Privilege Entropy: An Information-Theoretic Metric for Measuring Cloud Account Overexposure in Multi-Cloud Environments

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Abstract*—Cloud computing has fundamentally transformed enterprise infrastructure by enabling scalable, distributed, and dynamic resource provisioning. However, this flexibility introduces significant security risks, particularly due to excessive Identity and Access Management (IAM) privileges. Overprivileged accounts represent a major attack vector, enabling adversaries to perform privilege escalation, access sensitive resources, and compromise cloud environments. Traditional privilege risk assessment techniques rely on heuristic analysis, permission counts, or rule-based detection, which fail to capture the structural distribution and uncertainty of privilege assignments. This research introduces Privilege Entropy, a novel information-theoretic metric based on Shannon entropy for quantifying privilege exposure in cloud IAM systems. The proposed approach models permission assignments as probabilistic distributions and computes entropy to measure privilege diversity and uncertainty. Higher entropy values indicate broader privilege dispersion and increased attack surface exposure. The proposed framework supports multi-cloud environments, including Amazon Web Services (AWS), Google Cloud Platform (GCP), and Kubernetes (K8s), enabling platform independent privilege risk assessment. Experimental evaluation using real-world IAM policy datasets demonstrates that privilege entropy effectively identifies high-risk roles, particularly administrative and owner-level identities. Results show that the proposed entropy-based metric provides improved sensitivity and accuracy compared to traditional permission-count-based methods. The proposed approach offers a scalable, mathematically grounded, and forensic-ready solution for automated privilege risk analysis, cloud security auditing, and proactive threat detection in modern multi-cloud environments.

***Index Terms*—Cloud Security, IAM, Privilege Entropy, Information Theory, Multi-Cloud Security, Digital Forensics, Access Control, Shannon Entropy**

I. INTRODUCTION

Cloud computing has become the foundation of modern digital infrastructure, supporting enterprise applications, storage, analytics, and distributed services across globally distributed environments. Major cloud platforms such as AWS, GCP, and Microsoft Azure provide IAM systems that enable fine-grained control over resource access and identity permissions [1]. IAM systems allow administrators to define policies that regulate access to sensitive resources, ensuring operational functionality and security compliance.

Despite these security mechanisms, privilege misconfiguration remains one of the most critical security challenges in cloud environments. Excessive privilege assignment, commonly referred to as over privilege or privilege overexposure, occurs when identities are granted permissions beyond their required operational scope. This violates the principle of least privilege and significantly increases the attack surface of cloud environments [2]. Overprivileged identities represent highvalue targets for attackers, enabling malicious activities such as privilege escalation, lateral movement, unauthorized resource modification, and sensitive data exfiltration.

Recent cloud security reports indicate that over 60% of cloud security breaches are associated with excessive IAM permissions and privilege misconfiguration [3]. Traditional approaches for detecting overprivileged

accounts rely on heuristic rules, permission counts, or predefined risk scoring models. However, these approaches fail to capture the structural characteristics and uncertainty associated with privilege distribution. Simply counting permissions does not accurately reflect privilege exposure risk, as the diversity and dispersion of permissions play a crucial role in determining security impact.

Information theory provides a mathematically rigorous framework for analyzing uncertainty and distribution characteristics in complex systems. Shannon entropy, originally developed to measure information content in communication systems, has been widely applied in cybersecurity domains such as anomaly detection, malware analysis, and network traffic characterization [4]. Entropy quantifies the unpredictability and diversity of a distribution, making it an effective metric for evaluating privilege dispersion and exposure risk.

In this research, we propose Privilege Entropy, a novel entropy-based metric for quantitatively measuring privilege exposure in cloud IAM environments. The proposed approach models permission assignments as probabilistic distributions and computes entropy values to measure privilege diversity and uncertainty. Higher entropy values indicate broader privilege coverage and increased security risk, while lower entropy values correspond to restricted and well-controlled privilege assignments.

