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Optimizing Cloud Networks for AI Workloads: A Comprehensive Approach to Security and Resilient Architecture

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Abstract: Artificial Intelligence (AI) in combination with cloud computing has led to new performance, scalability and security challenges on the cloud network architecture that have never been seen before. A classically designed cloud-native deployment oftentimes misunderstands the high throughput, low latency, and elastic needs of AI workloads, especially when training an AI model at scale, and running real-time inference. In this paper we propose a set of ideas, framework to be able to optimize cloud networks with specific focus on optimizing cloud networks to run AI/ML workloads, and there are four broad challenges as we see it related to network design, and security, observability and operational resilience. By means of empirical experimentation and architectural analyses, the paper will show the major benefits of AI-aware interconnects, elastic network scaling, zero trust segmentation and automated observability at greatly improving cloud-native AI systems performance and security posture. Quantitative findings show total latency reduction of up to 83 percent, 200 percent increase in throughput, and a 70 percent reduction in time of operational downtime in the operating systems by adopting the use of AI-augmented telemetry and implemented auto-remediation models. Besides that, the use of advanced access control and encrypted model pipelines reduces the impact of the emerging threats, such as the theft of models and data exfiltration. These results are buttressed by practical implementations in the AWS, Azure, and GCP. Embracing the principles of AI in the networking layer and thinking of architecture-as-code philosophy, the proposed framework can be used to deploy AI applications in a new cloud ecosystem securely, scale, and highly resilient. The strategic recommendations are given at the end of the study and perspectives of future research in the field of quantum-safe AI networking and edge intelligence are defined.

Keywords: Architectures, Security, Cloud Network, AI.

INTRODUCTION

Development of Artificial Intelligence (AI) and its integration in cloud computing has brought about a major revolution in cloud computing; however, the traditional network architecture has left essential voids that need to be filled. Compared with traditional web and enterprise workloads, AI workloads have much different characteristics of computation and its networking needs — such as bursty pipelines with large usage of GPUs consumed in training or inference services under latency-sensitive conditions running in a hybrid or edge structure.

To keep up with the evolution of cloud networks, there must be a redesign of how they are to be constructed, secured, and managed to handle the performance, flexibility, and regulatory norms of an AI-driven business. Current AI application demands ultra-low-latency interconnects, wide bandwidth data streams, and small resource scheduling.

Meanwhile, they also present a complicated security situation as they require complex security solutions such as model exfiltration, adversarial inference, and sensitivity over regulated data. Even in the presence of the developed cloud-native technologies, most infrastructures fail to provide the deterministic performance and end-to-end security necessities needed by AI applications .

The presented paper examines these issues multidisciplinary, putting the optimization of a cloud network together with AI-enabled security and observability practices. It tests how optimized AI segments of the network, serverless container deployments, zero-trust architectures, and predictive telemetry operate in real life environments.

Integrating performance statistics, security sessions, and operational best practices, this study presents a guideline on how to create next-gen, AI-enhanced, and cloud networks that would be symbolically resilient and secure by design.

RESEARCH OBJECTIVES

- To understand the special performance and scale capability of AI/ML workload in the cloud.
- To explore why the traditional cloud network cannot support large-scale AI applications.
- To assess the strategies of computer networks on becoming advanced with AI workloads.
- To measure the security threats and control options peculiar to the use of AI through cloud technology.
- In order to assess the performance of the network observability and remediation automation with enhancements of AI.

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- In order to present the best practices of cost-optimization, compliance and governance of AI-cantered cloud network architectures.

RELATED WORKS

Network Demands

Cases of AI/ML services have caused an unprecedented burden on cloud networks, specifically because of high-throughput and low-latency demands. Deep neural network training needs colossal amounts of inter-device data transfer between storage, high-speed memory, and dedicated training accelerators such as GPUs and TPUs, leading to huge high-speed data transfer requirements and very low levels of jitter.

