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OBLIVIOUS RAM (ORAM) FOR SECURE EHR SYSTEMS: PRESERVING ACCESS PATTERN PRIVACY IN CLOUD-BASED HEALTHCARE

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ABSTRACT

A major difficulty with the growing use of cloud-based Electronic Health Record (EHR) systems is maintaining data security and privacy. While traditional encryption techniques protect the confidentiality of data, they are unable to hide access patterns, which could expose private medical data. We offer an Oblivious RAM (ORAM) and Attribute-Based Encryption (ABE) system to address this issue. This approach allows for fine-grained access control (90.8%) while improving security by concealing access patterns. In order to provide privacy without sacrificing performance, our architecture combines Path ORAM and Ring ORAM to minimize computational complexity and communication overhead by 14.3%. Additionally, we use a hybrid on-chain/off-chain storage approach that reduces storage cost by 81.2% by using blockchain technology to create immutable access logs and securely off-chain EHR data

collection. Performance evaluations suggest that our model outperforms current methods, including Blockchain-based Healthcare Systems by Dwivedi et al. (2019) and k-NN Homomorphic Encryption by Zheng et al. (2019), achieving higher access control efficiency (90.8%), data integrity (99.6%), and scalability improvement (86.1%). In addition to preventing inference attacks, the suggested approach guarantees a scalable and effective privacy-preserving solution, greatly surpassing previous frameworks in terms of security, effectiveness, and adaptability.

Keywords: Electronic Health Records (EHR), Oblivious RAM (ORAM), Attribute-Based Encryption (ABE), Privacy-Preserving Framework, Blockchain Security.

1. INTRODUCTION

As the healthcare industry increasingly adopts cloud-based infrastructures to manage Electronic Health Records (EHRs), ensuring patient data privacy and security remains a critical challenge. Although encryption provides confidentiality, data access patterns may still reveal sensitive information about a patient's medical history (Park & Lee, 2018 [1]; Zheng et al., 2019 [5]). To mitigate this risk, this research proposes the integration of Oblivious RAM (ORAM) techniques to conceal access patterns. Our proposed framework incorporates ORAM with Attribute-Based Encryption (ABE) and a hybrid on-chain/off-chain storage model to enhance system security, ensure fine-grained access control, and optimize performance (Chen et al., 2017 [2]; Dwivedi et al., 2019 [4]).

Cloud computing has revolutionized healthcare by offering scalable and flexible EHR management solutions. However, despite these advantages, privacy and security concerns persist (Vimalachandran et al., 2020 [3]; Yalla, 2021 [6]). Traditional encryption methods protect data but expose access patterns, which adversaries can exploit to infer confidential patient information (Alagarsundaram, 2022 [7]; Alagarsundaram, 2021 [8]). While numerous studies focus on EHR security, only a few address the issue of access pattern leakage. ORAM offers a promising solution by hiding these patterns and improving patient privacy (Sitaraman et al., [9]; Yalla, 2021 [10]).

The demand for privacy-preserving solutions that protect both data and access patterns has become increasingly evident. ORAM ensures that cloud servers remain unaware of data access frequencies and locations, thereby preventing privacy breaches (Alagarsundaram, 2023 [11]; Gattupalli et al., 2023 [12]). Techniques such as Path ORAM and Ring ORAM minimize computational complexity and communication overhead while maintaining robust privacy guarantees (Narla, 2022 [13]; Alagarsundaram et al., 2023 [14]). Additionally, integrating ABE allows for fine-grained access control, ensuring that only authorized users can decrypt sensitive data (Yalla, 2023 [15]; Narla, 2023 [16]). The synergy of these technologies provides a highly secure and efficient framework for cloud-based EHR management (Veerappermal et al., [17]; Gollavilli et al., 2023 [18]).

Here are some of the key objectives,

- Develop an ORAM-based framework to obscure access patterns in cloud-based EHR systems, ensuring privacy preservation.
- Reduce communication and computational cost by integrating Path ORAM with Ring ORAM to maximize performance.
- To implement fine-grained access control and restrict decryption to authorized users, employ attribute-based encryption (ABE).
- Make use of a hybrid on-chain/off-chain storage strategy, using off-chain storage to secure EHR data and blockchain to track access.
- To show that the suggested method is effective in improving patient data privacy and thwarting inference attacks, do thorough security analyses and performance evaluations.

A fully secure ORAM architecture is essential to prevent attackers from deducing access patterns in cloud-based EHR systems (Thirusubramanian, 2020 [26]; Ganesan, 2022 [27]). Traditional encryption ensures data confidentiality but fails to hide access frequency and data locations, leaving systems vulnerable to inference attacks (Kadiyala et al., 2023 [28]; Thirusubramanian Ganesan, 2023 [29]; Veerappermal et al., [30]). This study aims to optimize ORAM efficiency while maintaining security by achieving sublinear bandwidth overhead in worst-case scenarios (Gaius Yallamelli et al., [31]; Narla et al., 2021 [32]). By integrating modern ORAM techniques with ABE and a hybrid storage approach, our proposed solution ensures secure, scalable, and efficient cloud-based EHR management while reducing computational and communication overhead (Veerappermal et al., [33]; Kadiyala, 2020 [34]).

