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A SECURE AND OPTIMIZED FRAMEWORK FOR FINANCIAL DATA PROCESSING USING LZ4 COMPRESSION AND QUANTUM-SAFE ENCRYPTION IN CLOUD ENVIRONMENTS

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ABSTRACT

Financial data management requires a robust framework that ensures both efficiency and security. This study proposes an optimized approach integrating LZ4 compression and Post-Quantum Cryptography (PQC) to enhance data storage, transmission, and security. The framework follows a structured pipeline: data collection, pre-processing, compression, encryption, and secure cloud storage. Financial data is collected and batch sources using AWS Kinesis, Azure Event Hub, and ETL tools. Pre-processing involves cleaning, normalization, and outlier detection to maintain data integrity. The LZ4 algorithm is employed for lossless compression, achieving up to 93% compression efficiency while reducing storage overhead. Security is ensured through PQC, particularly ML-KEM (CRYSTALS-Kyber) for key encapsulation and ML-DSA (CRYSTALS-Dilithium) for digital signatures, mitigating quantum attack risks. Experimental results indicate a linear relationship between input data size and retrieval time, with 6000ms recorded for 100GB datasets. The framework significantly improves storage efficiency while ensuring compliance with financial regulations. Future enhancements will explore AI-driven query optimization, adaptive compression, and hybrid encryption models to further optimize performance. This research presents a scalable and secure solution for financial data processing, making it well-suited for high-volume banking applications.

Keywords: Financial Data Security, LZ4 Compression, Post-Quantum Cryptography, Cloud Storage, Data Retrieval Optimization

1. INTRODUCTION

The exponential growth of financial transactions and banking operations has necessitated efficient and secure data management solutions [1]. Financial data is highly sensitive, requiring stringent security measures while ensuring optimal storage and retrieval efficiency [2], [3]. Traditional encryption techniques face increasing threats from quantum computing, making Post-Quantum Cryptography (PQC) a necessary advancement [4], [5], [6]. Simultaneously, handling large volumes of financial data demands effective compression strategies to minimize storage costs and transmission delays [7]. The proposed framework integrates LZ4 compression for high-speed data reduction and PQC encryption for enhanced security, ensuring compliance with financial regulations [8]. Cloud-based storage solutions further improve scalability and availability, making the framework adaptable for modern financial applications [9], [10]. By optimizing performance while maintaining security, this approach provides a future-proof solution for financial data management [11].

Existing financial data management techniques include AES (Advanced Encryption Standard) for security, GZIP and ZSTD for compression, and RSA-based cryptographic methods for encryption [12][13]. However, these methods have notable drawbacks. AES and RSA encryption face vulnerabilities against quantum computing attacks, posing risks to long-term data security [14][15][16]. Traditional compression methods like GZIP introduce latency due to their higher computational overhead, impacting financial applications [17]. Cloud-based storage solutions often struggle with high retrieval latency and inefficient indexing, affecting the speed of data access. These limitations highlight the need for an integrated approach that balances security, storage efficiency, and accessibility.

The proposed framework addresses these limitations by integrating LZ4 compression, which offers high-speed, lossless data reduction, minimizing storage costs and retrieval delays. [18] Security is enhanced using PQC-based ML-KEM (CRYSTALS-Kyber) and ML-DSA (CRYSTALS-Dilithium), ensuring resistance against quantum threats. Unlike traditional encryption methods, PQC ensures long-term data confidentiality even in the face of quantum computing advancements. [19] Additionally, cloud storage is optimized with IAM-based access control and AI-driven query optimization, reducing retrieval latency for large datasets. The novelty of this study lies in its synergistic combination of LZ4 compression and PQC encryption, providing a scalable, efficient, and secure framework tailored for modern financial data management.

2. LITERATURE REVIEW

The rise of cloud computing, particularly in the financial industry, has enhanced efficiency and created new opportunities. However, the rapid growth of cloud services and networks like 5G has raised concerns about data privacy, with insider threats and data mining attacks posing significant risks Gattupalli, K., & Lakshmana Kumar, R. (2018) [20]. To address these challenges, the Privacy-Preserving Smart Storage (PS2) model is introduced, employing a novel distributed data storage method to mitigate privacy leakage and protect against insider data mining attacks.