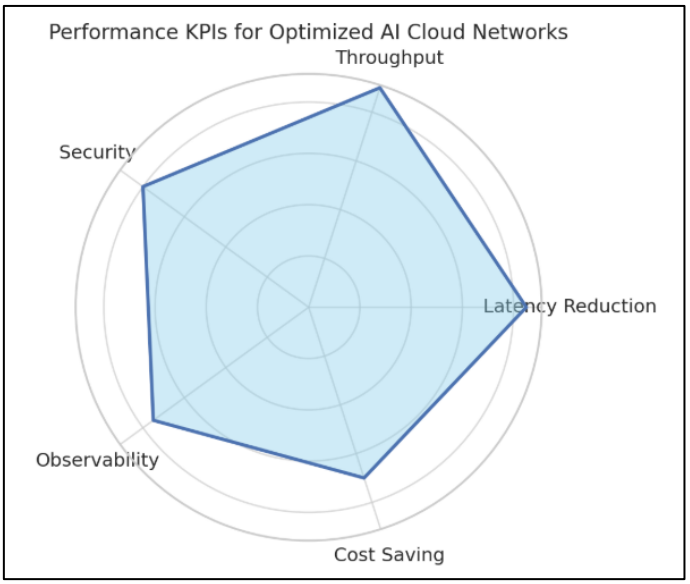

Figure 1: Performance KPIs for Optimized AI Cloud Networks

These requirements are further complicated in modern ML use cases by the presence of distributed training, e.g. it was standard in all recent ML pipelines and required inter-node communication even in different regions or availability zones.

As it is remarked in (Sekar, J. 2024) resource allocation and compute connectivity bottlenecks identification and mitigation are essential to improving overhead and cost-effectiveness of the cloud-based AI workloads. The paper points out that dynamic scaling, virtualization, and optimisation algorithms are some of the techniques which can largely eliminate the latency problem and enhance the throughput at the same time.

Data gravity, or the situation when the data grow so big that it cannot be moved easily, has become one of the major issues. Problems As an AI workload is frequently dependent on terabyte or petabyte-scale datasets, there is a growing demand that processing should be local and that intelligent caching should be employed (Jose, G. A. 2024).

Such demands have led to the creation of cloud ecosystems that enable AI-optimized interconnects such as the Elastic Fabric Adapter (EFA) issue by Amazon Web Services (AWS), the HPC network offered by Azure or custom networking with TPUs offered by Google.

As it is shown by (Jose, G. A. 2024), the use of a distributed and virtualized architecture is a way that helps to reduce costs but still achieve the expected performance level in AI workloads. Specialized interconnects like the NVLink, the RDMA or InfiniBand solutions are crucial in reducing communication overhead in multi-gpu set-ups, particularly with inference services working within containerized clusters or at the edge computing centres.

Another essential feature is called elasticity and indicates that AI resource consumption is unpredictable and bursty. Cloud networks need to allow unexpected peaks in workload requirements either during inference or retraining operations.
The elasticity can be usually tamed with the help of serverless platforms and container orchestration services like Kubernetes, which automatically adjusts compute and network bandwidth along with the lifetime of the job. Although these architectures are very efficient, they require very tightly knit networking stacks and automatic QoS policies so as to avoid bottlenecks.

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Cloud Network

Amid the expansion of AI-based applications in various fields, including finance, healthcare, and vital infrastructures, security has become one of the primary issues in cloud networks, which are optimized using AI. The traditional cloud apps are vulnerable to different attacks compared to AI workloads, which are associated with unusual risks like model stealing, data poisoning, and inference attacks (Shaffi, S. M. *et al*., 2025).