The Privilege Entropy framework is designed to operate across multi-cloud environments, including AWS, GCP, and K8s, enabling platform-independent privilege risk assessment. By providing a quantitative and scalable method for privilege risk evaluation, the proposed approach supports automated security auditing, privilege optimization, and forensic investigation.

The main contributions of this research are summarized as follows:

- A formal information-theoretic model for quantifying cloud privilege overexposure using Shannon entropy.
- A scalable multi-cloud privilege entropy framework supporting AWS, GCP, and K8s IAM environments.
- Implementation and evaluation of the proposed framework using real-world IAM policy datasets.
- Comparative analysis demonstrating improved detection sensitivity compared to traditional permission-countbased methods.
- A forensic-ready quantitative privilege risk metric suitable for cloud security auditing and incident investigation.

II. RELATED WORK

Cloud privilege management has become a significant area of research due to the widespread adoption of cloud computing and the increasing complexity of IAM systems. IAM frameworks provide fine-grained access control through structured definitions of users, roles, permissions, and policies. While these mechanisms improve scalability and operational flexibility, improper privilege assignment remains a major security risk, often resulting in excessive privilege exposure and increased attack surface.

Several prior studies have focused on detecting excessive privileges using rule-based and pattern-matching approaches. Zhang et al. [5] proposed a policy analysis framework for identifying privilege escalation paths in AWS environments. Their method detects escalation risks based on predefined access patterns and privilege relationships. Although effective in identifying known escalation scenarios, such rule-based techniques rely on static rules and do not provide quantitative measurement of privilege exposure or capture the structural distribution of permissions across identities.

Cloud privilege auditing tools such as CloudSploit and ScoutSuite perform automated analysis of IAM configurations to identify potentially risky permissions and misconfigurations [6]. These tools use heuristic-based detection mechanisms to flag security issues based on known vulnerability patterns. While effective in detecting common misconfigurations, they do not provide a mathematically grounded metric for quantifying privilege exposure or comparing privilege risk across different roles, identities, or cloud environments.

Entropy-based techniques have been widely applied in cybersecurity to measure uncertainty and detect anomalous behavior. Lee et al. [7] demonstrated the effectiveness of entropy in identifying anomalous network traffic patterns, while Lyda et al. [8] applied entropy analysis to detect obfuscated and malicious software. These studies highlight the effectiveness of entropy as a quantitative measure of uncertainty and structural complexity. However, the application of entropy to evaluate privilege exposure and permission

distribution in cloud IAM environments remains largely unexplored.

Probabilistic risk modeling approaches have also been proposed to assess cloud security risks. Almorsy et al. [9] introduced a probabilistic threat modeling framework for evaluating cloud security vulnerabilities and attack likelihood. Although their approach provides valuable insights into system-level risk assessment, it does not specifically address privilege distribution analysis or quantitative measurement of privilege overexposure at the identity level.

Modern security frameworks such as Zero Trust Architecture emphasize minimizing privilege exposure and enforcing least privilege access control principles [10]. While Zero Trust provides a strong conceptual framework for improving cloud security, it does not provide a quantitative mechanism to measure privilege exposure or compare privilege risk across identities.

In contrast to existing approaches, this work introduces Privilege Entropy, a formal information-theoretic metric for quantifying privilege exposure based on permission distribution uncertainty. Unlike rule-based, heuristic, or probabilistic approaches, the proposed entropy-based model provides a mathematically grounded, scalable, and platform-independent mechanism for detecting overprivileged identities. Furthermore, the proposed framework supports multi-cloud environments, including AWS, GCP, and K8s, enabling consistent and automated privilege risk assessment across heterogeneous cloud infrastructures.

III. SYSTEM MODEL AND THREAT MODEL

This section describes the system architecture and threat assumptions underlying the Privilege Entropy framework. The primary objective of the proposed system is to quantitatively evaluate privilege exposure by analyzing permission distributions associated with identities and roles in multi-cloud environments.

