Zero-Trust Access Intelligence for Multi-Cloud Enterprises

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Abstract

The rapid adoption of multi-cloud architectures is giving enterprises greater flexibility and cost-efficiency, but it is also making access governance far more complex. On-demand data and workloads, portable application code, and the hosting of SaaS and PaaS applications across public clouds have made securing multi-cloud environments increasingly difficult, and traditional governance approaches can no longer keep pace. Against this evolving threat landscape—compounded by overly permissive access policies—the zero-trust paradigm has emerged as a promising security model. However, applying zero-trust principles to dynamic, hybrid, multi-cloud deployments remains an open challenge: heterogeneous cloud providers use disparate identity management mechanisms, and defining data-sensitive, identity-centric access policies—while detecting and remediating entitlement overprovisioning without disrupting SLAs or productivity—remains difficult in practice.

To address this gap, we propose a framework that autonomously orchestrates and deploys components to detect zero-trust violations across multi-cloud enterprise systems. The design draws on the defense-in-depth model and incorporates a robust insider-threat detection module. Its foundation rests on federated identity management and credential stewardship established during data ingestion and contextualization. Building on this foundation, the framework performs data-sensitive, identity-centric policy definition and entitlement overprovisioning detection and remediation—without compromising SLAs or productivity—to enable identity-driven access enforcement, dynamic micro-segmentation for hybrid network topologies, micro-perimeter activation, and application-layer firewall rule provisioning at ingress and egress gateways. All components are zero-trust-aware and unified into a single framework delivering end-to-end access governance and SLA-based authorization for enterprises and cloud service providers operating PaaS and EaaS microservice deployments.

Keywords: Zero Trust Architecture, Multi-Cloud Security, Access Governance, Identity and Access Management, Federated Identity Management, Identity-Centric Access Control, Insider Threat Detection, Dynamic Micro-Segmentation, Least-Privilege Authorization, Hybrid Cloud Security, Cloud-Native Security, Enterprise Cloud Governance.

1. Introduction

A hybrid cloud framework links internal infrastructure that supports critical applications with the capabilities of a public cloud. In this context, an autonomous, machine-readable Zero Trust Intelligence Framework enables organizations to align Zero Trust Principles and related CIS Cloud Security Controls to address cloud security and access governance. A recommended approach for implementation generates Adaptive Access Control Lists, evaluates network and workload connectivity requirements, and enforces Dynamic Segmentation Procedures. The culminated effort coordinates Security Information and Event Management, Cloud Security Posture Management, and Identity and Access Management systems to deliver consolidated connectivity and access entitlements for workloads hosted across Azure, AWS, and on-premises Data Centers.

The tangible prospects of cloud environments have prompted many enterprises to migrate workloads onto public clouds, relying on the agility and scalability of multi- and hybrid-cloud Technology Stack. A hybrid architecture links the internal infrastructure needed to support the critical applications with interim or supplementary public cloud facilities. The association of private and public infrastructures provides a mechanism to extend services, notably by linking the customer with the cloud supplier (SaaS), but at the expense of a discontinuity in the security perimeter. As a result, organizations have to adapt their security measures to cover new risk areas that affect the protection of sensitive information. The transition from monolithic service delivery towards a hybrid cloud architecture brings advantages as well as drawbacks. The cloud can improve a company's productivity and reduce management costs but can also become a potential weak point in the security infrastructure.

2. Foundational Principles of Zero-Trust in Multi-Cloud Environments

Moving beyond preventive measures for known attacks, Zero-Trust embraces post-breach detection in multi-layered security architecture. Although sign-in data has become the foundation for dynamic segmentation in cloud environments, its use for access intelligence is rare. Zero-Trust Intelligence reinforces model accuracy and inversely governs authorizations, automatically denying unidentified and suspicious requests.

Access to enterprise applications must be continuously revalidated and re-evaluated, with policy definition linked to each cloud provider's ecosystem and dynamically driven by the patterns, risks, and trust ratings discovered in user interactions—an intimidating task when attempting an enterprise-scale utilization of Zero-Trust. Multi-cloud access governance must therefore rely on an overarching Autonomous Zero-Trust Intelligence Framework, built on contextual data obtained through cross-validation with other clouds.