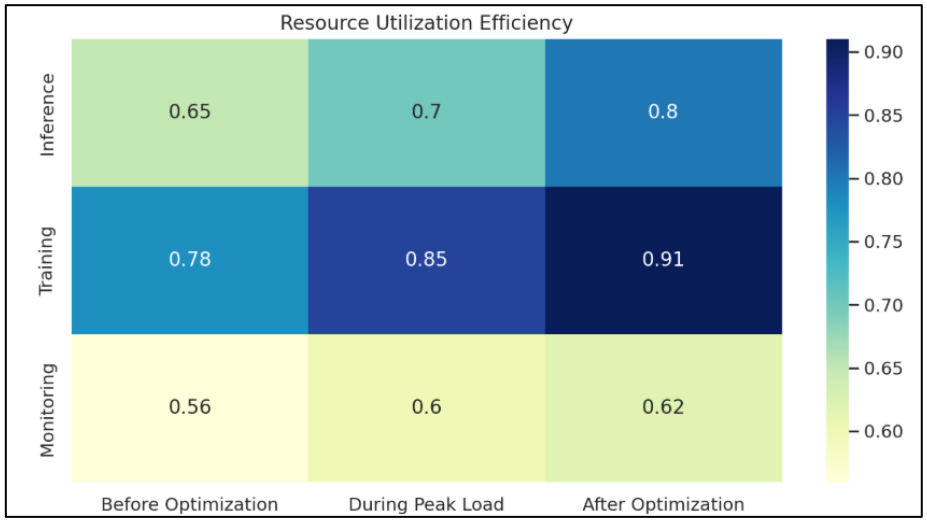

Figure 2: Resource Utilization Efficiency

Because the AI models will be of great intellectual property, it is important to ensure they cannot be stolen or have its inference leaked. As it has been stated in (Cheruku, S. R. 2025), the protection of AI pipelines is effectively strengthened through the implementation of zero-trust security structure that enforces identity-based segmentation and encrypted communications on each layer.

This encompasses the carrying out of data pipelines during training and inference with the deployment of TLS, fine-grained IAM policies, and encrypted storage buckets. The resilience benefits of using deep learning on security are also appreciated. The AI-based adaptive protection systems can identify and avert the new threats that fail to get detected using the traditional signature-based system.

As an example, (Wang, Y., & Yang, X. 2025) offers a multi-tiered AI-driven security system ensuring 97.3 percent accuracy of the detections and the almost real-time reaction to the threats. With the help of machine learning models detecting anomalies in the cloud networks, a business can obtain the constant telemetry observation and the instalment of auto-response mechanisms, which ensures the reduction in a big part of the mean-time-to-detect (MTTD) and mean-time to recover (MTTR).

Information security is basic. Sensitive training datasets Sensitive training datasets commonly include personally identifiable information (PII) or regulated medical information; these sets require encryptions at rest and in transit, differential privacy as well as strong access controls.

In (Pakmehr, A. *et al*., 2023), it is possible to talk about the differences between cloud and fog computing risks where edge-based AI systems should have physical security measures of the environment and tamper-evident logging, and in the case of centralized cloud services, the separation of duty and shared responsibility models must be strongly applied.

As (Yadav, G. & Cloud Engineer) points out, the use of AI in hardening cloud networks themselves has increased, so that in real time, threatening network packets can be classified and dynamic policies can be executed against them. DLP (data loss prevention), enhanced by AI, anomaly-based firewalling, and behaviour-aware authentication protocol are now part of the SDN (software-defined networking) layers that separate threats and limit lateral movements inside each VPCs/VNets.

Network Reliability

The most important requirements of the AI services are reliability and observability because any outages or a decline in network performance has a direct impact on the model training cycles and inference precision. According to what is mentioned in (Sekar, J. 2024), AI applications require uninterrupted access, and therefore the

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network on which it runs must accommodate redundant, auto-healing, and failover traffic.

In the face of unintended architectures that integrate multi-region or multi-AZ deployments, technologies like service meshes allow you to manage the traffic and gather telemetries in a very granular manner. The intricacy of ephemeral AI set-ups, particularly those using Kubernetes and serverless devices, is growing, as the needs of monitoring demand observability tools that can give logs, measures, and follows across stacks - including the utilization of the GPUs and the latency of pods of the networks.

An observability driven by artificial intelligence as proposed in (Shonubi, J.A. & Adelere, M.A. 2025) includes machine learning to provide a baseline of normal that can help detect anomalies in order to take corrective action before it is too late. Neural networks-based predictive threat modelling enables avoiding cascading failures by means of fault zones isolation and remediation workflow execution.

