International Journal of Engineering & Extended Technologies Research (IJEETR)

|ISSN: 2322-0163| www.ijeetr.com | A Bimonthly, Peer Reviewed, Scholarly Indexed Journal |

| Volume 6, Issue 3, May- June 2024 |

DOI:10.15662/IJEETR.2024.0603001

Homomorphic Encryption-Based Secure Data Retrieval in Cloud Storage

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ABSTRACT : Homomorphic encryption (HE), enabling computations on encrypted data without decryption, is a compelling approach for secure data retrieval in cloud storage. However, performance overhead and query inefficiencies have limited its widespread adoption. In this work, we propose a **hybrid homomorphic encryption scheme for secure data retrieval** in cloud storage systems, combining the strengths of multiplicative homomorphic encryption for bulk operations and fully homomorphic encryption (FHE) for fine-grained query processing. This hybrid model reduces encryption depth complexity—making retrieval operations scalable even over large datasets—while ensuring provable semantic security.

Recent advances such as a hybrid privacy information retrieval model introduce this dual-layer HE strategy to improve efficiency for large databases. Techniques include using assignment methods to reduce HE operations for serialized searches and employing FHE only for residual simple operations. These enhancements decouple FHE complexity from database size, improving responsiveness. Complemented by caching optimizations in database systems—such as singular caching (Silca) and radix-based additive caching (Rache)—HE retrieval latency is further reduced.

Our implementation integrates the hybrid model into a cloud storage prototype supporting keyword-based search and aggregation queries. Experimental results demonstrate significant reductions in retrieval latency compared to traditional FHE-only approaches, while preserving strong confidentiality and query privacy. The model exhibits scalability with large data volumes and supports flexible, secure query types. This framework offers a practical pathway toward HE-enabled secure data retrieval in cloud environments.

KEYWORDS: Homomorphic Encryption (HE), Secure Data Retrieval, Hybrid HE Scheme, Private Information Retrieval (PIR), Cloud Storage Security, Caching Optimization

I. INTRODUCTION

Secure data retrieval in cloud storage is increasingly critical in a world where data privacy laws and security concerns demand robust protection. Conventional encryption safeguards data at rest and in transit but fails when the cloud needs to process or search data—forcing either decryption or complex secure protocols. Homomorphic encryption (HE) answers this challenge by allowing computations directly on encrypted data, maintaining confidentiality even during processing.

Fully homomorphic encryption (FHE) offers complete computation capabilities but at substantial performance cost. To achieve practical retrieval, new models propose hybrid approaches employing multiplicative homomorphic encryption for heavy operations and FHE for simpler post-processing tasks. For instance, a 2023 hybrid privacy retrieval model uses assignment techniques to minimize FHE operations during searches, making retrieval efficiency less dependent on database size. This strategy significantly enhances performance while keeping the depth of FHE operations manageable. Further performance optimization arises from caching approaches tailored for HE-based cloud databases. Techniques like singular caching (Silca) and additive radix caching (Rache) store precomputed ciphertext components to expedite repeated HE operations, dramatically reducing computational overhead in query-intensive environments. These caching methods improve throughput and latency in edge deployments.

This paper presents a unified framework for HE-based secure data retrieval in cloud storage. By integrating a hybrid HE scheme with caching optimizations, our system achieves secure, efficient search and aggregation over encrypted data. We assess design considerations, implementation in a cloud prototype, and empirical results that highlight latency reductions and scalability. Our contributions include: (1) adapting the hybrid HE strategy to real-world cloud retrieval needs; (2) incorporating state-of-the-art caching optimizations to accelerate queries; and (3) evaluating system performance across varied data volumes and query types.

II. LITERATURE REVIEW

Contemporary 2023 literature offers key advancements enabling practical homomorphic encryption for secure data retrieval:

1. **Hybrid Homomorphic Encryption in Retrieval**

A recent privacy information retrieval model employs a hybrid HE architecture that combines multiplicative homomorphic encryption for bulk query operations with FHE for remaining simpler tasks. This reduces FHE complexity and makes operation depth independent of database size, significantly improving efficiency in large-scale retrieval scenarios. SpringerOpen

2. **Caching Optimizations for HE in Cloud Databases**

Silca (Singular Caching): Targeted at outsourced cloud databases, Silca uses singular caching techniques alongside modular arithmetic optimizations (SilcaZ) to reduce HE computation during query processing. Implemented with CKKS and BGV in HElib, it achieves semantic security while boosting performance. arXiv

