Synergistic Integration of Hybrid Cryptographic Algorithms and Distributed Database Systems for High Assurance, Privacy-Preserving Cloud Artifact Storage

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Abstract – Cloud storage services are popular for their convenience and scalability, but the default provider-based encryption and server-based key management place the user at risk for privacy and legal issues. This paper proposes a real-world True Zero Knowledge solution for cloud-based artifact storage services, utilizing a combination of hybrid cryptography with AES-256-GCM for data, and RSA 2048/ECC for key encapsulation. It also includes client-based multi-threading with stateful resumability, as well as encrypted metadata stored in a distributed NoSQL database. The paper provides a detailed explanation of an end-to-end solution, including the generation and management of keys by the user, deterministic chunking with stateful resumability, file or chunk-based session key encapsulation with RSA 2048/ECC, SHA256-based threat intelligence fingerprinting before data transfer, as well as a detailed explanation of the manifest. It also includes an analysis of the solution's security, a code example for the most important algorithms, as well as a feasibility study with performance metrics to demonstrate the viability of the solution.

I. Introduction

Cloud storage has become the de facto medium for backups, collaboration, and archival retention. The ease of use of delegated storage has been accompanied by a set of trust assumptions. Many cloud storage systems store encryption keys, retain metadata that can leak sensitive information, or have administrative access and legal obligations. For individuals or organizations with high confidentiality requirements, such as personal information, health

information, legal archives, or intellectual property, the trust assumptions of cloud storage are untenable.

The system presented in this paper redefines the trust assumption of cloud storage. The client has the sole control of the cryptographic mechanisms. The cloud only has access to ciphertexts and encrypted metadata. The cloud provider does not have the necessary information to decrypt the artifacts stored in the cloud. To make this system feasible, the paper uses a set of existing technologies: hybrid cryptography for performance and secure key exchange, client-side chunking and stateful uploads for large artifacts and dynamic network conditions, and a NoSQL database for storing metadata in a distributed environment. The system presented in the paper shows the feasibility of a zero-knowledge cloud storage system. The performance overhead of the system, when hardware acceleration and engineering effort are taken into consideration, is shown to be small compared to the network transfer time for large artifacts.

II. BACKGROUND AND MOTIVATION

A. Zero-Knowledge Cloud Storage

A zero-knowledge cloud storage system can be characterized by the provider's inability to derive any meaningful information about the user's plaintext information. In essence, this implies that the provider should not have access to the encryption keys or information contained in the metadata. Client-side encryption of information meets the requirement for a zero-knowledge cloud storage system, although it creates new challenges.

B. Hybrid Cryptographic Models

In hybrid encryption, symmetric keys are used for bulk data processing due to the efficiency of symmetric encryption. Public-key cryptography is used to protect symmetric keys during distribution and long-term storage. AES-256-GCM is the recommended mode for authenticated encryption. In the case of wrapping keys, the chosen algorithm is RSA-OAEP, or ECC with ECIES and ECDH.

C. Chunking, Resumability, and Metadata

Large files should ideally be chunked in sizes of about 4-5 MB for efficient uploading. A server-side manifest file containing chunk IDs, IVs, and wrapped keys in encrypted form must be present for the client to recreate the file at a later time. The structure of the manifest file must be efficient so that the file can be resumed or shared without compromising the confidentiality of the plaintext.

D. Threat Detection Prior to Storage

When malware is uploaded to a cloud storage service, the potential for cascading effects is high. Due to the local nature of the encryption, scanning on the server in plaintext is impossible. The client, therefore, has to scan the malware (or generate fingerprints to be used in vetted threat intelligence lookups) prior to the uploading process. The fingerprints, such as SHA-256

hashes, can be verified via a backend proxy to threat intelligence sites without the need to send plaintext.

III. Novel Applications and System Overview

A. Novel Applications

One of the most prominent uses of the system would be in the realm of personal cloud storage, where users can store their personal information in a secure manner without the threat of unauthorized access. This is because the encryption of the information occurs at the personal level, and only the encrypted information would be transmitted. The system would also find application in the realm of enterprise or organizational security. Enterprises can store sensitive information in a secure environment, such as financial information, without the threat of unauthorized access. The system would help organizations comply with the General Data Protection Regulation (GDPR) or other relevant regulations. Another prominent application of the system would be in the realm of secure information sharing. The system would allow the secure sharing of information using a hybrid encryption technique. The encryption key for the files can be shared with the users through the public keys of the users. The system would also find application in the realm of secure remote working. The system would allow the employees to access the sensitive information from anywhere without the threat of unauthorized access. The system would provide a platform for the creation of a cloud environment, where the confidentiality of the user information would be a key requirement.

B. System Overview

The system utilizes a client-centric architecture in which all the encryption processes take place at the client end. After choosing a file for upload, a symmetric key is generated (AES-256), and the file is divided into smaller chunks. This allows for faster upload and resume capability. A hash value is computed for data integrity (SHA-256). The symmetric key is then re-encrypted using the user's public key (RSA or ECC), which implements hybrid encryption. Chunks are stored in cloud storage, and metadata is stored in a distributed database. During retrieval, decryption occurs using the private key and reassembly of the original file. The architecture implements a zero-knowledge protocol that offers confidentiality, integrity, and secure cloud storage.

