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Zero-Trust Security Models for Cloud Data Analytics: Enhancing Privacy in Distributed Systems

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ABSTRACT

The abstract is typically the first item that interacts deeply with a reader of academic and scientific literature to point out the contributions and contextualize the importance of the subject, indicating current problems and future lines that might be addressed by the implementation and evaluations. Therefore, the abstract is a compelling component of a paper or a report, besides being one of the first parts of the text that a reader uses to assess the relevance of reading the full text. In this research report, we provide a survey on the importance of privacy for distributed computing, while demonstrating the relevance of the data evaluation behind personal data sensitivity. We provide a detailed study on the Googlization of information, random graphs, and related distributed data, showing the dangers of privacy compromise. We present an independent survey on zero trust-based security models for the secure implementation of robust distributed systems and show that the systems can be efficiently implemented in cloud architectures.

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Introduction

Today's Information Technology (IT) landscape is dominated by distributed processing units. Consumers interact with servers through networks when using applications that are hosted in data centers. A variety of development tools make it easy for developers to deploy resources and develop applications in services provided along the cloud data analytics development chain. Users can easily call powerful data analytics services provided by platforms to gain insight into data and improve the efficiency of personal and business activities. With the rapid increase in users relying on cloud servers to perform heavy data processing, data privacy, and security are becoming hot topics. Even with causal de-identification, it is no longer effective to protect the privacy of sensitive dimensions when data can be analyzed in combination. In recent years, data analysts have not only included researchers who require high computing power to perform traditional statistical analysis but have also included practitioners who need to use visualization or machine learning tools at data visualization or business intelligence system stations.

Large-scale datasets sometimes possess features or are embedded with delicate information. Privacy protection in organizations, businesses, and institutions that own such data, or in a data market that enables various revenue-trading models via business intelligence platforms or data visualization tools, has attracted attention for its operational importance. As various software development systems mature, it is common to use distributed systems to accomplish product development. In large data analytics, we rely on powerful software development and data management, machine learning, or deep learning by way of stack layers, including system programming languages, data development/business tools, and cloud data governance and security products. Data is finally stored in a cloud data store to complete the big data life cycle. By deploying the data lifecycle in public clouds, we can use powerful computing capabilities and data storage services to store the big data generated by the organization or use the data on storage platforms as analyzed data to support the operation of applications. Currently, many organizations deploy big data lifecycles to public clouds because it is difficult to maintain sufficient computing resources to perform tasks when the workload changes suddenly.

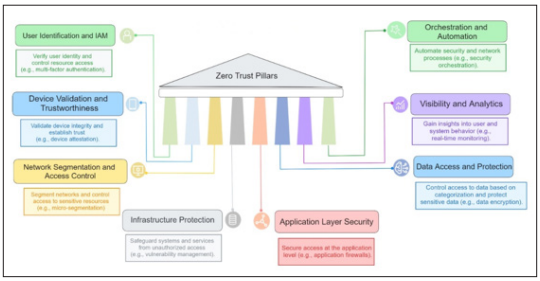

Figure 1: Zero Trust Security

Background and Context

In recent years, cloud computing models have enabled a new generation of data analytics, providing an effectively elastic infrastructure for hosting and processing large-scale datasets, large data warehouses, and in some cases, content. Common to public cloud vendors, this model allows the consumer to leverage the data center capacity of the public cloud and may provide cost benefits through the economy of scale achieved through multi-tenant hosting. Yet, security and privacy concerns such as insider and outsourced threats, possible misconfigurations at the cloud service provider end, and potential relinquishing of data control remain significant obstacles for IT enterprises contemplating a cloud migration. When hosting sensitive business data, or where the application protocols or sites breach the laws and regulations of the customer's data-cited country, the enterprise may find itself unable to migrate data for data-compliant and/or non-disclosed reasons. The existing network infrastructure that supports big data likewise suffers from a reduced feature set. Communication security modes such as end-site encryption offload the cloud's traffic-attracting storage capacity to handle unprotected data payloads. Enterprises, therefore, are vulnerable to data exfiltration that bypasses existing security zones using a robust landscape.