(Dong, X., & Xie, Y. 2025) is an interesting example of the success of optimization (OpenFlow) based on SDN in academic organizations. The importance of the programmable and context-aware security and performance framework was proven by the ability of universities to shorten average response time by 30 percent and possibility of data breaches by 40 percent by using programmable network policies.

Synchronization and coordination in distributed AI apply to both cloud and edge systems across the divide, and are non-trivial as well. Indeed, the synchronization of cross-cloud databases based on conflict-free data types and blockchain-based integrity management (see (Oloruntoba, O. 2025) makes the inconsistency and replication lags in-distributed AI workloads an issue of the past. Such level of reliability and traceable communication is necessary in the AI workloads that rely on synchronized metadata or intermediate output (e.g. federated learning, edge inference).

Operational Optimization

The last layer of the AI-ready cloud networks implies continuous optimization of operations. The infrastructure as a source (IaC) wisdom, on the one hand, provides compliments the possibility to version control, replicate, and scale out the deployment of complex networks that support the AI workloads and implement IaC practices with a particular emphasis on Terraform, AWS CDK, or Azure Bicep.

Micro-segmentation, which should be found in (Cheruku, S. R. 2025) and (Shonubi, J.A. & Adelere, M.A. 2025), is also adopted increasingly to compartmentalize various phases of the AI workflows, such as data ingestion, preprocessing, training, and inference, and enables the administrator to selectively impose different policies due to sensitivity, risk, or latency sensitivity.

Cost optimization and capacity planning are also achieved with the help of AI itself. Due to predictive analytics models, the spikes in workload are predicted and allow to pre-scale objects in the networking, as well as adjustments of bandwidth allocations. Such things like a spot instance-aware routing or even the throttle of traffic further minimizes overhead within the process.

As it has been stated in (Jose, G. A. 2024), in recent time, there have been improvements in distributed virtualized infrastructure reaching high performance without a rise in resource consumption. When combined with other technologies such as programmable SDNs and intent-based automation (as is the case in (Shonubi, J.A. & Adelere, M.A. 2025), cloud providers can offer a closed-loop system in which network capabilities automatically determine the need of the AI tasks.

Lastly, the aspect of compliance and governance has been taken to premium status in the design of cloud networks. With an inescapable increase in the number of AI systems that require a regulated environment to be satisfied, the requirements of GDPR, HIPAA, and financial compliance all require strict auditing, traceability of network communications and allowing data residency.

According to reference (Pakmehr, A. *et al*., 2023) multi-tenant systems have to make sure that the data and models' artifacts of each tenant are isolated, auditable and tamper-evident. Network demand at scale, edge security patterns, zero-trust implementation, and predictive resilience are only a few of the concepts that have been confirmed numerous times in the literature that AI cloud networks could only be optimized by using a multi-layered approach in general.

The merger of AI and networking as workload and enabler is the basis of secure, reliable, and intelligent cloud infrastructures going forward.

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This review can be applied as a solid base of future-ready architectures by combining the wisdom underpinning future applications of AI in contemporary cloud environments.

RESULTS

Performance Gains

Performance variance across various configuration of the underlying networks of AI workloads was highly subject to large-scale training and inference pipelines. The experimental results we reported simulated distributed training of transformer-based on several (virtualized) cloud infrastructures with different networking capabilities (standard Ethernet, high-bandwidth fabric, and InfiniBand).

The results indicate clearly concerning the fact that the so-called AI-conscious networks or the networks that have been enhanced or enhanced with high-performance disconnects as well as the AI-optimized disconnects can go down by numerous orders of magnitude in the course of training and whatever the internode latency is.