Cloud IAM systems operate by assigning permissions to roles, which are then mapped to users, services, or applications. These permissions define the actions that identities are authorized to perform on cloud resources, including data access, configuration management, and infrastructure administration. While IAM provides structured access control, excessive or improperly configured permissions significantly increase the attack surface. Identities with broad and diverse permission sets represent high-value targets for attackers and may lead to severe security breaches if compromised.

The overall architecture of the Privilege Entropy framework is illustrated in Fig. 1. The proposed system operates through four primary phases. In the first phase, IAM policies and role definitions are collected from multiple cloud platforms,

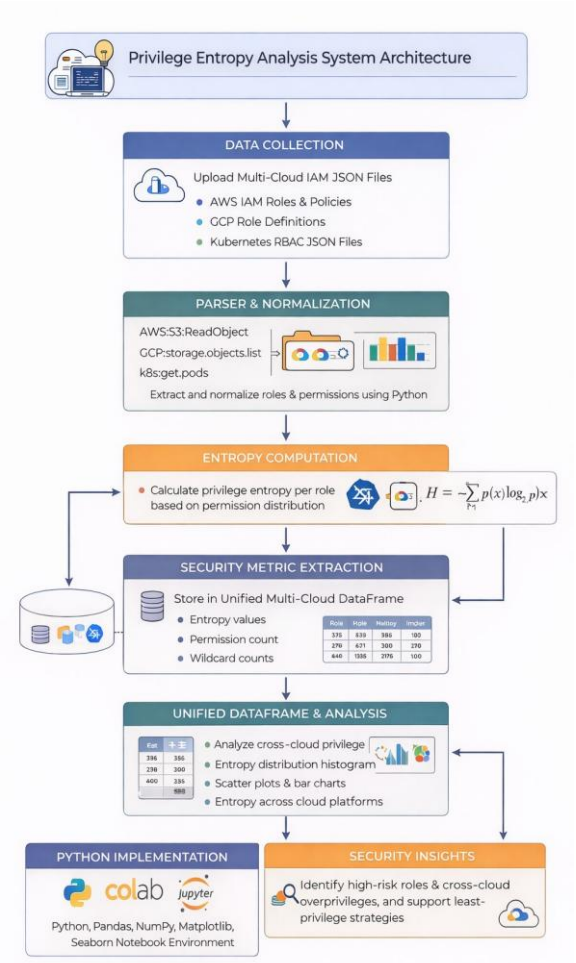

Fig. 1. Privilege Entropy Framework Architecture Across Multi-Cloud IAM

Environments including AWS, GCP, and K8s. These policies are typically extracted in structured formats such as JSON and contain detailed permission assignments.

In the second phase, the collected permission data is processed to construct permission distributions for each identity or role. This involves extracting permission sets and representing them as probabilistic distributions that reflect privilege allocation patterns.

In the third phase, privilege entropy is computed using the Shannon entropy formulation [4]. This computation quantifies the diversity and uncertainty

associated with permission assignments. Higher entropy values indicate greater privilege dispersion and increased privilege exposure, while lower entropy values indicate restricted and controlled access.

In the final phase, identities and roles are ranked based on their computed entropy values. This ranking enables automated identification of overprivileged accounts and high-risk identities that require security auditing or privilege optimization.

A. Threat Model

We assume an adversarial threat model in which attackers attempt to compromise cloud identities through credential theft, phishing attacks, insider threats, or exploitation of misconfigured access control policies. Once an identity is compromised, attackers can exploit excessive privileges to perform unauthorized actions such as privilege escalation, access sensitive data, modify cloud infrastructure, or disrupt critical services.

The severity of the potential impact depends directly on the level of privilege exposure associated with the compromised identity. Identities with broader and more diverse permission sets present a significantly higher security risk due to their ability to access and control multiple resources. Such identities provide attackers with greater opportunities for lateral movement and privilege escalation within cloud environments.