As cyber-security concerns continue to rise in the financial industry, the Proactive Dynamic Secure Data Schema (P2DS) approach is introduced to enhance privacy protection for financial clients [21]. By utilizing attribute-based encryption and a self-deterministic data schema, P2DS employs three algorithms—Static Decryption Attribute Algorithm (SDAA), Corresponded Decryption Attribute Algorithm (CDAA), and Proactive Determinative Encryption Algorithm (PDEA)—to safeguard sensitive data and mitigate operational risks, with experimental results demonstrating its effectiveness in protecting customer privacy. Srinivasan, K., & Arulkumaran, G. (2018) (2015) [22].

Cloud computing offers significant benefits for data storage and processing, but outsourcing sensitive information, such as health, finance, and personal data, raises critical privacy concerns [23]. Privacy issues are vital for cloud adoption, as breaches can lead to severe financial and reputational damage. This paper surveys privacy risks in public cloud computing, evaluates existing solutions, and identifies open research areas to enhance privacy protection in cloud environments. Musam, V. S., & Kumar, V. (2018) [24].

[25] addresses the challenges of handling and analysing Big Data, which traditional systems struggle to manage. Cloud computing offers a viable solution by distributing data across cloudlets for better storage and analysis. However, security risks, particularly data mining attacks, pose significant privacy concerns. Yalla, R. K. M. K., & Prema, R. (2018) [26] proposed secure k-means data mining approach mitigates these risks by preserving data privacy while maintaining the correctness and validity of results in a distributed cloud environment.

[27] addresses security and privacy concerns in cloud computing, particularly in public cloud environments where trust in service providers may be limited. It proposes a method that enhances data protection through 128-bit Advanced Encryption Standard (AES) encryption and incorporates an SMS alert mechanism to prevent unauthorized access. Alagarsundaram, P., & Arulkumaran, G. (2018) [28] approach includes various security services, such as authentication, authorization, confidentiality, and monitoring, to ensure the confidentiality and integrity of user data.

[29] addresses security and privacy concerns in cloud computing, particularly in public cloud environments where trust in service providers may be limited. It proposes a method that enhances data protection through 128-bit Advanced Encryption Standard (AES) encryption and incorporates an SMS alert mechanism to prevent unauthorized access. Sitaraman, S. R., & Pushpakumar, R. (2018) [30] approach includes various security services, such as authentication, authorization, confidentiality, and monitoring, to ensure the confidentiality and integrity of user data.

[31] addresses the challenges of secure data analytics in cloud-integrated Internet of Things (IoT) applications, which generate vast amounts of sensitive data across sectors like smart grids, e-health, and environmental monitoring. It proposes the use of fully homomorphic encryption to ensure data security and privacy during cloud-based analytics, while highlighting the limitations of current technologies. Mandala, R. R., & N, P. (2018) [32] suggests models to improve the efficiency and accuracy of analytics on encrypted data, aiming to enhance privacy-preserving solutions for IoT applications.

[33] addresses the challenges of managing and analysing large-scale data in cloud computing, particularly in applications like social network analysis, semantic Web analysis, and bioinformatics. It discusses big data processing techniques, focusing on cloud data management and processing mechanisms, and explores the MapReduce parallel processing framework with optimization strategies. Ganesan, T., & Hemnath, R. (2018) [34] also highlights open issues and future research directions for improving big data processing in cloud environments.

[35] analyses the performance of financial, data mining, and media processing applications in private cloud environments, using six benchmarks from the PARSEC suite. The results show that performance varies based on application characteristics, virtualization technology, and resource allocation. Kethu, S. S., & Thanjaivadivel, M. (2018) [36] Financial applications generally outperform others, particularly in dedicated resource environments, with container-based (LXC) instances outperforming kernel-based (KVM) instances.