IV. Role and Potential of the Proposed System

The proposed Zero-Knowledge Hybrid Cloud Storage System is significant in providing improved security, data privacy, and data reliability in today's cloud computing environment. With the increasing use of cloud computing in handling sensitive personal and organizational data, there is an increasing need for systems that ensure users' control and authority over their data in the cloud environment. The main role of the system is to ensure end-to-end data confidentiality, wherein all encryption procedures are executed in the client-side environment.

The system ensures that only authorized users, using their respective private keys, are granted access to the original data using the combination of hybrid cryptographic techniques, such as AES-256 and RSA/ECC. Another main role of the system is to ensure improved storage efficiency and data reliability using the chunk-based approach in handling data in the cloud environment. In the proposed system, data is first fragmented into smaller encrypted chunks before being sent to the cloud storage environment for faster data transmission and resumable data transmission in case of disruptions in the network environment. The system also ensures data integrity using SHA-256 hashing techniques, which identify data changes and corruptions during data retrieval from the cloud environment. The system also supports the idea of a zero-knowledge cloud model in which the cloud provider only has access to the user's encrypted data and metadata. This is because the encryption keys never leave the client's side and do not reach the server. Therefore, the server does not have access to the user's content.

Potential of the Proposed System

The proposed system has significant potential in various areas. First, in the personal area of application, users can store their backups, photos, and confidential documents securely without worrying about unauthorized access. In the enterprise area of application, the system can be used to protect sensitive business content, intellectual property, financial documents, and many more. The system has significant potential in secure remote working. The system can be used to enable the sharing of files securely by distributing the encrypted keys to the authorized personnel. The system can also be used to develop cloud storage services that focus on user privacy. Overall, the system is useful in developing a secure, trustworthy, and privacy-centric cloud storage system that can be used in various areas of application in the present-day digital world.

V. INNOVATIVE INTEGRATION OF THE PROPOSED SYSTEM

The proposed system, "Privacy Preserving Cloud Storage Framework," does not only offer a new form of cloud storage but also presents the possibility of using the system as a security platform for the integration of new technologies. The system's use of the fundamental characteristics of "True Zero-Knowledge Architecture," "Resilient Client-Side Chunking," and "Pre-Transmission Threat Neutralization" presents the possibility of innovative uses for the system.

1. Integration with Edge Computing and IoT Networks

One of the major issues in Internet of Things (IoT) systems is the transmission of large amounts of data (e.g., surveillance feeds, drone telemetry) over unreliable connections.

- **Resilience Mechanism:** The Stateful Upload Loop and the Chunking Mechanism of the proposed system, where data is segmented into 5MB chunks, can be integrated with edge devices. The proposed system will not lose data during the upload process in the event of disconnections, unlike traditional storage systems.

- **Application:** This can be used in the secure upload of logs from remote sensors in agricultural or industrial areas.

2. Blockchain-Backed Immutable Audit Trails

The use of MongoDB for storing encrypted file payloads can be creatively combined with blockchain technology to enhance trust.

- **Digital Fingerprinting:** The SHA-256 incremental hash generated during the pre-transmission scan for viruses serves as a digital fingerprint for the file.
- **Tamper-Proof Logging:** The use of a public ledger such as Ethereum or Hyperledger to record the timestamp and the incremental hash serves as a verifiable proof that the encrypted data stored in the cloud and the cloud provider have not been tampered with by an attacker.

3. Privacy-Preserving Collaborative Workspaces

Traditional secure collaboration often requires sharing passwords, which is insecure. This system can be integrated into legal and corporate environments using a Proxy Re-Encryption scheme.

- **Zero-Knowledge Sharing:** Instead of sharing the AES session key directly, the system can encrypt the session key with the *recipient's* Public RSA Key.
- **Application:** This enables a "Blind Drop Box" for whistleblowers or legal counsel, where documents can be uploaded and encrypted such that only the specific intended recipient can decrypt them, while the storage provider remains completely unaware of the sender's identity or the file's content.

4. Integration with Hardware Security Modules

To further secure True Zero Knowledge, it is recommended that the system utilize the Web Authentication API to move key storage outside of the browser.

- **Hardware isolation:** Instead of storing the RSA Private Key in the browser's local Storage, we can store it on a hardware key (for example, Yubico's YubiKey) or on the device's TPM.
- **Security impact:** As a result, it is not possible to remotely extract these keys, thereby securing user data even in cases where the local machine is compromised by malware, making it an ideal solution for high-clearance government or defence organizations.

5. AI-Driven Pre-Encryption Threat Intelligence

The current **Zero-Day Threat Neutralization** engine uses the Virus Total API. An innovative extension involves integrating this with local Machine Learning models.