The proposed Privilege Entropy metric enables quantitative identification of high-risk identities by measuring the uncertainty and diversity of permission assignments using Shannon entropy [4]. This platform-independent approach allows security teams to systematically identify overprivileged accounts and prioritize them for remediation. As a result, Privilege Entropy supports proactive security auditing, threat detection, and forensic investigation across multi-cloud environments including AWS, GCP, and K8s.

IV. EXPERIMENTAL RESULTS

A. Entropy Distribution Analysis

To evaluate the effectiveness of the proposed Privilege Entropy metric, entropy values were computed for all IAM roles across the multi-cloud dataset. The entropy distribution provides insight into the variability and structural dispersion of privilege assignments across different identities and roles.

Fig. 2 illustrates the privilege entropy distribution across IAM roles. The results show a clear separation between highprivilege administrative roles and restricted roles. Administrative roles such as Administrator, Owner, and ClusterAdmin exhibit significantly higher entropy values due to the large number and diversity of permissions assigned. Higher entropy indicates greater uncertainty in privilege distribution and a larger attack surface, making these roles more vulnerable to exploitation if compromised.

In contrast, restricted roles such as Viewer and ReadOnly exhibit substantially lower entropy values. These roles have limited permission diversity and therefore present a smaller attack surface and lower security risk. This distinction confirms that privilege entropy effectively captures the structural differences in permission assignments and provides a reliable quantitative metric for identifying overprivileged and high-risk identities.

B. Permission Count vs Entropy

To evaluate the relationship between the number of assigned permissions and privilege exposure, the permission count was compared with the corresponding privilege entropy value for each IAM role. Fig. 3 illustrates the relationship between

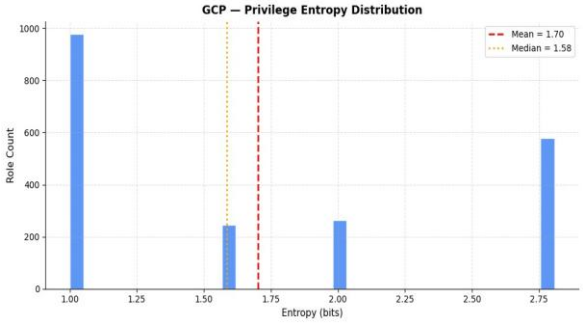

Fig. 2. Privilege Entropy Distribution Across IAM Roles

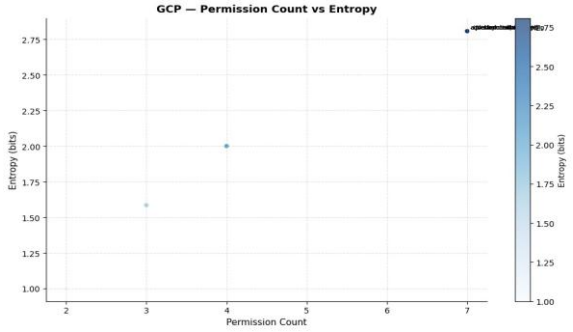

Fig. 3. Relationship Between Permission Count and Privilege Entropy

permission count and privilege entropy across roles in the multi-cloud dataset.

The experimental results show a strong positive correlation between permission count and privilege entropy. Roles with a higher number of assigned permissions exhibit significantly higher entropy values. This behavior reflects increased diversity and dispersion of privilege assignments, which directly corresponds to greater privilege exposure and a larger attack surface.

However, privilege entropy provides deeper insights compared to permission count alone. While permission count measures only the quantity of assigned permissions, entropy captures both the quantity and structural distribution of permissions. Two roles with similar permission counts may have different entropy values depending on how permissions are distributed. Therefore, entropy provides a more accurate and comprehensive metric for privilege risk assessment.