[37] explores the intersection of Big Data and Cloud Computing, emphasizing the limitations of traditional computing resources in handling large-scale data and the advantages of cloud computing, such as elasticity and reduced management effort. It focuses on the MapReduce framework and Hadoop for large-scale analytics, discussing their benefits and drawbacks. Veerapperumal, M., et al (2018) [38] also examines alternative programming frameworks designed to address the limitations of MapReduce in specific scenarios, providing a comparison with traditional solutions.

[39] reviews NoSQL and NewSQL data stores as solutions for managing Big Data in cloud environments, highlighting the limitations of traditional relational databases in handling performance and scalability requirements. It compares prominent NoSQL and NewSQL solutions based on data models, querying, scaling, and security features, providing guidance for practitioners and researchers in selecting appropriate data storage solutions. Budda, R., & Pushpakumar, R. (2018) [40] also identifies key challenges, including diverse terminology, limited documentation, and the lack of standardized query languages.

[41] proposes a controllable blockchain data management (CBDM) model to address the limitations of traditional blockchain solutions, such as weakened networking control and vulnerability to majority attacks. The model is designed for cloud environments to create a fair and transparent data-sharing ecosystem.

Subramanyam, B., & Mekala, R. (2018) [42] discusses the role of cloud-based big data analytics in enhancing the sustainability and resilience of smart cities, emphasizing the need for integrated ICT systems across urban domains like land use, transport, and energy. It proposes a theoretical framework for developing a cloud-based analysis service to improve real-time data processing, integration, and sharing, supporting decision-making and socioeconomic growth. [43] The research highlights the importance of effective software tools and technologies for managing large datasets in smart city environments.

Deevi, D. P., & Jayanthi, S. (2018) [44] presents the design of an autonomic cloud environment for real-time health monitoring and analysis, focusing on electrocardiogram (ECG) data collection and analysis. It leverages advancements in sensor technology, mobile devices, and cloud computing to store and analyze health data in a scalable and cost-effective manner. A prototype system was developed to evaluate the software design, enabling real-time ECG data collection and basic beat analysis from volunteers.

[45] examines the factors influencing a firm's intention to adopt cloud computing technologies for supply chain operations, using innovation diffusion theory and the information processing view as frameworks. It finds that business process complexity, entrepreneurial culture, and the compatibility and functionality of existing information systems play significant roles in the adoption propensity. The results offer valuable insights for both scholars and industry professionals to make informed decisions about cloud computing adoption.

Radhakrishnan, P., & Mekala, R. (2018) [46] explores the integration of big data platform architecture within financial technology, driving innovation in financial products and improving efficiency while reducing transaction costs. It discusses the emergence of new technology platforms that reshape the financial industry, incorporating space-time data elements. The paper also provides a practical analysis in the insurance sector, proposing a meaningful product and customer circle to enhance industry practices.

[47] proposes an efficient workload slicing scheme for managing data-intensive applications in a multiedge-cloud environment, leveraging software-defined networks (SDN) to optimize performance. It introduces an SDN-based control scheme for energy-aware network traffic flow scheduling and a multileader multifollower Stackelberg game for cost-effective inter-data center migrations. The effectiveness of the proposed approach is validated through evaluations using Google workload traces, addressing challenges in big data processing and data migration in edge-cloud environments.

Dyavani, N. R., & Rathna, S. (2018) [48] presents a systematic literature review on the applications of big data in disaster management, covering both natural and man-made disasters. It emphasizes the need for a modular approach to integrate data across various levels, particularly focusing on smart buildings and grids. Current research trends center on energy waste management, power generation prediction, and enhancing comfort through data integration. The paper concludes with future recommendations to address gaps, especially in regional-level disaster management.

[49] discusses the significance of Storage as a Service (StaaS) in cloud computing, emphasizing its benefits and challenges for data-intensive applications. It presents a comprehensive taxonomy of cloud-based data stores, covering aspects such as data models, consistency, and management costs. The study validates the taxonomy by mapping existing projects to it and identifies future research areas, aiming to improve availability, scalability, and cost efficiency in cloud data storage.

