International Journal on Science and Technology (IJSAT)
E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

A Review on Cloud Storage Management: Architectures, Security, Performance Analysis, and Future Directions

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Abstract

With more digital assets stored on business systems, IoT devices and online platforms, businesses need storage systems that accommodate growing amounts of data, are impervious to security risks and can accommodate their budgets. Cloud storage management systems have become a viable substitute by giving businesses a virtualized, internet-connected location for their data that can supplement their legacy on-premises storage array instead of completely replacing it. The papers review of cloud storage management will cover the following, the architectures and different layers used by cloud storage management systems, the most common cloud security threats and the steps being taken to stop them, methods for measuring performance in quantitative terms and A side-by-side comparison of leading providers like Amazon Web Services (AWS) S3, Microsoft Azure Blob Storage and Google Cloud Storage (GCS). Several different quantitative metrics for evaluating reliability, availability, efficiency, fault tolerance, replication and read/write speed are examined and five corresponding models can be viewed below. When discussing reliability and availability, there is no difference between the three cloud storage giants, when comparing their operational pros and cons, the biggest differences can be seen. Some of the problems that continue to occur when storing data in the cloud include, provider dependence, security risk exposure, lag and cost control. A look at AI-driven cloud storage management, distributed ledger (blockchain) storage audits, zero trust security and post-quantum encryption is discussed toward the end of the paper.

Index Terms- cloud storage management, distributed systems, data security, reliability modelling, multi-cloud architecture, AI-driven optimization, post-quantum cryptography.

1. INTRODUCTION

The growth in digital commerce, healthcare, education and government has created more information than the traditional paper or physical storage systems that preceded the digital age. Today, mobile transactions, in-vehicle devices, sensors that form the Internet ofThings (IoT), interactive systems that monitor and modify environments and social communication and sharing generate enormous amounts of data in structured (i. e. , arranged into records), unstructured (e. g. , free-text data, images, videos, audio and multimedia) and semi-structured formats. Fixed-capacity hardware that once could accommodate business needs at an affordable price has run its course, now, massive, fluidly growing collections of this data exist,

which fixed-capacity solutions simply cannot cost-effectively manage. Cloud computing is a fundamental alternative to this predicament. Armbrust et al. Described cloud computing as the on-demand self-service, over the Internet, pay as you go with metering, with elasticity and scalability, of access to a pool of configurable computing resources (networks, servers, storage, applications, services), which can be rapidly provisioned and released with minimal management effort or provider interaction [10]. As discussed in this article, cloud storage management encompasses everything involved in organizing, securing, monitoring and controlling the data hosted on virtualized remote storage - basically, the control of data access independently of how the underlying hardware is owned. As pointed out by Mansouri et al. , the effective management of cloud storage is multidisciplinary and spans numerous fields. It sits at the junction of information systems management, distributed systems, network throughput, information security, governance, regulatory compliance, risk management, quality of service and operations management [1]. Many of the desirable features of cloud storage managers are in opposition: We wish to have our data distributed geographically to achieve resilience in case of disaster and yet have low latency when accessing it for interactive workloads. We want minimum costs through consolidation and optimum resilience through redundant replication of our data. We want the most restricted possible access while still permitting effortless access to all authorized parties. This paper outlines the major aspects involved in cloud storage management, such as architecture, security, the application of quantitative performance models for modeling, assessment and testing, commercial platforms comparison, operational issues, research directions and other factors contributing to cloud storage management. This paper has presented a review of relevant aspects and has provided a basis for both further academic study and practical deployment in an enterprise cloud environment.

II. CLOUD STORAGE ARCHITECTURE

A. Deployment Models

There are four deployment models available that offer different controls, economies and scalability options [1][4][10].

**Public cloud: ** Service providers manage virtualized infrastructure across shared computing resources-e. g. , Amazon S3, Azure Blob Storage, Google Cloud Storage-for multiple customers (tenants). This service is virtually elastic and comes at a pay-as-you-go price, the major drawback is the lack of physical control of the data, since it resides on hardware shared among many tenants. **Private cloud: ** All infrastructure is operated by a single organization to make its use private. This form of cloud provides a stronger degree of isolation and compliance control but loses some scalability of sharing by necessity of requiring infrastructure provisioning well in advance of its use, than drawn from a shared pool when needed.