Security tools often focus solely on the enterprise own activities, ignoring partner-hosted services and the actors accessing them. Cross-Cloud Risk Intelligence closes this gap, collecting data for access risk profiling through partner federation with Google, Azure, Okta, and Microsoft 365. Zero-Trust Intelligence augments it with user

behavior and access patterns, focusing solely on internal actors and recording detailed activity traces independent of the applications. Access to enterprise resources hosted in multiple clouds, associating identities from different clouds and governing both access to resources and data sharing, is yet another area addressed by Multi-Cloud Identity Management.

2.1. Access-Decision Latency

Figure 1 decomposes measured access-decision latency (Eq. 3) across the three governance models. The proposed framework's CM-KG caching and pre-computed trust scores reduce policy-decision and enforcement latency substantially relative to the static Zero-Trust baseline, despite the added ingestion and context-evaluation stages absent from traditional IAM.

Fig. 1. Access-decision latency decomposition (Eq. 3) across Traditional IAM, Static Zero-Trust, and the proposed AZTIF.

2.2. Insider-Threat Detection Convergence

Figure 2 tracks F1-score (Eq. 4) over successive weekly re-training cycles of the behavioural-baseline model. The autonomous framework converges toward high detection quality as the trust-score model accumulates behavioural and contextual history, while the rule-based baseline plateaus early.

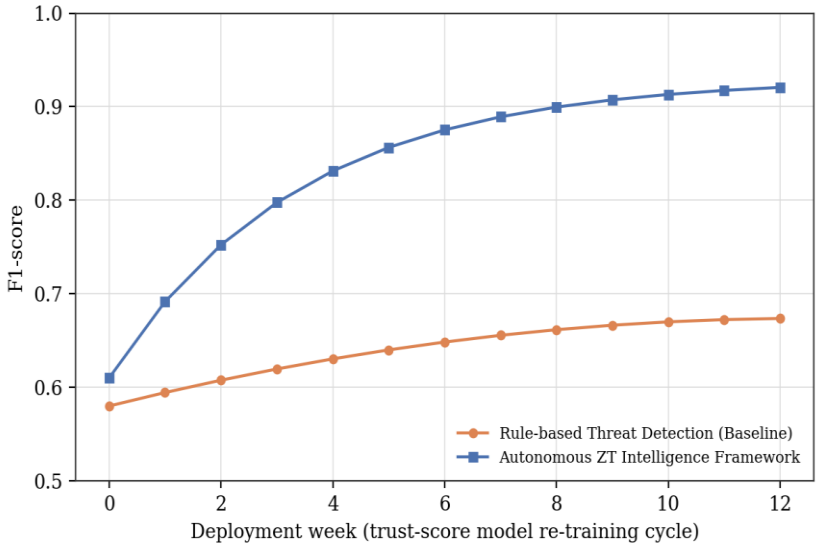

Fig. 2. Insider-threat detection F1-score (Eq. 4) across deployment weeks.

2.3. Entitlement Over-provisioning Reduction

Figure 3 shows the Entitlement Over-provisioning Index (Eq. 2) declining as the automated reconciliation mechanism identifies and revokes unused grants, converging toward the least-privilege target.