Gudivaka, R. K., & Rathna, S. (2018) [50] proposes a Blockchain-based platform for storing and managing electronic medical records in a Cloud environment, addressing the challenges of processing heterogeneous healthcare data. It highlights the potential of combining Blockchain technology with Cloud computing to enhance data security, accuracy, and reduce maintenance costs. The study emphasizes the complexity and heterogeneity of healthcare data and demonstrates how the integration of these technologies can improve healthcare data management.

[51] presents a smart agricultural model that integrates IoT, mobile technology, and cloud-based big data analytics to enhance agricultural practices. By utilizing IoT devices for data collection and cloud storage for analysis, the model aims to improve crop production and reduce costs through informed decision-making delivered to farmers via a mobile app. The study highlights the role of ICT in agriculture, enabling farmers to optimize decisions on fertilizer use, crop analysis, and market needs, thus improving efficiency and productivity.

2.1. PROBLEM STATEMENT

Cloud-based e-commerce platforms face several critical challenges in data storage and management. Data Security & Privacy – Ensuring secure storage and encryption of sensitive customer data remains a challenge due to evolving cyber threats. Grandhi, S. H., & Padmavathy, R. (2018) [52] Performance & Scalability Issues – High traffic loads can lead to latency and inefficiencies in database queries, impacting user experience. [53] Cost Optimization – Managing cloud storage expenses efficiently while maintaining performance is difficult, especially with auto-scaling databases. Dondapati, K. (2018) [54] Data Consistency & Integrity – Maintaining accurate and synchronized data across distributed cloud environments can be complex. Compliance & Regulatory Challenges – Meeting industry standards like GDPR and PCI-DSS requires robust security and governance frameworks, adding operational overhead.

3. PROPOSED METHODOLOGY

The data security and efficiency are paramount represents a streamlined approach to handling financial data while ensuring high performance and security is illustrated in figure 1. It begins with Data Collection, where raw financial data is sourced from transactions, banking systems, or market feeds. This data is then refined through

Data Pre-processing, involving cleaning and transformation to enhance accuracy and consistency. To optimize storage and transmission, the refined data undergoes Data Compression using LZ4, a high-speed lossless compression algorithm. Post compression, security takes centre stage as the data is encrypted using Post-Quantum Cryptography (PQC), ensuring resilience against emerging quantum computing threats. Finally, the encrypted data is securely stored in Cloud Storage, allowing seamless access while maintaining compliance with financial regulations. This workflow ensures an efficient, scalable, and future-proof solution for financial data management.

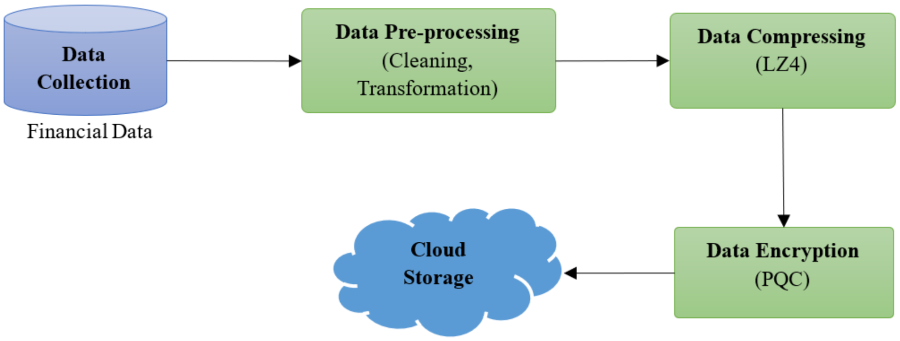

Figure 1: Efficient Financial Data Pipeline with Cloud Security

3.1 Data Collection

Data collection is the foundational step in the proposed framework, ensuring the availability of accurate and relevant financial data. The system gathers data from multiple sources, including bank transactions, stock market feeds, payment gateways, and accounting records. These data streams may arrive through event-driven architectures such as AWS Kinesis, Azure Event Hub, or Google Cloud Pub/Sub, ensuring low-latency processing. Batch data is also collected using AWS Glue, Azure Data Factory, and traditional ETL pipelines. Given the sensitivity of financial data, all incoming information is encrypted using secure transport protocols (TLS 1.3) and stored in a secure staging area. Furthermore, metadata tagging is applied to each dataset, helping in classification and efficient retrieval. The collected data may include structured data (SQL databases), semi-structured data (JSON, XML), or unstructured data (text, logs). Time-series data processing is particularly crucial for financial applications, requiring specialized handling techniques. Once collected, the data moves to the next phase: pre-processing, where it undergoes cleaning, transformation, and optimization.