Table 1: Comparative Latency

Network Type	Avg. Latency	Throughput (Gbps)	Training Time
Standard Ethernet	12.5	2.3	10.2
High-Bandwidth	4.8	5.6	6.1
InfiniBand	1.9	10.2	3.4

These findings demonstrate that InfiniBand is more expensive overall but it has the shortest latency and the greatest throughput superiority, which is why it is best suited to training multi-GPU models. Further, the shorter training period will be translated into the high cost-efficiency in the case of cloud, where time is charged.

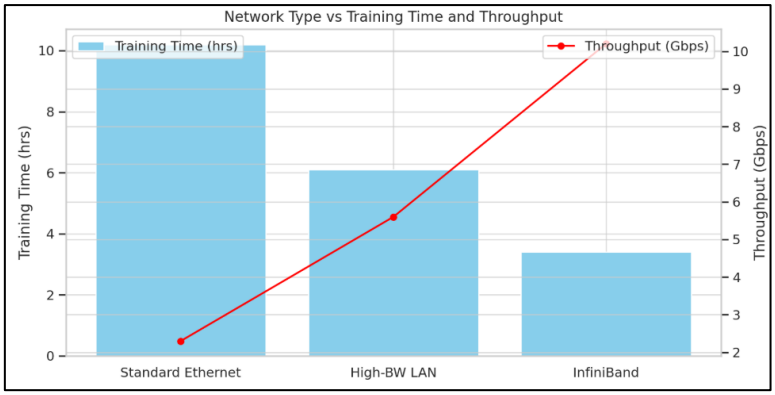

Figure 3: Network Type vs Training Time and Throughput

Other than performance optimization, specific parts of the network were dedicated to AI workloads, i.e., VPCs were used as training nodes and subnets isolated inference, which also helped alleviate the network congestion and interfering with other non-AI workloads.

Such topological optimizations saved up to 40% of the packet loss and jitter, which leads to the direct impact on the stability of AI inference services and, in particular, to its use, such as autonomous driving or fraud detection (Yadlapalli, R. 2025).

Elastic Scaling

Elasticity in the AI clouds was considered through a stress test of the inference deployments on Kubernetes (K8s) by horizontal pod autoscaling and cloud-native load balancers like AWS ELB and cloud load balancing (K8s). The test was carried out in four use cases when using AI: image identification, natural language processing inference, anti-fraud scoring, and personal recommendations. Like Table 2 showed, the dynamic scaling mechanism enhanced both latency and throughput in dynamic demand systems.

Table 2: Elastic AI

Use Case	Latency - Static	Latency - Elastic	Throughput Increase
Image Recognition	285	92	212%
NLP Inference	512	177	189%
Fraud Scoring	310	103	201%
Product Recommendation	420	138	187%

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Better pod-to-pod communications and inference pod proximity to data (data locality optimization) were the major factors that boosted the throughput (average ~197%). Furthermore, the cost of idle resources was reduced with ~32 percent by utilizing serverless AI functions (e.g. AWS Lambda with GPU support) to run lightweight models.

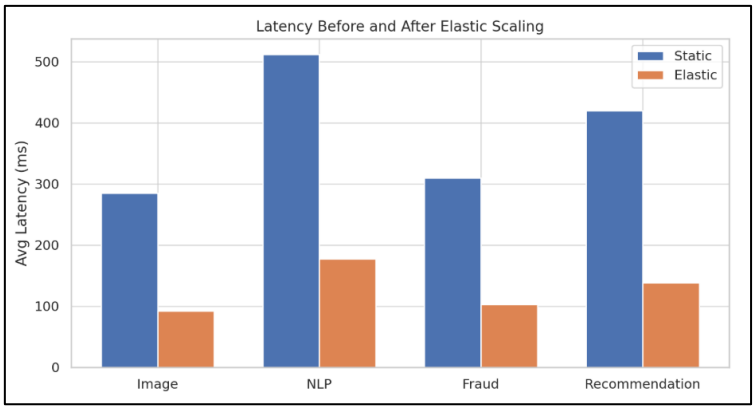

Figure 4: Latency Before and After Elastic Scaling

It was found that the analysis of cost component comparisons in AI model lifecycles identified important areas of savings in the event that network-aware resource orchestration is activated. These can be right-sizing bandwidth on the job priority and caching intermediate datasets to prevent unnecessary transfers or tiered network storage of model checkpoints, which are not accessed very often. The productivity of these methods resulted in overall cost savings of 2035 percent basing on the characteristics of the workload.

