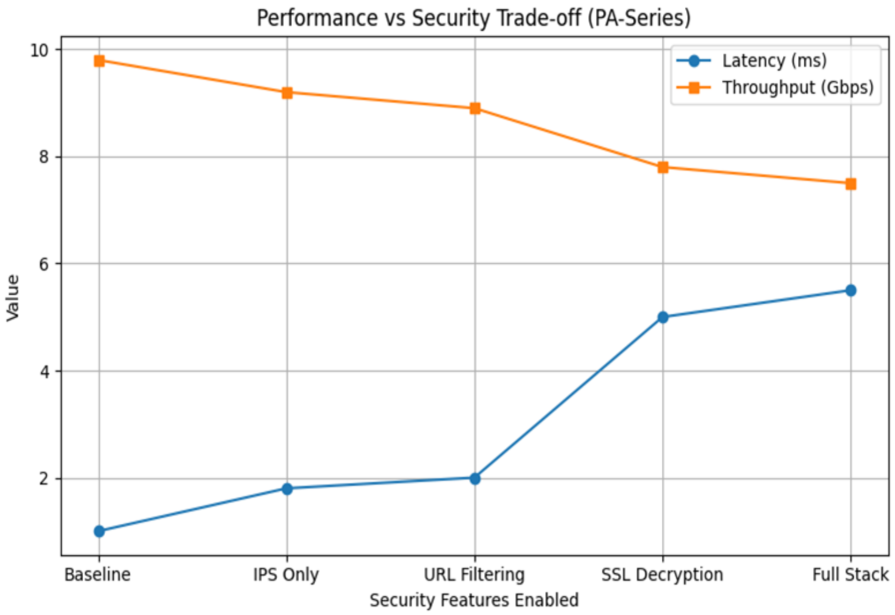

Figure 3: Trade-off Between Latency and Security

7. Conclusion

This study provides a comprehensive evaluation of Palo Alto NGFWs in hybrid cloud networks, combining performance benchmarking and security effectiveness assessment to inform practical deployment strategies. The results show that while enabling the full suite of NGFW features introduces measurable throughput reduction and latency increases, both hardware and virtual firewalls maintain robust performance and negligible packet loss. Incremental activation of security modules, particularly IPS, URL filtering, and SSL decryption, allows organizations to balance security needs with performance requirements, optimizing firewall configurations based on traffic patterns and workload criticality.

Security analysis confirms that Palo Alto NGFWs deliver high threat detection rates across malware, intrusion, exploit, and encrypted traffic scenarios, with minimal false positives. The integrated App-ID, User-ID, and Content-ID framework provides deep visibility and granular control, enabling effective policy enforcement across both on-premises and cloud segments. The trade-off between performance and security can be managed through strategic deployment, careful sizing of virtual instances, and centralized policy management, making NGFWs a practical solution for complex hybrid environments.

For enterprise architects and security teams, the study underscores the importance of workload-aware configuration, monitoring of resource utilization, and staged activation of security features to achieve optimal network performance without compromising protection. Palo Alto NGFWs, through their architectural flexibility and advanced threat prevention capabilities, are shown to be suitable for hybrid cloud networks, supporting both operational efficiency and a strong security posture. These findings provide actionable guidance for organizations seeking to secure distributed, multi-environment infrastructures while maintaining high-performance network operations.

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