**Hybrid cloud: ** Different datasets and workloads, based on security and performance requirements, are kept in either public or private cloud environments. To work effectively, requires capable cloud management middleware to manage diverse resources and present them as one interface. (See Voulodimos et al. , " Hybrid Cloud as an IoT Environment for Smart Applications" [5].) *Multi-cloud: ** Customers use more than one cloud service provider's infrastructure to improve flexibility and mitigate vendor dependency. This approach requires abstraction layers to deal with heterogeneous API standards and disparate pricing models and costs between the different clouds.

B. Storage Types and System Layers

Three types of storage organization exist, all supported by cloud environments, catering to the specific application needs. Object storage, ideal for unstructured data such as media files, backup data and log archives. Data is typically accessed by key through a flat namespace, objects have a RESTful interface and are accessed with GET and PUT operations. Block storage stores data in small, fixed-size blocks of contiguous storage that can be addressable through high-speed I/O interfaces, this system works well for transactional databases or when a large system disk is needed for a server virtual machine. File storage accesses files in hierarchical directory structures and is available through standard NFS or SMB protocols, fitting well with the demands of file sharing and cooperative working environments, etc. [2][7]. All types are typically managed by means of a four-layer architecture [1][5]: *Front-End Interface Layer: ** The APIs and tools for cloud access, such as REST APIs, Web consoles and developer SDKs

*Middleware Layer: ** Mediates access, including authentication, policy enforcement, data placement and replication scheduling, while handling data consistency

*Virtualization Layer: ** Abstracts the underlying physical storage hardware, allowing logical management and dynamic capacity allocation across physical devices

**Physical Storage Layer: ** The raw disk drives, SSDs, and tape libraries housed in data centers, often geographically distributed

III. SECURITY IN CLOUD STORAGE MANAGEMENT

A. Threat Landscape Analysis

Cloud storage attracts numerous malicious actions that are categorized as cyber threats, these threats are distinguished by probability and by the degree to which the data is exposed.

Pearson and Benameur divide threats into three types depending on the source of attack (outsider vs. Insider), method of attack or goal of attack.

The most severe includes attacks using ransomware (making organizations unable to use their data), as well as zero-day exploits against management of cloud storage interfaces. Other significant attacks include insiders, those carrying authorized credentials and acting inside permitted ranges, which can be difficult to detect because it is hard to distinguish malicious behaviour from the normal behaviour of legitimate insiders.

More common attacks on cloud storage include credential stuffing attacks, phishing, SQL injection, distributed denial of service floods, etc. , accounting for 90% of security threats, which can require multiple security protections due to its prevalence.

B. Cryptographic Protection and Access Governance

Security in cloud storage revolves around three interconnected pillars: ensuring confidentiality, preserving integrity and guaranteeing availability. In terms of confidentiality, encryption is paramount. AES-256 symmetric encryption is commonly used for data at rest because of its high performance. Transport layer security protocols, such as TLS 1.3, secure data while it travels across the network. For key management, envelope encryption, which consists of encrypting each data object with a separate symmetric DEK (used for encrypting the data), encrypting the DEK using a KEK, allows for the protection of multiple data

objects using one key without needing to perform computationally intensive operations on the large number of individual keys used to encrypt the objects. For greater privacy, customers can use CMEK, which ensures that cloud providers are unaware of their encryption keys. RBAC and ABAC are two key approaches for managing access. RBAC assigns permissions to various roles, which are then assigned to individual users. This approach helps organizations manage security at a large scale by applying security policies based on people's job functions. In contrast, ABAC focuses on assigning authorization rules based on policies that can evaluate various context attributes. These attributes could include the department and device security of the user attempting to access a resource or the classification and sensitivity of the data that they are trying to retrieve. An ABAC access policy will check these attribute values at the time each authorization decision is made to see if a user can or cannot access a resource. To protect the integrity of stored data, SHA-256 (Secure Hash Algorithm) hash values are typically used. Each data object is cryptographically hashed. An attacker cannot tamper with the underlying data object without it being detected since this would result in a completely different hash value. To handle the vast quantity of data in cloud storage systems efficiently, hash values can be combined into a Merkle tree. This allows for the retrieval of the hash of a particular data block without needing to download the entire stored file.