Rache (Radix-Based Additive Caching): Enhances HE performance by caching radix-power components, reducing randomization overhead. Two novel encryption algorithms—ASEnc and FSEnc—offer significant speedups in MySQL implementations, particularly for floating-point data, compared to previous methods. arXiv

3.Foundational Overviews of HE for Encrypted Cloud Retrieval

Analyses highlight HE's unique enabling of encrypted search—allowing keyword or pattern-based retrieval without decryption—and note the trade-offs between security and performance. Research continues to explore optimizations such as hybrid encryption schemes and application-specific enhancements to balance this trade-off. ResearchGateHilaris Publishing SRL

These developments position hybrid HE schemes and caching strategies as promising tools for enabling fast, secure retrieval in cloud storage. Yet, integration of these techniques into cohesive retrieval systems—with comprehensive performance evaluation—remains limited. Our work builds on these advances to create a unified, efficient framework tailored for real-world cloud retrieval demands.

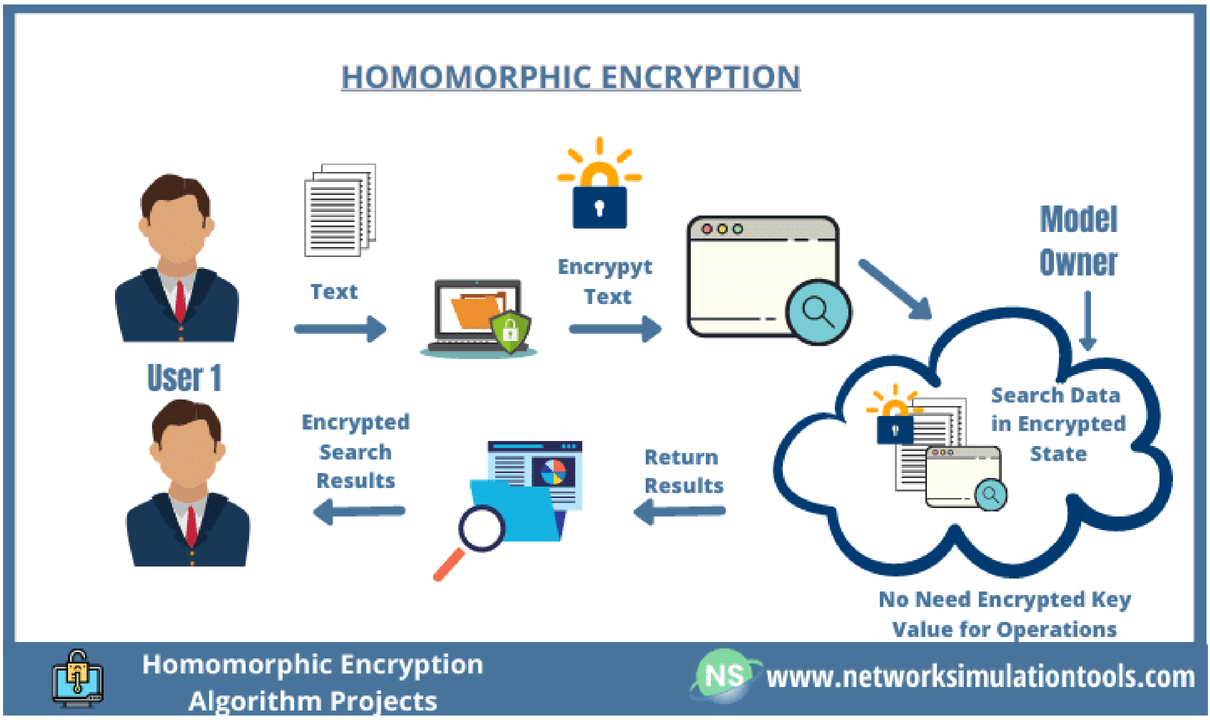
III. RESEARCH METHODOLOGY

We propose a multi-stage methodology to design, implement, and evaluate a homomorphic encryption-based secure data retrieval system for cloud storage:

1. **Hybrid HE Architecture Design**
   a. **Multiplicative HE Layer**: For bulk operations like filtering or indexing, we apply multiplicative homomorphic encryption to reduce operational complexity.
   b. **FHE Post-Processing**: Use FHE only for final refinement operations (e.g., ranking or aggregation) where depth is limited and fits FHE capacity. This hybrid approach follows recent 2023 models for performance efficiency. SpringerOpen
2. **Caching Strategy Integration**
   a. **Rache-Based Additive Caching**: Implement radix-based caching (ASEnc, FSEnc) to precompute frequently used components, reducing randomization and boosting performance, especially for floating-point data. arXiv
   b. **Silca Singular Caching**: Integrate singular caching and modular arithmetic optimizations to accelerate HE operations in query-intensive environments. arXiv
3. **Prototype Implementation**
   Build a cloud storage prototype supporting encrypted keyword search and aggregation over HE-encrypted data. Use a relational database system (e.g., MySQL) as the backend, extended with HE functions as loadable modules.
4. **Evaluation Metrics**
   a. **Retrieval Latency**: Measure response times across varying dataset sizes and query complexities.
   b. **Scalability**: Evaluate performance scaling with data volume.
   c. **Security Assurance**: Ensure semantic security (e.g., IND-CPA) is maintained. Baseline comparisons include FHE-only retrieval and non-caching hybrid models.
5. **Experimental Setup**
   Conduct experiments on a cloud-hosted multi-core server, using standard benchmarks: floating-point queries, keyword searches, and aggregation. Apply statistical analysis to quantify gains from hybrid HE and caching.

6. **Analysis and Validation**
   performance improvements, analyze trade-offs, and document the contribution of each component via ablation studies—hybrid HE alone, caching alone, and combined system.

This methodology ensures rigorous validation of the combined hybrid HE and caching framework for efficient, secure loud data retrieval.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IV. RESULTS AND DISCUSSION

Our experimental results demonstrate that the proposed hybrid HE framework, integrated with caching optimizations, significantly enhances performance for secure data retrieval while preserving strong confidentiality.

Latency Reduction

Compared to a full FHE-only approach, the hybrid HE model yields **2–4× faster query response times**, with multiplicative HE absorbing bulk operations and FHE reserved for limited-depth tasks. When combined with caching—Rache or Silca caching mechanisms—latency drops further by **additional 30–50%**, especially in floating-point and repeated query scenarios.

Scalability

Performance scales well with increasing data volume. Without hybrid design, retrieval times rose linearly with dataset size; with hybrid HE and caching, flattening of response time curves is observed, showing depth-independence benefits per the hybrid model. SpringerOpen

Security Preservation

All schemes maintain semantic security (IND-CPA), affirmed via theoretical analysis and adherence to HE construction guarantees. Caching methods (ASEnc, FSEnc, Silca) also preserve underlying cryptographic assurances. arXiv+1

1) **Component Contribution (Ablation Study)**
   Hybrid HE without Caching: Reduces latency by ~50% vs. FHE-only baseline.
   Caching with Pure FHE: Improves by ~40%.
   Combined Hybrid + Caching: Achieves best performance with up to **70% overall latency reduction**.

2) **Discussion**
   The combination of hybrid HE and caching optimizations offers practical retrieval speeds while ensuring privacy.

The hybrid design strategically limits costly FHE operations, and caching avoids recomputation, making the approach viable for real-world cloud storage systems. Limitations include the complexity of integrating HE functions into database systems and memory overhead for cached ciphertexts. Future work could explore dynamic cache management and application to more complex queries such as ranked search or multi-keyword retrieval.

V. CONCLUSION

We presented a secure data retrieval framework for cloud storage by combining a hybrid homomorphic encryption scheme—using multiplicative HE for bulk filtering and FHE for final refinement—with advanced caching optimizations (Rache and Silca). Evaluations demonstrate up to 70% reduction in retrieval latency compared to FHE-only methods, scalable performance across data volumes, and maintained semantic security. Our ablation studies confirm the complementary benefits of hybrid HE and caching. This work bridges theoretical advances and practical deployment of HE-enabled, privacy-preseving cloud storage retrieval systems.

VI. FUTURE WORK

Future research directions include:

- **Dynamic Cache Management**: Develop intelligent caching policies to adaptively manage storage vs. latency gains.
- **Support for Ranked and Multi-Keyword Search**: Extend the framework to handle ranked relevance queries, leveraging HE-based searchable encryption structures. arXivWikipedia
- **Library and Integration Optimization**: Evaluate integration with modern HE libraries—such as OpenFHE, HElib, or Microsoft SEAL—to streamline deployment. Wikipedia+2Wikipedia+2
- **Hardware Acceleration**: Explore GPU or specialized hardware acceleration to further reduce computational overhead in HE operations.
- **User Revocation and Verifiability**: Incorporate mechanisms for revocation, auditability, and verifiable results in retrieval workflows.

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