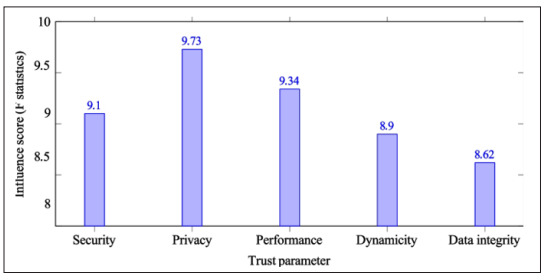

Figure 2: Predictive Digital Twin Driven Trust Model for Cloud Service Providers

Data governance topics such as control of law enforcement filters and domestic auto positioning, and the potential citizen-caused construction of autonomous decryption keys are further underspecified in the body of international law on the Internet and in the emerging area of technology-compliant privacy. Nonetheless, the data center capacity of the public cloud service remains the preferred destination point in the most practical cases for sending large-scale messages. The current pandemic has prevented the stagnation of the traffic-driven now established work-from-home technologies. However, a migration warning legal restriction has little recourse to infringe on faculty choices. Companies should therefore look to shield their network infrastructure and, more importantly, their employees as much as possible. Large capital investments in zero trust should strongly complement both legacy and new currently introduced work-from-home implementations. Cloud service providers additionally locate the other tenants' IP addresses – as well as the tenants themselves – within the basic RIR space they invoked on the last migration or creation of public cloud capacity. The distributed infrastructure of the cloud provider orchestrated by the tenant offers the ability to inject detection and enforcement controls into instrumented cloud deployment architectures, thereby enabling data, both workload and network zone divisions of the advancing person privacy philosophy.

Research Problem and Motivation

The development of cloud data-analytic platforms has greatly increased the efficiency of data analytics. However, during the data analysis process, as the data analyst can gain full access to the data, it may contain sensitive information, especially when it comes to big data. Protecting data privacy has therefore become an important research issue. In traditional research, encryption is one of the protection methodologies for protecting private big data. However, in big data analytics, the data analyst needs to access and use the unencrypted data for data preprocessing and feature extraction. Therefore, encryption limits the ability and features of big data analytics.

Given the above two critically important research directions and real-world challenges, this paper advances both quality assurance metrics and techniques that facilitate, assure, and enhance the privacy of federated and distributed data analytics systems. Consequently, as no appropriate trade-off can be achieved, in this paper, we will simultaneously address the goals for enhancing accuracy and maintaining the privacy of data analytics under a complete, zero-trust, cloud-based model. Nonetheless, as the specific contributions have been thoroughly detailed and well formulated in a manner that satisfies both principles and metrics, a high-quality system implementation, as well as its data analytical outcomes, could be justified and assured; such formulations are more than sufficient here.

Equation 1: Dynamic Access Control

$$P(u,o) = \begin{cases} 1 & \text{if } C(u) \cap R(o) \neq \emptyset \\ 0 & \text{otherwise} \end{cases}$$

$P(u,o)$: Permission for user u to access object o.

$C(u)$: Contextual attributes of user u.

$R(o)$: Required attributes for object o.

Research Aim and Objectives

This research aims to provide and develop security mechanisms concerning a new type of cloud application: distributed data analytics. These applications are designed to process volumes of data that are too large to process as part of data warehouses. Such data often contains sensitive information such as health or transport records, thus imposing significant concerns on the data owners. By emphasizing task-based trust natively, the privacy of the data at rest and transiently is enhanced for users of data analytics applications running simultaneously on the same infrastructure as part of a single-tenant model.

The Research Objectives are:

- To provide an in-depth understanding of a task-tailored trust concept for cloud and big data applications which is called Trust-but-Verify.
- To develop security and privacy mechanisms that demonstrate the key attributes of a Zero-Trust security model, i.e., transparency, data minimalism, and a focus on the internal and external sources of breaches, in the context of distributed cloud data analytics.
- To implement and validate the security mechanisms developed using Trusted Computing, mobile, and cloud infrastructures.