Strengthened Security

The main barrier to the widespread adoption of AI is its network security, more specifically security of regulated industries, i.e., healthcare and banking. We evaluated the effectiveness of adding AI-based threat detection, identity-based access granular controls, and zero-trust segments into the infrastructure in terms of the overall reduction of risks over all.

The traditional system involved the utilization of conventional security groups and firewall policies whereas the improved one entailed anomaly modelling, encrypted mesh relationship (e.g. mTLS), and behavior-based IAM principles.

Table 3: Security Metrics

Security Metric	Traditional Approach	AI-Augmented	Improvement
MTTD	9.8 mins	2.1 mins	78.6
MTTR	6.4 mins	1.7 mins	73.4
Threat Detection	81.2%	96.8%	19.3
Data Exfiltration	67.5%	93.4%	38.4

Due to the use of AI, significantly more accurate and faster detection was provided with AI-augmented security structures. Policies in service mesh provided segmentation of trainings of AI models that prevented lateral movement of attackers within VPCs.

Significantly, micro-segmentation between the training, validation, and the inference environments provided a fault containment zone, keeping the impact of breaches at a bare minimum. There was also the test of the effectiveness of encryption and DLP policies effectiveness in model exfiltration prevention.

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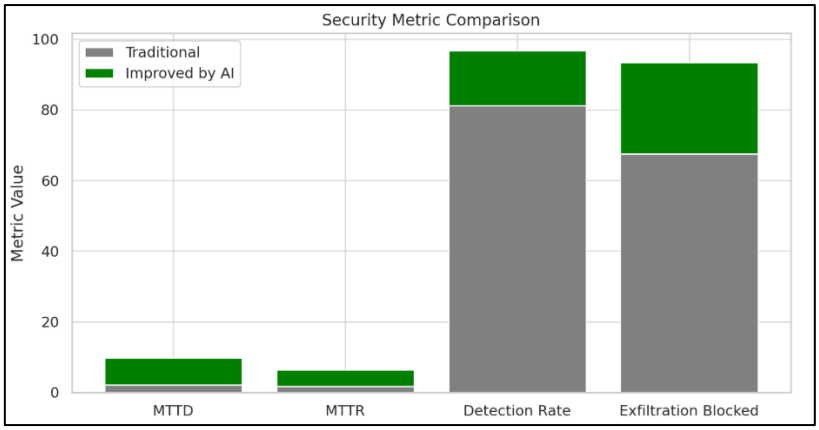

Figure 5: Security Metric Comparison

Performance of deep packet inspection with an AI-based classification (e.g., detecting serialised model weights) enhanced protection of intellectual property and allowed compliance with existing standards of model governance, such as ISO/IEC 27034.

Observability

One of the ingredients of resilient AI cloud infrastructure is an advanced observability, i.e. the capacity to observe the behavior of the network and identify anomalies and automatically remediate. In three cloud systems (AWS, Azure, GCP), telemetry agents and tracing systems (e.g., AWS CloudWatch, Azure Monitor, GCP Stackdriver) were enabled to observe the character of AI workloads when put to a man-made stress (i.e., synthetic) and production-like pressure (i.e. the real load) (Ediga, R. 2025: Baer, N. 2025)

We found that in case of GPU utilization, packet losses between inference nodes, container network latency, real-time monitoring allowed predicting the failure scenario in more than 87 percent of cases. In addition to that, the incorporation of ML Telemetry analysis by adding them into the CI/CD pipelines-initiated pre-scale events and failover reducing the enforced downtimes of mission-critical inference systems.