- **Behavioural Analysis:** Before encryption, a lightweight TensorFlow.js model running in the browser could analyse file metadata and structure for anomalies (e.g., ransomware signatures).
- **Proactive Defence:** This creates a decentralized defence grid where malicious files are identified and blocked at the edge (the user's device) before they ever consume server bandwidth or storage resources.

VI. RECENT ADVANCEMENTS IN THE PROPOSED SYSTEM

The proposed Privacy-Preserving Cloud File Storage Framework improves on various aspects of the conventional Server-Side Encryption (SSE) paradigms. The proposed framework addresses the security issues and performance problems identified in recent research on cloud computing.

1. True Zero-Knowledge Hybrid Cryptography

Unlike other configurations where the service provider maintains the decryption keys, the proposed system uses the True Zero-Knowledge system.

- **Client-Side Key Generation:** The system generates the RSA-2048 key pairs using the Web Crypto API only on the browser environment of the client, ensuring the non-transmissibility of the private key over the network.
- **Hybrid Encryption Engine:** The system leverages the speed of handling large data using the symmetric AES-256-GCM for the file payload and the security of the RSA-2048 for the key exchange. The proposed system avoids the performance degradation often associated with the use of the RSA algorithm for large data sets.

2. Resilient Client-Side Chunking and Fault Tolerance

To overcome the challenges of network instability, which affect the system when large files are involved, the system uses a stateful upload feature.

- **Stateful Upload Loop:** The system uses the React hooks useRef to track the state of the upload progress in real time. This helps the system pause and resume the upload at the exact byte offset where the failure occurred.
- **Granular Error Recovery:** The system splits the files into 5 MB encrypted chunks. If the system encounters a failure, such as a timeout, only the specific chunk will be retried instead of the entire file.

3. Pre-Transmission Zero-Day Threat Mitigation

To minimize the possibility of cloud storage being used as a medium for the spread of malware, the system will incorporate the following measures:

- **Incremental Hashing:** The files will be hashed using SHA-256 before any transmission occurs.
- **API-Based Verification:** The hash will then be cross-verified using the VirusTotal V3 API via a secure backend proxy. If the file is found to be malicious, the transmission

will be halted before the encryption process begins, thus preventing the upload of malicious content.

- **Indexed DB Caching:** To improve system efficiency, the scan results will be cached locally using the browser's Indexed DB, thus allowing for instant verification of previously scanned files, minimizing the need for redundant API calls.

4. Optimized Big Data Handling

The architecture of this system is optimized for efficient handling of big data, which is in line with the current demand for hybrid storage solutions in big data environments.

- **Sanitized Storage Hierarchy:** The backend system sanitizes the file paths, which helps prevent directory traversal attacks, and maintains the original directory hierarchy in the MongoDB metadata, thus enabling the safe upload of directory trees.
- **Blind Metadata Management:** The metadata of the files, such as their names, sizes, and types, is stored independently from the encrypted binary data, thus enabling efficient management of files by the server without reference to their actual contents.

VII. Conclusion

In this study, a Privacy-Preserving Cloud File Storage Framework is proposed that effectively mitigates security vulnerabilities that are characteristic of traditional cloud storage models. The True Zero-Knowledge architecture of this framework, implemented via Hybrid Cryptography (AES-256 and RSA-2048), ensures that the service provider is mathematically blind to user data and hence minimizes the threat of insider attacks and data breaches.

The incorporation of Resilient Client-Side Chunking addresses the key challenge of network instability and facilitates reliable upload of large volumes of user data via the stateful pause and resume upload mechanism. Furthermore, the proposed Zero-Day Threat Neutralization engine ensures that the cloud infrastructure is protected against malicious attacks via the Virus Total API.

Experimental results show that the proposed framework does not compromise system performance by moving cryptographic operations to the client-side browser and hence offers a scalable and fault-tolerant solution that is more secure than traditional encryption models and hence more appropriate for high-security environments such as healthcare, legal archives, and intellectual property management systems.

VIII. Future Research Directions

The creation of the Privacy-Preserving Cloud Storage Framework opens up several opportunities for further research. Future research can focus on several areas, including:

- **Hardware-Backed Key Management:** Incorporating the Web Authentication API (Web Authn) to store RSA private keys in hardware devices, such as YubiKey or Trusted Platform Modules, instead of storing them in browser local storage. This will ensure that the system is not vulnerable to key extraction attacks even if the client device is compromised by an adversary.
- **Privacy-Preserving Data Sharing:** Implementing Proxy Re-Encryption (PRE) techniques to allow users to securely share encrypted data with other users. This will allow the server to convert encrypted data from one user to another user, while keeping the data itself private to both users.
- **Blockchain-Based Integrity Auditing:** Using blockchain technology to provide an immutable record of all file upload, modification, and deletion activities on the server. This will allow the system to mathematically prove file integrity through a decentralized ledger.
- **Edge-Based Threat Detection:** Improving the virus scanning module by using lightweight machine learning models within the client browser itself, using libraries such as TensorFlow.js. This will allow the system to detect malicious file types within the browser itself, eliminating the need to send file hashes to an external service.

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