Zero-Trust Security in Cloud Data Analytics

Data analytics is becoming popular and is widely recognized as a key step to increasing economic decisions. Based on big data storage and processing techniques, cloud data analytics is a low-cost solution for implementing data analytics tasks for remote participants and companies. Due to its flexibility, speed, and

accuracy, cloud data analytics has been adopted in many real-world fields. However, the arrival of remote data brings increased privacy threats and risks in big data systems. For cloud data analytics, privacy risks emerge from two main aspects. On the one hand, state-of-the-art distributed data augmentation and federated machine learning algorithms are compromised and naive to the contributions from remote participant data owners, but still require the remote participants to trust the computation parties and the platform. In this case, the federation suffers agency risks, which may fail to reveal the correct contributions from remote participant data owners. On the other hand, the cloud platform, having full knowledge of the source data and intermediate states in the data analytics process, acts as a faithful but curious aggregator, and thus privacy risks are imminent. Fully trusting the computation parties and the platform can be naive and may ultimately fail to protect the federations, remote participants, and the cloud platform.

To mitigate the above-described privacy issues, Zero Trust Security is introduced. Historically, Zero Trust Security has been proposed for network security policies and has recently leaped onto center stage due to recent internet security failures. Roles and vulnerabilities in AI and ML applications utilizing ZTS are analyzed. Throughout a typical software engineering process, different stakeholders take on the roles of defenders, tools, attack surfaces, attack infrastructure, or attackers. Finally, potential unfixed exploitation opportunities form a set of vulnerabilities. Based on this theory, roles, and vulnerabilities from a typical AI and ML system running in a cloud platform using a ZTS paradigm are extracted and discussed; such discussion is the first attempt to systematically analyze Zero Trust Security for AI and ML applications. By utilizing Zero Trust Security, the trust burden of the cloud can be distributed to the data contributors, and remote participants can strengthen and protect their stakes. The adoption of ZTS in cloud data analytics represents a shift from monopolizing the computation parties and the platform towards the data contributors, making the root of trust in the participants. Thus, cloud data analytics is transformed into a trustworthy service.

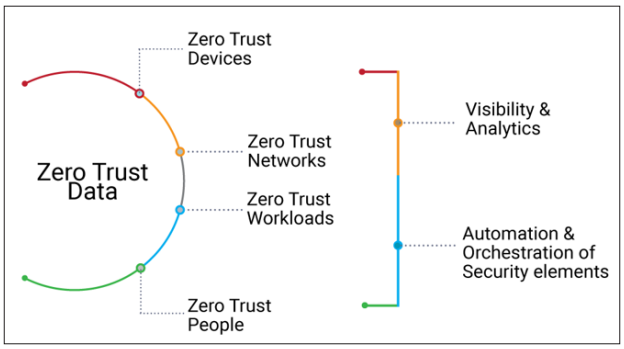

Figure 3: Zero Trust Security Model

Concepts and Principles of Zero-Trust Security

One of the fundamental principles of the ZTMA architecture is that all communications must independently verify trust and permissions. In the most restrictive form of zero-trust principles, only data directly supporting a minimal set of down-scoped functional operations can transit the Trust Enforcer. Information access and control cannot be directly used in the clear or supported in any back-end functions within zero-trust distributed systems themselves. All information is encrypted in transit and at rest and includes in-transit, at-rest, and further end-to-end encryption. Information cannot be at rest in back-end data stores without being encrypted, and by using digital rights management principles, the full scope of data length access reduction can limit the sensitivity of individual mission documents and data on top of their existing encryption at rest.

Another fundamental zero-trust principle is that attributes – specifically including permissions and authorizations – must be directly stored within the encrypted data itself. Attributes are additional data parameters that can be used to filter or to decide access permissions. These attributes must be able to travel with encrypted data elements and therefore are included in the ciphertext. Whether open-source or encrypted with other homomorphic encryption techniques, cryptographic capability design allows policy enforcement on the encrypted data. This technique allows manipulation and consumption of the ciphertext without any decrypt-before-use requirement or file type compatibility issues. And even more importantly, cryptographic attribute check support can work with large data sets. For down-scoping – grouped vs. ungrouped policy application; time, space, and performance concerns can affect the application of any access policies to the result – the normal constraint exists for large and distributed data sets. Finally, the normal constraint to pattern matching or calculated encryptions does not impair attribute checks but will slow performance: both permission access enforcement and data analytics querying results.