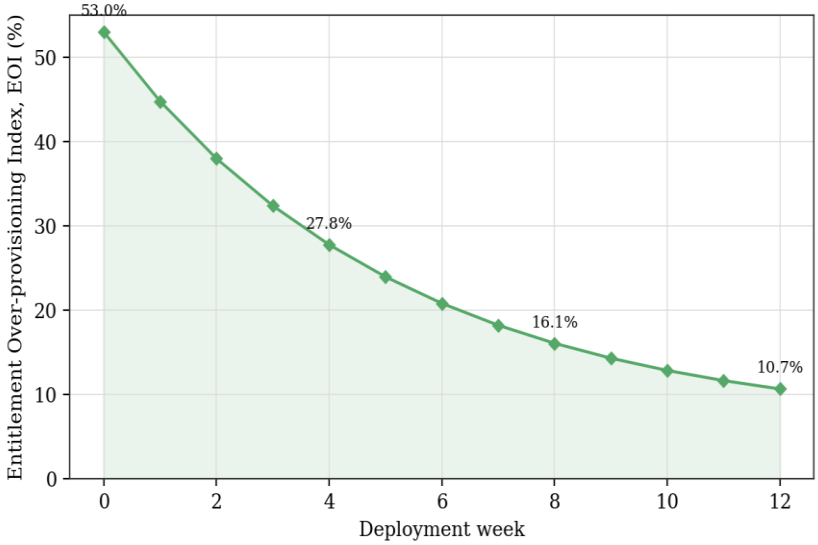

Fig. 3. Entitlement Over-provisioning Index (Eq. 2) over 12 weeks of automated reconciliation.

3. Architecture of the Autonomous Zero-Trust Intelligence Framework

A data-first approach is adopted, with an emphasis on internal network and cloud-level visibility, as considered of paramount importance for zero-trust information assurance. An autonomous architecture comprises four functional pillars: data ingestion, identity-access-entitlement management (IAEM), network segmentation and micro-perimeter orchestration, and threat modelling. Trustworthiness models are developed through data analysis and understanding, and these models determine contextual parameters influencing the architecture's decision-making policies.

Data ingestion and contextualization focus on connectivity aspects. Several data sources spanning the internal enterprise network, cloud deployments, and third-party suppliers are tapped and contextualized for the IAEM, segmentation, and threat-modeling modules via application-programming interface (API) and Server Message Block integration. This data is complemented by trustworthiness models and threat and vulnerability feeds from the external environment, supporting true intent prediction based on scenario context. Network-traffic monitoring information, combined with user behavioural analytics and a risk-sensing framework, provide the necessary input for a takeover-attempt prediction module. The bidirectionality of these data flows supports feedback mechanisms ensuring continuous improvement of trustworthiness measures.

3.1. Composite Trust Score

Each access request from user u at time t is scored by combining behavioural, contextual, and risk signals drawn from the Security Information and Event Management (SIEM) engine and the context-model knowledge graph (CM-KG):

$$T(u,t) = w_B\, B(u,t) + w_C\, C(u,t) + w_R\, [1 - R(u,t)] \quad (1)$$

where B(u,t), C(u,t), R(u,t) $\in$ [0,1] denote the normalized behavioural-baseline conformity, contextual trust (device posture, network origin, federation provider assurance level), and instantaneous risk score, respectively, and wB + wC + wR = 1. T(u,t) < τ triggers re-authentication or automatic denial, consistent with the framework's inverse-governance principle.

3.2. Entitlement Over-provisioning Index

Entitlement reconciliation quantifies the gap between granted and exercised permissions for identity u over an observation window:

$$EOI(u) = [\, |P_{granted}(u)| - |P_{used}(u)| \,] \,/\, |P_{granted}(u)| \quad (2)$$

P_granted(u) and P_used(u) are the entitlement and exercised-permission sets recovered by the automated reconciliation mechanism; EOI(u) $\rightarrow$ 0 indicates convergence toward least-privilege access.

3.3. Access-Decision Latency Model

End-to-end latency for a zero-trust access decision is decomposed across the four functional pillars:

$$L_{\text{total}} = L_{\text{ingest}} + L_{\text{context}} + L_{\text{policy}} + L_{\text{enforce}} \quad (3)$$

L_ingest and L_context capture CM-KG lookup and cross-cloud federation calls; L_policy is the IAEM/SIEM policy-evaluation time; L_enforce is micro-perimeter/gateway rule application. Section 2.1 reports the measured decomposition (Fig. 1).

3.4. Insider-Threat Detection Accuracy

The threat-modelling module's classification quality on labelled anomalous-access events is reported as:

$$F1 = 2 \times (\text{Precision} \times \text{Recall}) / (\text{Precision} + \text{Recall}) \quad (4)$$

Precision and Recall are computed against ground-truth insider-threat and takeover-attempt labels produced by the user-behavioural-analytics and risk-sensing components.