IV. COMPARATIVE PLATFORM ANALYSIS

Table I presents AWS S3, Microsoft Azure Blob Storage and Google Cloud Storage comparisons across eight important parameters of the technologies, based on the findings of the referenced studies [1][6][7][10].

TABLE I. CLOUD STORAGE PLATFORM COMPARISON

Feature	AWS S3	Azure Blob	GCS
Durability	11-nines	11-nines	11-nines
Storage Tiers	6 classes	4 tiers	4 classes
Encryption	AES-256/CMEK	AES-256/CMEK	AES-256/CMEK
Access Control	IAM + Policies	Azure AD+RBAC	IAM + ACLs
Replication	AZ + CRR	LRS/ZRS/GRS	Regional/Multi
Max Object	5 TB	190.7 TB	5 TB
Key Strength	Global footprint	Enterprise M365	Analytics depth

All providers achieve eleven-nines reliability in durability (the value of P(error) derived from Equation (4) for large n) because each employs its own technology implementation for both erasure coding and replication. They differentiate themselves primarily across application workloads. AWS S3 provides region availability worldwide, best suited for global coverage. Azure Blob Storage is the best option for

integrating with a company's Microsoft 365 subscriptions and Active Directory environment. Google Cloud Storage is superior for analytics-intensive workflows through tight integration with services like Google BigQuery and Google Dataflow [6][8].

V. CHALLENGES IN CLOUD STORAGE MANAGEMENT

A. Shared Responsibility and Compliance Complexity

Most organizations struggle to grasp the edge of the shared responsibility model. We manage cloud provider infrastructure and hypervisors but have complete ownership and accountability for storage access rules, identities, permissions and classifying sensitive information. Any mistake at our end, even by accident-say an open storage bin, a role assignment with access it should not have or not even turning on audit logs-is the sole reason a breach happened. It continues to fuel cloud data loss [9]. It also comes with its own set of difficulties. Multiple regulations such as the EU's GDPR, California's CCPA, HIPAA rules for healthcare, etc. , require different policies on where to store data and how long to retain it, plus notification in the event of a breach. If you are a global company, you have to keep up with all of them using geography-controlled storage, compliance dashboards and automated monitoring tools.

B. Vendor Dependency and Latency Trade-offs

Moving off of proprietary cloud APIs like, say, Google Cloud's is costly. Most have service specific ways to query and deal with data. As such, migrating large amounts of data out of the Cloud would require rewriting a good chunk of your codebase and potentially significant engineer/financial expenditure that is almost always severely underestimated by architects choosing a stack. Because of this, even organizations who are fully aware of the costs eventually wind up stuck and beholden to the vendor, forever having their negotiations hampered by the effort it would take to move away. There is a trade-off between putting the data in multiple remote locations for fault tolerance (e. g. In case of natural disaster) and putting it close to your users in the region where most activity happens, as physical distances (and therefore speeds of light and travel through glass) will inevitably govern the speed at which your software responds to your users [4].

C. Cost Structure and Migration Overhead

Cloud storage charges come in at least four categories: usage-based based on amount of storage you provision, egress charge for data transferred OUT, usage based on number of operations on the storage tier and then any charges for features like object versioning, lifecycle management rules, cross-region replication, etc. Capacity-based estimations will underestimate by more than half the total bill if you do not account for egress and operations - for most workloads that require reading a lot of data or making many small object calls [6]. So the problem is, if you have to move lots of data off your AWS or other clouds, then there will be lots of egress fees for doing so. Bandwidth limitations could also extend the timeline, forcing you to continue running both environments concurrently until all data is migrated - in which case you are doubling your infrastructure costs, proportionally with data size [3].