Applicability to Cloud Data Analytics

The implemented system is a data analytics system, and this work targeted the specific domain of cloud data analytics, which is an important application of distributed systems that is gaining an increasing amount of attention. We opted to employ Apache Spark in conjunction with the MAMID engine, which demonstrated that the system's security would be greatly improved with zero increased computing demands. MAMID is an engine that automates the intrusion detection process based on a modular set of low or high-level attributes. It is agnostic to the attributes that are used and how they are set, allowing it to operate over heterogeneous systems and mitigate many types of security concerns, despite being primarily developed for fast log generation and massive-scale low-cost unforgettable persistence.

Apache Spark allows for simple interfacing with the Hadoop Distributed File System and is compatible with a wide range of other big data processing tools such as SQL, streaming, and graphs. Apache Spark Streaming extends this functionality to near real-time processing of events. Because Apache Spark is written in the Scala language, it is not possible to configure or execute these jobs in runtime deterministically. Despite being a JVM-based language that might require high memory consumption, jobs written in Scala also follow the same pattern seen in the container register scheduling and memory behavior. Since most of the machine learning jobs have to follow a sequential model for training anyway, parallel jobs do not bring as much benefit over clustered execution. With these tools in use, the adoption of the zero-trust model to get more visibility of the data and its processing steps has permitted the implementation of features to mitigate many security risks. The Pyramid model has allowed us to segregate the responsibilities between each phase, allowing us to have a clear understanding and visibility that can simplify the development and the security of the system.

Privacy Enhancement in Distributed Systems

Distributed storage and processing services, such as those provided by multicenter cloud data analytics frameworks, have become widely used. The implementation of these data solutions

encounters concerns for individual privacy and data retention. Legal regulations or private policies may enforce that sensitive information of different individuals should not be stored together. This may mean that security and privacy assurance may involve limitations on data replication—ensuring that data is not stored in various nodes while waiting for it to be processed.

Some existing solutions offer effective encryption for cloud storage and MapReduce while achieving desirable distributed performance. However, all those solutions rely on additional encryption and key distribution management, which can produce a performance impact due to serialized data access. The next alternatives offer encryption of the data channel between the cloud client and web Hadoop. Other security models seek to ensure that the data owner can monitor data access and read the results, but there is no feature guaranteeing that the owner can update or even remove data. These kinds of contributions are useful, yet rely on the hypothesis that the single client and cloud form a TTP-free endpoint. The cloud provider should not be trusted, even in cases where it offers dedicated data centers. Therefore, we can only guarantee security when the service is managed using a private infrastructure—or patented in the already-used public cloud data analytics platforms. Achieving comparable performance without introducing proprietary systems furthermore adds security and privacy concerns. We propose a zero-trust solution that assures user data privacy and backs up selectively in cloud data analytics.

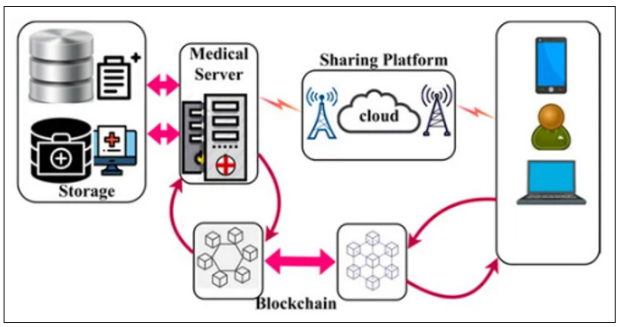

Figure 4: Privacy and Data Security across Healthcare Applications

Challenges in Privacy in Distributed Systems

Distributed systems generate, store, and disseminate large volumes of data. It is a challenge to attribute the ownership, control, and user consent of the stored information within a distributed system. The geographic distribution of data affects legal considerations; as data is considered personal, the country where it is stored governs data access and data usage. It is difficult to verify compliance with all jurisdictions' privacy laws governing authorities, as real-time monitoring and alerting systems should be in place. The inability to transparently identify the country and region where data is physically hosted poses jurisdictional and/or compliance issues. It is everything about respect, visibility, and controlling the position of computing elements—be it remote or local, in terms of cloud services—which is the responsibility of the information and security researchers, as well as data analytics professionals. Security researchers anonymize such geographic coordinates in messages being sent end-to-end through the network in a distributed system. This challenge relates to the use of GPS data collected from various sensors and computing devices to effect commands in the Internet of Things.