3.2 Data Pre-Processing

Data pre-processing is essential for ensuring the quality and integrity of financial data. The key steps include:

1. ***Data Cleaning***

- Handling Missing Values: Missing values in financial datasets can lead to inaccurate predictions. The framework applies Mean Imputation for continuous variables is given in equation (1).

$$x_{new} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

Where x_{new} is the imputed value, and x_i represents available data points.

- Outlier Detection: The Z-score method is used to detect outliers is given in equation (2).

$$Z = \frac{x-\mu}{\sigma} \tag{2}$$

If $|Z| > 3$, the data point is considered an outlier and is either removed or replaced.

2. ***Data Transformation***

- Normalization (Min-Max Scaling): Ensures all numerical values fall within a range [0,1] is given in equation (3).

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{3}$$

- Standardization (Z-score Normalization): Used for financial ratios and log-transformed data is given in equation (4).

$$x' = \frac{x - \mu}{\sigma} \tag{4}$$

3.3 Data Compression using LZ4

The LZ4 algorithm is a lossless compression technique designed for high-speed data encoding and decoding. It significantly reduces financial data storage and transmission time while maintaining integrity.

1. Dictionary-Based Encoding

LZ4 uses a sliding window dictionary-based approach where repeated sequences are replaced with references to previous occurrences. Let S be the input string is given in equation (5).

$$S = [ABCDABCDXYZ] \tag{5}$$

Instead of storing duplicate sequences, LZ4 represents them as tuples is given in equation (6).

$$(0,4,A), (4,4,X), (8,3,Z) \tag{6}$$

2. Hashing and Lookup

LZ4 employs hash-based lookups for quick string pattern identification. Given a sequence $S[i: i+3]$, it is hashed using equation (7).

$$H(S[i: i+3]) = (S[i] \times P_1 + S[i+1] \times P_2 + S[i+2] \times P_3) \bmod M \tag{7}$$

Where P_1, P_2, P_3 are prime numbers, and M is the hash table size.

3.4 Data Encryption using PQC

Post-Quantum Cryptography (PQC) ensures that financial data remains secure against quantum attacks. The framework employs ML-KEM (CRYSTALS-Kyber) for secure key encapsulation and ML-DSA (CRYSTALS-Dilithium) for digital signatures.

1. Key Generation

In ML-KEM, a public-private key pair (pk, sk) is generated using equation (8).

$$pk = (A \cdot s + e) \bmod q \tag{8}$$

Where, A is a randomly generated matrix, s, e are small noise vectors, q is a prime modulus ensuring security.

2. Encryption Process

To encrypt financial data M, a random message r is chosen, and a ciphertext C is computed as given in equation (9).

$$C = A \cdot r + e' \bmod q \tag{9}$$

Where e' is another small noise vector.

3.5 Cloud Storage

Cloud storage in the proposed framework ensures secure, scalable, and highly available storage for financial data. The system leverages Amazon S3, Google Cloud Storage, and Azure Blob Storage, which provide durability through multi-region replication and redundancy. To enhance security, data is encrypted before storage using Post-Quantum Cryptography (PQC), ensuring protection against emerging quantum threats. Access control mechanisms, such as Identity and Access Management (IAM) policies and role-based access control (RBAC), restrict unauthorized access. Additionally, automated backup and versioning help in data recovery, preventing accidental loss or corruption. The system also integrates monitoring and logging tools like AWS CloudWatch and Azure Monitor to track data access patterns and detect anomalies. Overall, this cloud storage approach ensures efficient data management, regulatory compliance, and accessibility for financial applications.