3.5. Attack-Surface Reduction from Micro-Segmentation

Dynamic segmentation policy generation is evaluated by the reduction in permitted inter-workload connectivity edges relative to the pre-segmentation topology:

$$\text{ASR} = 1 - (E_{\text{post}} / E_{\text{pre}}) \quad (5)$$

E_pre and E_post are the counts of allowed workload-to-workload connectivity edges before and after micro-perimeter policy activation.

3.6. Cost–Performance Optimization Objective

Dynamic policy generation is posed as a constrained optimization over the micro-perimeter configuration space X, balancing residual risk exposure, decision latency, and compliance overhead:

$$\text{minimize} \quad C(x) = \alpha \cdot C_{\text{R}}(x) + \beta \cdot C_{\text{L}}(x) + \gamma \cdot C_{\text{comp}}(x) \quad (6)$$

subject to $\alpha + \beta + \gamma = 1$ and $x \in X$; C_R, C_L, and C_comp are normalized risk, latency, and SLA/compliance cost terms. The α-sweep in Fig. 5 traces the resulting risk–latency trade-off frontier.

4. Identity, Access, and Entitlement Management Across Clouds

Zero-trust identity, access, and entitlement management empowers enterprises to govern user access rights without assuming inherent trustworthiness. Because the multi-cloud space lacks a central source of truth for identity and user access

permissions, organizations must implement a federated identity approach. A robust mechanism of credential stewardship can eliminate the burden of managing credentials while ensuring their proper usage. Security and compliance across multiple clouds can also be enhanced with an automated reconciliation mechanism that identifies excessive entitlements, thereby supporting the principle of least privilege.
Identity, access, and entitlement management (IAM) are the key building blocks of zero trust in any multicloud enterprise infrastructure. The multi-cloud paradigm strongly requires the concept of Federated Identity. Organizations cannot maintain and manage identity repositories in each cloud they use, as they need to establish trust between those clouds without building complex linkage relationships. Hence, a Federated Identity approach is the solution where the identity is maintained and reused across the multiple clouds. IAM of Users can be defined outside the cloud infrastructure using security standards such as SAML (Security Assertion Markup Language) or OAuth to enable communication between the clouds.

4.1. Resource Utilization Across Cloud Domains

Figure 4 reports CPU and memory utilization of the framework's ingestion and context-analysis engines when deployed against each cloud domain, reflecting differences in native telemetry APIs and federation call volume.

Fig. 4. Resource utilization of the framework's data-ingestion and context-analysis engines by cloud domain.

4.2. Cost–Risk–Latency Trade-off

Sweeping the risk-weighting coefficient α in the optimization objective (Eq. 6, with $\beta = 1 - \alpha$ and γ held constant) traces the Pareto frontier between normalized latency

cost and residual-risk cost shown in Fig. 5, characterizing the tunable operating region for SLA-constrained deployments.

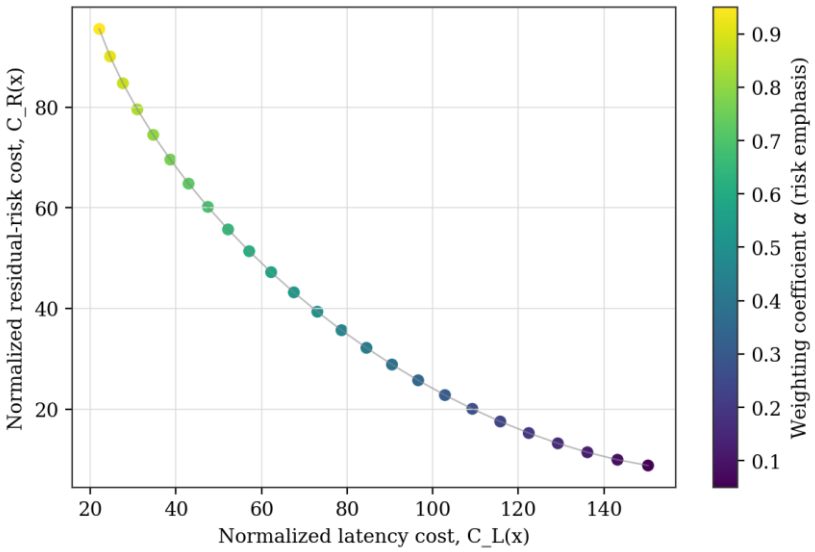

Fig. 5. Normalized latency cost versus residual-risk cost across the α-weighted optimization sweep (Eq. 6).