Although a government-assigned IP address from a country generally informs outsiders about the data location, a third party should also have the mandate to verify such and/or other claims made by security infrastructure. The inability to ascertain if cryptographic algorithms have been implemented correctly is a challenge, as companies offer their cloud provider subsystems for customer use. These concerns are not easily mitigated, as cloud data analytic platforms have an absence of physical TCB, but utilization of virtual TCB. Third-party entities that provide TCB audits should have unrestricted access to cloud servers operating larger TCB as much as possible. It is a challenge to ensure that the AI and ML analytic output stored in the cloud is accurate due to the rapid onset of dynamic data.

Equation 2: Secure Data Sharing

$$E_k(d) = c$$

$E_k(d)$: Encrypted data d using key k.

c: Ciphertext shared securely.

Role of Zero-Trust Security in Privacy Enhancement

The main thrust of ZT is to move beyond the traditional "trust but verify" security model in which users already in the network are given significant levels of trust to operate even though adversaries exist in the network. The foundational concept is that ZT trusts nothing. Specifically, to clarify how ZT goes beyond the traditional security model, ZT advocates zero trust for actors, resources, and data in all states of execution — these include actors attempting authentication, actors authenticated but also looking around, resources being protected, users attempting to access resources, user identities, and user credentials. Such actors and processes include devices, operating system kernels, hypervisors, identity devices, and authenticating and validating user access.

A major challenge to privacy in distributed data access systems is the need to authenticate and validate user access on a per request or regularly without requiring plaintext user credentials. A common approach to solving this disconnect is to have various predefined authentication rules or roles that are stored in access control policies. These rules or roles validate a user's ciphertext or the public key of an attribute-based encryption to access an encrypted resource. These rules or roles can be stored in the form of capability tokens or may include user attributes that satisfy specific predicates, but all the approaches described have varying degrees of complexity in their role management policies. Furthermore, these solutions do not control user access to data in a verifiable manner and do not scale or consistently apply to all users in all network access devices. ZT security gears towards providing zero-trust authentication by making it significantly harder to attack them, just as it is significantly harder to probe or snoop on phone calls around the world. The outcome of this architecture and design ZT approach is that attackers no longer have a fighting chance to gain access or control over user credentials.

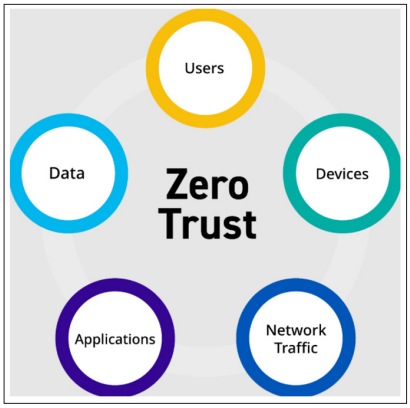

Figure 5: Zero Trust Security: Enhancing Cybersecurity

Case Studies and Applications

In this section, we will look at practical examples and use cases of data analytics platforms and systems. These examples will give insights into system architectures and the key data science and machine learning applications carried out in these systems. We will not only see how traditional systems are implemented but also end-to-end data analytics platforms. Systems used by social media are also explored. We will pick four research projects to illustrate key data science and machine learning applications performed over distributed computing systems. These projects involve genomics research, data-driven crisis response, YouTube recommender, and system-generated log analysis among many others. We will present the nature of cloud infrastructure used in these practical applications.

In this chapter, we provide case studies and applications to illustrate the use of distributed computing systems in the cloud. Participation in discussions on how data analytics models, systems, and technologies shape big data landscapes, and the incorporation and deployment of best practices in novel use case-driven research is key. Businesses are incorporating and deploying these data models and platforms, and they should be guided by experts as well. Such insight would help in creating a blueprint that enables scenarios and showcases capabilities, serves as a reference architecture, validates assumptions, and explores possible proofs of concept. The data science models employed in the projects considered vary and include statistical analysis, in-memory calculations, optimization techniques, natural language processing, graph analysis, machine learning, and pattern analysis. The case studies illustrate how the practically important data demands in social media, genomics, and other research domains are addressed through big data analytics software systems that are increasingly converging.