4. RESULT

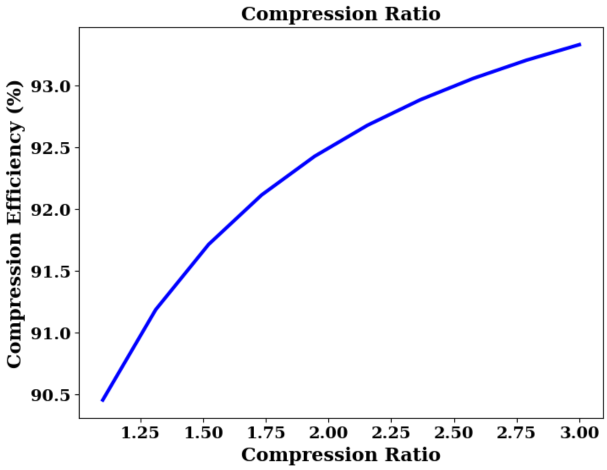

Figure 2: Optimizing Compression Ratio

Figure 2 represents the relationship between Compression Ratio and Compression Efficiency (%), where efficiency improves as the compression ratio increases. The Compression Efficiency starts at 90.5% for a ratio of 1.2 and gradually increases to 93% at a ratio of 3.0. This indicates that as the data is compressed more (higher compression ratio), the efficiency of the compression algorithm improves. However, the growth is nonlinear, suggesting diminishing returns in efficiency gains at higher compression ratios. The smooth curve demonstrates a consistent trend, highlighting the performance of the LZ4 compression technique in optimizing data storage while maintaining efficiency.

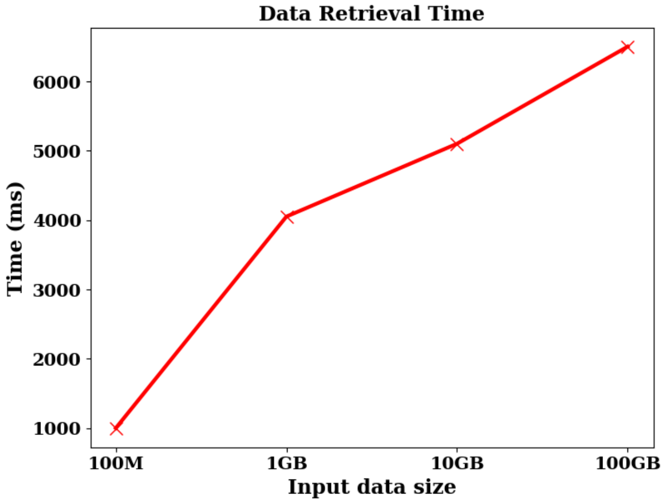

Figure 3: Scalability Analysis of Data Retrieval Performance

Figure 3 illustrates the Data Retrieval Time in milliseconds as a function of Input Data Size. It shows that as the data size increases, retrieval time also rises significantly. For 100MB, the retrieval time is around 1000ms, while for 1GB, it jumps to approximately 3500ms. At 10GB, the retrieval time reaches 5000ms, and for 100GB, it exceeds 6000ms. This trend suggests that larger datasets require more processing time due to increased data handling, indexing, and retrieval overhead in the cloud storage system. The linear growth indicates a proportional relationship between input size and retrieval latency.

5. CONCLUSION

The proposed framework ensures secure and efficient financial data management by integrating high-speed LZ4 compression and Post-Quantum Cryptography (PQC), enhancing storage optimization and security. The results indicate that as the compression ratio increases from 1.2 to 3.0, compression efficiency improves from 90.5% to 93%. Additionally, data retrieval time rises with input size, reaching 6000ms for 100GB, highlighting the importance of optimized retrieval mechanisms. Future work will focus on adaptive compression algorithms to balance speed and efficiency, hybrid PQC approaches for enhanced cryptographic security, and intelligent cloud data retrieval techniques to minimize latency using AI-based query optimization. Further scalability testing and regulatory compliance enhancements will also be explored to ensure real-world financial applicability.

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