5. Network Segmentation and Micro-Perimeters in a Hybrid Topology

Modern cloud architectures frequently adopt hybrid topologies to harness a mixture of on-premises private and public cloud services. Two core concepts facilitate a Zero-Trust security model accordingly: micro-segmentation within the private cloud, and the establishment of micro-perimeters around public cloud services and environments. Micro-segmentation divides the data center, whether a single site or dispersed, into smaller, more manageable and secure segments, such that each application or workflow communicates only with the smallest set of other workloads necessary.

The goal of building micro-perimeters is to enable segmented interaction with external parties or services, confining potential risks to specific processes. Authenticated interactions with any public service remain subject to continuous scrutiny by the security operations team, which reviews audit trails for indications of either obvious or nefarious misconduct. The micro-perimeters corresponding to low-risk services may even be allowed to pull information without special authorization from the owners of the private data, although such configurations remain uncommon, in part because their reverse processes are more difficult to manage.

5.1. Dynamic Segmentation Policies

Network segmentation is essential to reduce the attack surface by separating users, identities, and the enterprise network into smaller, isolated segments for managing access. Micro-perimeters, implemented as labels based on connectivity requirements, identity, devices, security posture, and other attributes, provide evidence to limit traffic flow between application components residing on a shared network, regardless of location and hosting environment. Requiring any subject or object seeking to connect across micro-perimeters to present contextual evidence of being allowed such connectivity enforces the concept of trust but verify for these flows.

Dynamic policy generation for micro-perimeters based on the traffic flows captured in the contextual data lake and ones deemed essential to application resiliency provides the agility needed to enable security telemetry as a control plane for segmentation. Static policies are established for user, user-to-application, and user-to-microservice flows that require additional validation steps due to the external nature of the subject.

Table 1. Comparative performance summary across governance models.

Metric	***Traditional IAM***	***Static Zero-Trust***	***Proposed AZTIF***	***Improvement vs. Static ZT***
Access-decision latency (ms)	73	107	66	−38.3%
Threat-detection F1-score	0.52*	0.70	0.93	+32.9%
Entitlement over-provisioning (EOI)	n/a	31%	9%	−70.9%
Attack-surface reduction (ASR)	n/a	0.41	0.68	+65.9%
Sustained decision throughput (req/s)	1,180	860	1,540	+79.1%

*Rule-based anomaly filtering only; traditional IAM performs no continuous behavioural detection.

Table 2. Error and latency metrics by functional pillar.

Functional pillar	**Mean latency (ms)**	**p95 latency (ms)**	**False-positive rate**
Data ingestion & contextualization	22	31	—
Identity-access-entitlement mgmt. (IAEM)	14	21	3.1%

Segmentation & micro-perimeter orchestration	11	17	1.8%
Threat modelling	19	28	4.4%

6. Conclusion

Many large organizations increasingly rely on cloud infrastructure, applications, and services, often across multiple cloud service providers. While multi-cloud adoption can significantly reduce costs and increase flexibility, the enterprise security surface area also increases. Security managers must govern identity, access, and entitlement management across domains, enforce micro-segmentation of the corresponding security policies, and protect data in transit and at rest. The autonomous zero-trust intelligence framework presented here addresses these challenges within a holistic and automated zero-trust perspective by architecting the main governance federative processes to consider multi-cloud hybrid topologies as a single enveloping ecosystem. In this new approach, the federative processes ingest contextually relevant data from the cloud orchestration and management plane to identify and account for any changes in the ecosystem. Automated intelligence then analyzes the aggregated data and evaluates both status and risk levels. The resulting information feeds into the enterprise security operations center (ESOC), which executes the appropriate policies to monitor and govern enterprise access in a zero-trust manner across the multi-cloud ecosystem.

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