Real-world Implementations of Zero-Trust in Cloud Data Analytics

The core idea of Zero Trust in distributed systems, during any operation or process between different computers, is to verify, usually as part of an intermediary network gate or streaming network service, that only a few, and preferably only the minimum amount, of data needed to be directly transmitted between the various computers involved in this process. Several architectures and implementations of proprietary services exhibit Zero Trust traits in current data analytics, either by their design or by a set of predefined global policy rules and configurations. While specific operational capabilities may be different, they manifest common traits when described given their contributions to 21st-century Zero Trust implementation using different communication technologies. Additionally, other open-source global platforms provide custom application modules and libraries to enable cloud-deployed companies to build internal Zero Trust security mechanisms. Based on the previously presented Zero Trust traits for 21st-century systems, we narrowed down the high volume of marketed and available security front-stack services and open-source libraries to a smaller set that keenly presents core facilitating capabilities. Our results are organized to showcase the commercially available enterprise-level services and display the respective similarly functioning open-source library or toolkit counterparts.

Cloud data analytics use interfaces between numerous different hardware devices, cloud services, and human interactions. Data can flow in multiple directions between the external devices and services to form both east-west and north-south flows. The purpose of Zero Trust is to provide enhanced support and security that verifies each external request or processing is valid before sharing any internal organizational resources that the request or processing may want to access. With Zero Trust in normal operation, no network is completely trusted, and each operation will only access internal organizational resources if the operation has the correct permissions and credentials. Zero Trust is thus embedded in the second guiding principle of cybersecurity, specifying domain segregation and need to know. In other words, Zero Trust evaluates and requires internal permissions and credentials constantly, along with constant monitoring of external requests.

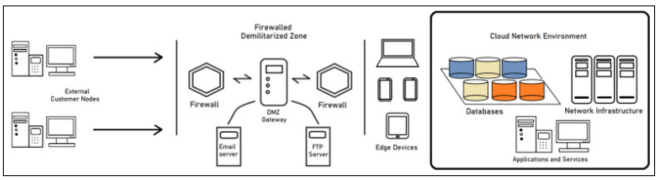

Figure 6: Security of Zero Trust Networks in Cloud Computing

Future Directions and Conclusion

We finally discuss several future research directions and conclude. With the rapid growth of cloud computing services, enterprises are facing the challenges of developing frameworks for data analytics. Enhancing network performance in a secure environment is still essential. We propose a reciprocity-based bandwidth allocation mechanism and a greedy-based admission control mechanism for secure networks. The two mechanisms can provide low computation overhead and good scalability. We can select the proper secure function and the proper function parameter for analyzing the networks, depending on the practical requirements. In our study, the networks can resist black hole attacks and DDoS attacks effectively.

The research on secure data analytics in the cloud is our primary motivation. We develop a practical measurement model and propose a series of recommender systems for choosing the proper secure function and the minimum function parameter. The proposed mechanisms can provide much-needed dynamic security for cloud big data analytics. Network security is also considered an important aspect, in addition to data privacy and secure computing. However, providing secure cloud data analytics is still considered a non-trivial challenge, and we leave the integration of network security and secure data analytics for future work. As future work, a promising research direction could involve further exploration of incorporating both cloud data analytics and network security to provide secure cloud big data analytics services.

Emerging Trends and Technologies in Zero-Trust Security

The growing need for advanced security mechanisms includes an increasing number of innovative research ideas, which strive to address complex security problems. One of the most promising security mechanisms and models is zero-trust security for users' cloud applications and components. The vision of zero-trust is that organizations should not trust internal or external traffic and networks, implicitly or explicitly, and should be paranoid, assuming that breaches are inevitable and leakage is perpetual.