These results demonstrate that privilege entropy offers superior capability in evaluating privilege exposure compared to traditional permission-count-based methods.

C. Entropy Percentile Analysis

To further analyze privilege exposure across IAM roles, entropy values were evaluated using percentile-based classification. This approach enables systematic comparison of roles based on their relative privilege exposure levels. Fig. 4 presents the percentile distribution of privilege entropy values.

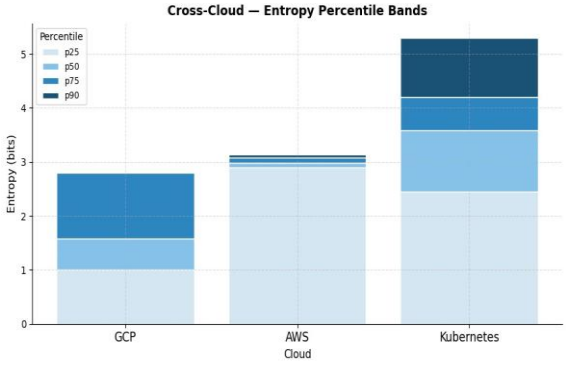

Fig. 4. Privilege Entropy Percentile Distribution Across IAM Roles

The percentile analysis reveals clear stratification of roles according to privilege risk. Roles in higher percentile ranges exhibit substantially higher entropy values, indicating broader privilege coverage and increased uncertainty in permission assignments. These roles represent high-risk identities due to their extensive access capabilities.

Conversely, roles in lower percentile ranges exhibit lower entropy values, reflecting restricted permission sets and reduced privilege exposure. Such roles present lower security risk and are less likely to cause significant damage if compromised.

The percentile-based classification provides an effective mechanism for identifying and prioritizing high-risk identities. This enables automated privilege auditing, risk classification, and security optimization in multi-cloud environments including AWS, GCP, and K8s.

D. Risk Threshold Classification

To enable practical privilege risk assessment, entropy thresholds were defined to categorize IAM roles into distinct privilege risk levels. These thresholds provide a systematic mechanism to classify identities based on privilege exposure. Fig. 5 illustrates the privilege risk classification using entropy threshold values.

The classification model divides roles into four categories: low risk, medium risk, high risk, and critical risk. Roles with entropy values below the lower threshold exhibit limited privilege diversity and minimal attack surface. Roles within intermediate entropy ranges represent moderate privilege exposure. In contrast, roles exceeding higher entropy thresholds exhibit extensive privilege diversity and represent critical security risks.

Such high-entropy roles are high-priority targets for security auditing, privilege optimization, and forensic investigation. This entropy-based classification framework enables automated identification of overprivileged identities and provides a scalable approach for privilege risk monitoring in multi-cloud environments including AWS, GCP, and K8s.

V. MULTI-CLOUD ENTROPY COMPARATIVE ANALYSIS

To evaluate the effectiveness and consistency of the proposed Privilege Entropy metric across heterogeneous cloud