VI. EMERGING TECHNOLOGIES AND FUTURE DIRECTIONS

A. AI and Machine Learning in Storage Orchestration

Data tiering using predictive analytics. Instead of relying on time-based access policies, predict data access trends to perform data tiering. Train ML models using the file attributes including the access frequencies, file types, owning departments, date created, date of the last access and business-cycle information. These

models can predict whether a data object will be accessed again or when it will be accessed. Accordingly, you can move such objects to a fast storage tier prior to anticipated access. Similarly, you can demote objects to slow archival storage, saving money in the process. Liu et al. [6] confirmed that these adaptive policies yield much better cost-performance ratios in real-life environments than rule-based policies do with their 10%-90% varying production workloads. Security Monitoring. ML models can improve security monitoring by identifying anomalies in storage access. When access patterns deviate from norms - perhaps reading data for long durations that may point to an exfiltration attack or writing data many times in a short duration suggesting a ransomware encryption - the anomalies can trigger automated containment strategies. These actions can occur at speeds orders of magnitude faster than any human security analysts can take.

B. Blockchain-Based Integrity and Zero-Trust Security

Blockchains make a cryptographic record available, to an unlimited audience, of events that happen related to data in storage and how the data might be accessed or changed. While the cloud vendor can add to this record, none of the other participants can alter it backdated, nor can the vendor either, without anyone noticing. This makes blockchain audit logs tamper-evident, with a cryptographically secured audit trail providing a way to prove that specific events happened, without reliance on promises made by the cloud vendor [3][9].

Zero Trust architecture implies that there should be no distinction between insider and outsider, anyone accessing the network is a threat and every user or device must be continuously authenticated, and every access request needs fine-grained validation, whether it is coming from inside the perimeter or outside. For cloud storage, this means validating every request, ensuring that each request is verified according to identity and context, partitioning storage namespaces into granular sections (micro segmentation), monitoring data activity behaviourally at each point and implementing granular access policies (least privilege) so that the blast radius from the compromise of one user account remains contained. Zero trust is also a good architectural pattern for the cloud, Wang and Chen [3] write, "in the cloud paradigm, there no longer exist distinct notion of trusted and untrusted network zone. "

C. Post-Quantum Cryptography and Multi-Cloud Portability

As quantum computing is being developed at the fastest pace ever, public key cryptosystems commonly in use today are facing risks. Shor's algorithm would efficiently solve such computationally difficult problems as integer factorization and discrete logarithm (in particular the equivalent problems for the RSA cryptosystem and the elliptic curve cryptography algorithm) once it is being run on a quantum computer that is large enough [3]. So, in data whose secrecy needs to last decades, it is already needed that they start migration to the standards adopted by NIST in 2024 which are the algorithms CRYSTALS-Kyber for key encapsulation and CRYSTALS-Dilithium for digital signatures. These cryptosystems rely on computational hardness of problems in lattice mathematics, which are believed not to be solvable in polynomial time by any quantum computer [9].

Vendor lock-in is a problem about the move to the cloud. APIs standardization and vendor agreements among cloud providers are needed to guarantee portability of data in a cross-cloud environment. Mansouri et al. [1] rank portability of data in cloud environments among the hardest open problems in cloud storage management. They claim that solving the issue requires efforts by standard bodies, cloud engineer

companies and regulatory organizations to secure vendor neutrality about data storage at the service provider level.

VII. CONCLUSION

The management of cloud storage has progressed considerably in the past few years, with various architectural and security frameworks, numerous methods to quantify the performance of cloud storage, commercial cloud storage offerings and their management/operational issues, and the direction of cloud storage technology. One of the most important observations related to the engineering and operating aspects is the maturity with which the engineering works produce eleven-nines data durability, global level data durability, and the elasticity of the provisioned resources with all levels of control. There are still many issues that will require research and the development of cloud storage.

The key metrics presented here are performance (1) and reliability (2) of the storage system, availability (3) and fault tolerance (4) of offered services, and measurement of the data transfer (5). They create a unified comparison of storage systems and serve to introduce levels of measurement and comparison of offered services.

Amazon Web Services, Microsoft Azure, and Google Cloud illustrate that a convergence of core durability and significant differentiation compared to competing services are developing in the support of cloud services. The many areas of research and the development of the cloud storage framework are related to the challenges (in no particular order) of vendor lock-in, compliance, and latency and the cost of migration. AI storage tiering, blockchain-based cloud services with support of zero trust frameworks and post-quantum cryptography are a few examples of newer technologies. For overcoming these challenges and developing a production-ready cloud storage system, a close and focused collaboration of cloud storage researchers, cloud storage developers, and standards developers will be needed.

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