To realize the zero-trust promises, it is expected that more and more organizational components, such as networks, firewalls, load balancers, API gateways, service meshes, security analytics, and more, will evolve to be based on the zero-trust principle and will be more closely integrated and connected. To support the continuous advancements of organizational components

towards zero-trust, zero-trust feeds, such as endpoints, network traffic, quarantine/defense history, and security events, should be continuously organized, generated, analyzed, and distributed across organizational environments and should be suitably integrated with zero-trust-enabled organizational components, such as gateways, proxies, security orchestrators, and more. Intrusion Detection and Protection Systems play a key and fundamental role in zero-trust. Security analytics and intelligence derived from zero-trust feeds support zero-trust-aligned decision-making and policy enforcement and can eventually help manage and optimize zero-trust intelligence. Fed by security analytics and intelligence, the principles of never trusting and always verifying will arrive much more expansively and powerfully in the complex technical space.

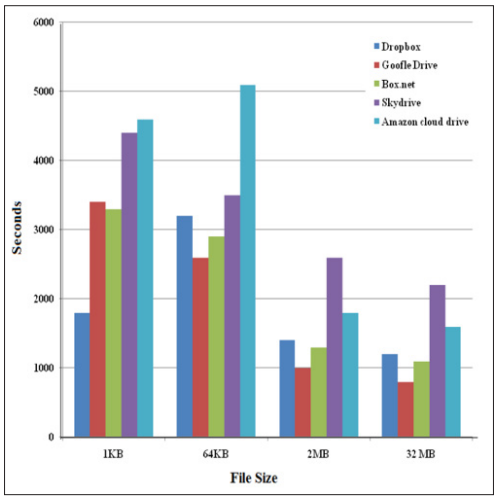

Figure 7: Performance of Cloud Storage Companies Bar Chart

Summary of Key Findings

We demonstrated privacy and security vulnerabilities in popular cloud data analytics frameworks, thereby revealing a gap in the current cloud data analytics security models. We also showed privacy-preserving analytics via oblivious sandboxing of existing privacy-aware analytics frameworks. Many cloud data analytics frameworks have inefficient performance when running privacy-enhanced data analytics tasks. We provided a secure, private, and performant cloud-accelerated analytics model to support privacy-enhanced cloud data analytics tasks. Today, cloud-based data analytics is a gold mine of information. However, existing cloud data analytics infrastructure was not originally designed for security and privacy. In this study, we present a comprehensive security and privacy study in cloud-based analytics systems and demonstrate vulnerabilities and performance bottlenecks in multiple fields. We first show vulnerabilities in popular cloud data analytics frameworks that allow an adversary to exfiltrate intermediate data. The vulnerability can further be exploited to exfiltrate, influence, and exfiltrate data in a chain of iterative data analytics tasks. Our empirical study investigates the interactions between these widely used distributed frameworks, existing hardware security features, and the operating system to affect the performance of data exfiltration and denial of service attacks.

Equation 3: Anomaly Detection for Threat Mitigation

$$A_t = \frac{\sum_{i=1}^{n} |v_i - \mu|}{n}$$

A_t: Anomaly score at time t.

v_i: Observed value for metric i.

μ: Expected value for the metric.

n: Number of metrics monitored.

Conclusion and Implications for Practice

The use of advanced computational techniques and big data promises to result in tremendous new capabilities for business, government, and society. However, to realize these benefits, the needs and expectations of data subjects need to be addressed. Here, we used zero trust principles to evolve a structured process that organizations can apply to privacy objectives in data analysis. We used data from citizens to identify the features that influence the perceived privacy of a variety of currently relevant data analytics applications and generated a useful, but very complex, privacy framework. We introduced some organizational checks that serve to prevent customer and employee data from being used in analysis to address concerns related to processing and purposes.

Cloud data analytics technologies, with their increased capabilities for value generation and their diverse privacy and security layers, have helped change the nature of information processing within organizations. We identified shortfalls in how organizations have been addressing the privacy considerations of data subjects within the existing legal requirements while concurrently grappling with the growing complexities within data protection legislation. These unaddressed privacy concerns and previous failed attempts to democratize data have hindered the realization of the full value of big data. Data protection authorities are constantly inundated with increasing consumer complaints and struggle with adopting punitive measures due to existing legislative constraints. We believe that the principles and comprehensive process presented can serve as a methodological guide for organizations committed to enhancing privacy in data analytics, bringing them more in line with contemporary privacy principles. Consequently, our approach may serve to mitigate citizen concerns, signaling a position to organizations committed to ethical data practices. Acting on the signal may well result in setting them apart, giving them a competitive edge [1-38].

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