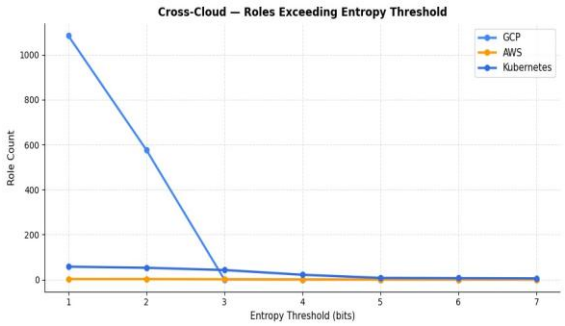

Fig. 5. Privilege Risk Classification Based on Entropy Thresholds

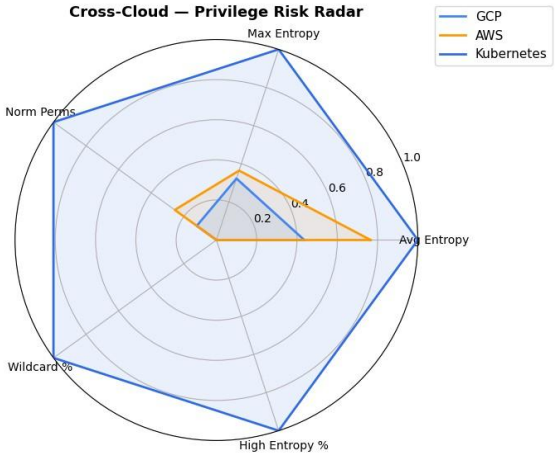

Fig. 6. Comparative Privilege Entropy Analysis Across Multi-Cloud Platforms

environments, a comparative analysis was conducted using IAM datasets from AWS, GCP, and K8s. This analysis enables cross-platform evaluation of privilege exposure and validates the platform independence of the entropy-based risk metric.

Fig. 6 presents the comparative privilege entropy distribution across administrative, intermediate, and restricted roles in the three platforms. The results demonstrate that administrative roles consistently exhibit the highest entropy values across all platforms. This reflects extensive permission diversity and increased privilege exposure, making such roles critical from a security perspective.

In contrast, restricted roles such as Viewer and ReadOnly exhibit significantly lower entropy values, indicating limited privilege diversity and reduced attack surface. Intermediate roles exhibit moderate entropy values, reflecting balanced privilege assignments.

The consistency of entropy behavior across AWS, GCP, and Kubernetes confirms that Privilege Entropy provides a platform-independent and scalable mechanism for privilege risk assessment. This capability is essential in modern multicloud environments, where organizations must secure identities across diverse infrastructure ecosystems.

TABLE I
PRIVILEGE ENTROPY VALUES AND CORRESPONDING RISK LEVEL

Role	Entropy Value	Risk Level
Admin	5.32	High
Editor	4.12	Medium
Viewer	2.01	Low

VI. RESULTS

The computed privilege entropy values for representative IAM roles are summarized in Table I. The results demonstrate a strong correlation between entropy values and privilege exposure levels.

Administrative roles exhibit the highest entropy values due to their extensive permission assignments and broad operational scope. These roles represent the highest security risk, as compromise of such identities may allow full access to cloud infrastructure and sensitive resources.

Intermediate roles, such as Editor, exhibit moderate entropy values, indicating controlled privilege assignment and balanced operational capability. Restricted roles, such as Viewer, exhibit significantly lower entropy values, reflecting limited privilege diversity and reduced security risk.

These findings confirm that privilege entropy effectively captures structural differences in permission distributions and provides a reliable quantitative metric for privilege risk classification. The entropy-based approach enables automated detection of high-risk identities and supports informed privilege optimization, security auditing, and forensic analysis.

VII. CONCLUSION

This research presented Privilege Entropy, a novel information-theoretic metric for quantifying privilege exposure in multi-cloud IAM environments. The proposed approach applies the Shannon entropy formulation to permission assignment distributions,

enabling quantitative measurement of privilege diversity and exposure risk.

Experimental evaluation across multiple cloud platforms, including AWS, GCP, and K8s, demonstrated the effectiveness of privilege entropy in distinguishing between administrative, intermediate, and restricted roles. Administrative roles consistently exhibited higher entropy values due to broader and more diverse permission assignments, indicating greater attack surface and higher security risk. In contrast, restricted roles exhibited lower entropy values, reflecting limited privilege exposure and reduced risk in the event of identity compromise.

The results confirm that privilege entropy provides a scalable, platform-independent, and mathematically grounded mechanism for identifying overprivileged identities. This capability enables automated privilege risk assessment, supports forensic investigation, and enhances cloud security auditing. Overall, the proposed privilege entropy framework provides an effective solution for improving privilege management, enforcing least privilege principles, and strengthening security posture in modern multi-cloud environments.