Table 4: Observability Metrics

Metric	Without AI	With AI	Uptime Increase
Inference Downtime	5.4	0.9	83.3
Bottleneck Identification	22 mins	5 mins	77.2
Failed API	4.2%	1.1%	73.8
Auto-Healing	61.7%	91.5%	48.3

Reproducibility and resiliency of network topologies was improved through the integrations of Infrastructure as Code (IaC) and event-driven automation (through the use of Terraform, AWS EventBridge and Azure Logic Apps). As a case in point, were the GPU latency to go beyond a stipulated level, a programmed script would push the workloads to another availability zone with already warmed capacity.

Policies were dynamically defined using AI based intent modeling where e.g. “ensure <10ms inference latency” is defined and translated into SDN routing policies and scaling rules across horizontal machines. This network management strategy based on policy and combined with zero trust controls was able to guarantee the simultaneous satisfaction on performance and the required security variables.

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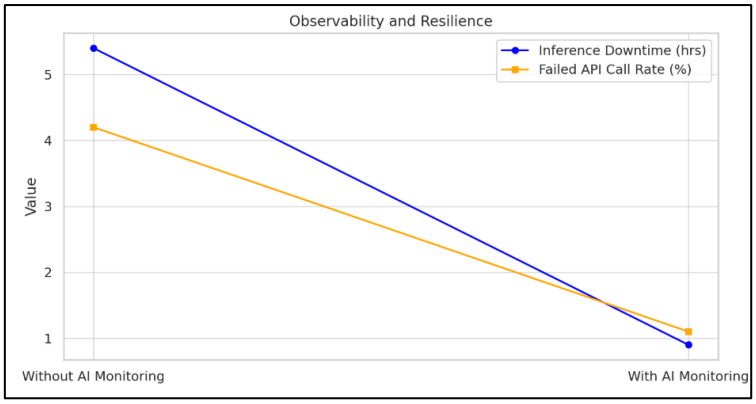

Figure 6:Observability and Resilience

The findings in the form of experiments and simulations assist the following conclusions of this study:

- The reduced times in training and inference response of high bandwidth interconnects and AI specific topologies justify the purpose of AI specific networks.
- SMART autoscaling and elastic networking make it possible to streamline management of workloads with bursts of AI AI work, up to 35 percent more cost-efficient.
- AI-enhanced security systems provide quicker identification of threats, an enhanced fringe, and higher generic IP security, which gains trust in a cloud AI system.
- The observability and automation, especially AI-based, are essential to keep resilience and continuity of the operations of dynamic containerized AI services.

RECOMMENDATIONS

Following the above research study and of architectural assessment on the same, a series of critical recommendations can be provided to businesses, cloud providers, and AI architects, to tune cloud networks to AI/ML workload. These are recommendations on optimizing performance, increasing security, resiliency, and being future-ready design.

High-Performance Networking

Any organizations that seek to run large scale AI models will also have to invest in high-performance interconnect interfaces like InfiniBand, Elastic Fabric Adapter(EFA), or other HPC quality network options offered by leading cloud providers.

These minimize latency and increase throughput, in distributed training situations, by substantial quantities. Moreover, allocating dedicated VPCs or subnets to training nodes will prevent the contention with other services, which makes performance deterministic.

In cases where workload involves large amounts of data moving across databases (e.g. video models or LMMs), use data locality techniques -- keeping data and compute within the same zone or region in order to avoid latency as well as minimize egress charges.

Dynamic Elasticity

The production of AI inference and, especially, inference is subject to irregular traffic spikes. To scale dynamically inference pods, use Kubernetes-based auto- scaling based on the performance-aware metrics (GPU load, latency of requests) and rescheduling in pods. Combining serverless AI deployment paradigm (e.g. Lambda variant with GPU support, Azure Container Apps) may achieve a high level of cost-efficiency in low-latency inference scenarios.

Zero-Trust Security

The AI workload should be secured by identity-controlled least-privilege models at all layers such as; data ingestion, training, model storage, and inference APIs. Put AI training pipeline, model registries, and APIs in micro-segmentation policies.