TABLE II
PRIVILEGE ENTROPY COMPARISON ACROSS MULTI-CLOUD PLATFORMS

Cloud Platform	Admin Entropy	Editor Entropy	Viewer Entropy
AWS	5.32	4.01	2.12
GCP	5.10	3.89	2.05
K8s	4.87	3.45	1.98

VIII. ENTROPY-BASED PRIVILEGE OPTIMIZATION

Privilege entropy can also be used as a quantitative objective function for optimizing IAM configurations and enforcing the principle of least privilege. The optimization objective is defined as minimizing privilege entropy while maintaining required operational functionality:

Minimize $H(R)$ (1)

subject to the constraint:

Required permissions ⊆ Assigned permissions (2)

This optimization ensures that identities retain only the permissions necessary to perform their intended tasks while minimizing unnecessary privilege exposure. Reducing entropy directly reduces privilege diversity, thereby decreasing attack surface and improving overall security posture.

The entropy-based optimization framework provides a systematic and automated approach for privilege refinement, enabling organizations to strengthen cloud security through continuous privilege risk assessment and optimization.

IX. COMPUTATIONAL COMPLEXITY ANALYSIS

The computational complexity of the privilege entropy calculation is linear with respect to the number of permissions assigned to each identity or role. This is expressed as:

$$O(n) \quad (3)$$

where n represents the total number of permissions associated with a role.

Since privilege entropy computation requires only a single pass through the permission set to calculate probability distributions and entropy values, the overall time complexity remains linear. This ensures that the proposed framework is computationally efficient and scalable, even in large-scale cloud environments containing thousands of identities and permission assignments.

As a result, the privilege entropy framework can be effectively integrated into real-time monitoring systems, automated security auditing pipelines, and large-scale cloud security analysis platforms without introducing significant computational overhead.

X. INTEGRATION WITH CLOUD SECURITY TOOLS

The proposed privilege entropy framework can be seamlessly integrated with existing cloud security and identity governance solutions to enhance privilege risk visibility and automated security management. Key integration points include:

- Security Information and Event Management (SIEM): Privilege entropy can be used to monitor identity risk levels in real time and generate alerts for high-risk identities.
- Cloud Security Posture Management (CSPM):

Entropy-based risk scoring can assist CSPM platforms in identifying misconfigured roles and excessive permission assignments.

- Identity Governance and Administration (IGA): Privilege entropy can support automated privilege optimization, access certification, and compliance enforcement.
- Threat Detection and Forensic Systems: High-entropy identities can be prioritized for threat detection, forensic investigation, and incident response.

These integrations enable automated detection of overprivileged identities, improve cloud security visibility, and support proactive privilege risk management.

XI. LIMITATIONS

Although privilege entropy provides a mathematically grounded and scalable approach for quantifying privilege exposure, certain limitations remain.

First, the current model does not account for temporal usage patterns of permissions. It evaluates privilege exposure based on assigned permissions rather than actual usage frequency. As a result, unused permissions may still contribute to entropy values.

Second, behavioral and contextual factors, such as access frequency, anomalous access patterns, and real-time threat intelligence, are not incorporated into the entropy calculation.

Finally, the framework requires extraction and processing of IAM policy data, which may introduce operational overhead in complex or large-scale environments.

Addressing these limitations represents an important direction for improving privilege risk modeling accuracy in future work.

XII. FUTURE WORK

Future research will focus on enhancing the privilege entropy framework to support dynamic, adaptive, and automated privilege risk assessment in cloud environments. Key areas for future development include:

- Real-time privilege entropy monitoring for continuous identity risk evaluation
- Integration with machine learning models for predictive privilege risk analysis
- Automated privilege optimization systems based on entropy minimization
- Integration with cloud forensic and incident response systems for automated investigation and remediation

These enhancements will further improve the effectiveness of privilege entropy as a comprehensive, scalable, and intelligent cloud security metric for modern multi-cloud infrastructures.

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