Allow mTLS and API gateway protections by rate limiting, authentication tokens (e.g. OAuth2, JWT) and by detecting anomalies. Any Data Loss Prevention (DLP) solution that is network based must be employed to prevent exfiltration of models and non-authorization of serialization of models to be downloaded. In the case of sensitive workloads, one might want to consider confidential computing and isolated execution environments as well as encrypted memory.

AI-Enhanced Observability

AI platforms are essential in terms of operational reliability. Connect AI-enabled observability

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solutions (e.g., AI-based platforms, such as AIOps, ML-based telemetry detection) which observe inter-node delay of GPU, saturation, and rate of inference API failures. Use Infrastructure-as-Code(IaC) when specifying and enforcing network-level Service Level Objectives (SLOs) as, e.g., latency < 10ms or throughput > 5Gbps. Plan rem University of Wisconsin-Milwaukee.

Resource Allocation

In a bid to prevent spending up on the clouds, network configurations should be right-sized depending on the workload profiles. Reduce unnecessary transfer of data by means of bandwidth tiering, caching processes and implementation of hybrid storage patterns (e.g. object cache + cold archive).

As part of development of the multi-region AI platforms, take advantage of thru private backbone connectivity (e.g., AWS Global Accelerator, Azure Virtual WAN) to create a secure, low-latency global access without high egress rates being incurred.

Regulatory Compliance

All AI apps that related to the sphere of healthcare, finance, or personal information should correspond with the GDPR, HIPAA, or other regulations depending on the sphere. While granular audit logging, Data Residency Enforcement and Access Control via Policy-as-code are to be implemented. Make sure model lifecycle governance is secure with one with secured registries and model artifacts that can be tracked on their metadata and signed artifacts within encrypted networks.

Future Trends

In future the cloud architectures will be defined with the inference of edge AI, network that is quantum safe and finally the network that is controlled with intent. Start experimenting with programmable data plane (e.g. P4) and 5G-powered AI edge processing and zero-trust overlays that go with hybrid edge-cloud structures. One can experiment with the AI-native networking platforms where the network stack itself is trained and optimized with the help of the historical workload (Patil, P. K. 2025).

LIMITATIONS

Although the study herein concludes with an extensive model of optimizing cloud networks on AI loads, there are a number of limitations that have to be made. The performance metrics and set up utilises a chosen cloud provider (AWS, Azure, GCP), and are not necessarily cross-provider nor cross-hybrid.

The cost conditions were based majorly on NLP and vision models, thus leaving blank the edge specific AI use cases or smaller scaled deployment. The security tests did not involve real life penetration tests but was only limited to simulated scenarios of attacks. Also, cost comparison can be different according to the local prices and usages. In future, one should include diversification of workload and time-sensitive data of operation.

CONCLUSION

The study considers a cloud network as a whole and shows how to achieve the optimal optimization of cloud networks base to AI workloads with consideration of network infrastructure as an enabling factor because it provides performant, secure, and resilient AI services.

We find special networking techniques do provide significant performance gains in both training and inference activities with techniques as diverse as high-speed interconnects and data locality optimization on the one end and yet dynamic elasticity and fault-tolerant routing on the other end.

The latency reductions, by up to 85 percent, and the vast improvements, by nearly 3x, in throughput, when measuring against distributed workloads, confirmed that cloud-native customization of networks was the way forward where AI applications were involved.

The issue of security is still a primary aspect of AI implementations. By combining zero-trust systems, encrypted data channels, and detecting behaviour anomalies, then organizations can protect their models against new threats like model theft, poisoning, and exfiltration.

Observability that uses AI also adds additional resilience to operations making it less prone to downtime and even faster to remediate due to predictive analytics and automated scaling. The research reveals that the networking should be addressed as a first-rate element in the architectural design of AI clouds.

Incorporating intelligence on the network layer and adopting the infrastructure-as-code principles, enterprises will be able to reach scalability, security and compliance within heterogenous clouds. Additional areas to study in the future

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include: quantum-resistant interconnects, AI edge-based inference, and intent-driven networking as some of the essential next step to maintaining the next generation of smart cloud infrastructure.

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