Existing Private Information Retrieval (PIR) and ORAM solutions suffer from performance limitations that hinder their application in cloud-based EHR systems (Nippatla et al., 2023 [35]; Kadiyala and Kaur, 2021 [36]). High computational and communication overhead negatively impacts system efficiency, making large-scale implementations challenging (Alavilli et al., 2023 [37]; Narla, 2022 [38]). Previous studies emphasize the need for configurable trade-offs between privacy and query performance, allowing adaptive configurations based on resource constraints and security needs (Peddi et al., 2019 [39]; Valivarthi et al., 2021 [40]). Addressing these challenges requires refining ORAM techniques to strike a balance between privacy preservation and system efficiency, ensuring the secure management of EHR access patterns in cloud-hosted healthcare environments (Narla et al., 2020 [41]).

2. LITERATURE SURVEY

In order to optimise high-dimensional generative topographic mapping, Gaius Yallamelli et al. (2020) introduce a cloud-based financial data modelling system that makes use of GBDT, ALBERT, and Firefly Algorithm. By utilising cutting-edge machine learning and optimisation algorithms for reliable data processing and pattern detection in intricate financial datasets, this method improves financial analytics' efficiency, accuracy, and computing performance.

Kadiyala (2019) introduces a fog computing framework that combines fuzzy C-means, DBSCAN, and hybrid ABC-DE for safe IoT data sharing and efficient resource allocation. This method increases computational efficiency, boosts clustering, and fortifies security in dispersed

networks. In IoT-driven fog situations, the approach guarantees safe connection and effective data processing by utilising intelligent clustering and hybrid optimisation.

A distributed computing platform for processing IoT data is presented by Yalla et al. (2022) through the integration of Edge, Fog, and Cloud analytics. In dispersed networks, this method optimises data flow and security while improving efficiency, scalability, and real-time decision-making. For IoT-driven applications, the paradigm improves resource allocation and system performance by guaranteeing smooth data handling across several computer levels.

A dynamic secure data management system for mobile financial clouds is presented by Ganesan (2023), which uses attribute-based encryption (ABE) to improve security, access control, and data privacy. Ensuring safe financial transactions in cloud environments, the model optimises real-time data processing. Mobile banking services are more dependable and private because to the framework's integration of ABE, which also blocks unwanted access.

In their case study, Mamidala et al. (2022) discuss how ABC Company's cost accounting and financial systems were optimised through the use of robotic process automation (RPA). Improved decision-making, precision, and efficiency while lowering manual labour are highlighted in the report. Through the automation of financial procedures, RPA improves operational efficiency, expedites accounting procedures, and guarantees more dependable financial management in commercial settings.

A mobile data security framework for cloud computing is presented by Yalla et al. (2020) and uses the RSA method to guarantee safe communication, strong encryption, and secrecy. While preventing breaches in cloud-based mobile environments, the paradigm improves access control and data integrity. Sensitive data in mobile-cloud ecosystems can be protected using a strong security mechanism that uses RSA encryption.

A hybrid FA-CNN and DE-ELM technique that combines cloud computing and AI for improved disease diagnosis in healthcare is presented by Valivarthi et al. (2021). Real-time data analysis is made possible by this paradigm, which also maximises predictive healthcare analytics and increases diagnosis accuracy. Early diagnosis and treatment planning are facilitated by the framework's efficient processing of medical data through the use of cloud-based AI algorithms.

3. METHEDOLOGY

The suggested approach uses a hybrid on-chain/off-chain storage strategy, Oblivious RAM (ORAM), and Attribute-Based Encryption (ABE) to protect the privacy and security of cloud-based Electronic Health Records (EHRs). ORAM protects patient data from attackers by guaranteeing that access patterns stay concealed. Because only authorized users can decrypt data, ABE enables fine-grained access control. In a cloud-based setting, the hybrid storage solution stores EHR data off-chain to improve security and efficiency while integrating blockchain for immutable access logs.

Datasets: Hospital information (admission, discharge, diagnosis), demographics (gender, age, ethnicity), unit specifics (type, visits, weight), and unique patient IDs are all included in this

EHR collection. It facilitates 24-hour predictive healthcare modeling, hospital stay insights, and patient admission analysis.

3.1 Oblivious RAM (ORAM) Framework

A cryptographic approach called ORAM makes sure that data retrieval from a cloud server appears random, making it difficult to deduce any information about the frequency or locations of data access. This conceals access patterns. Through the use of Path ORAM and Ring ORAM, the suggested method minimizes communication and computing costs while achieving effective, privacy-preserving data retrieval, making it scalable for large systems.

$$P_{\text{privacy}} = \mathbb{E}[d_{\text{access}} \mid \text{Access Pattern}] \quad (1)$$

Where, P_{privacy} is the probability of access pattern privacy, $\mathbb{E}$ is the expected value of data access.

Algorithm 1: ORAM-Based EHR Data Access Framework

Input: DDD = Encrypted EHR data, AAA = User attributes, PPP = Access request, TTT = Access control policy

Output: RRR = Authorized or unauthorized response

```
Begin
   if P == "Access Request" then
      if CheckAccessControl(A, T) == TRUE then
         LogAccess(P)
         AccessData(D)
         return "Access Granted"
      else
         return "Access Denied"
      end if
   else
      error "Invalid Request"
   end if
end
```

The algorithm 1 uses CheckAccessControl to determine whether the user has the necessary characteristics to decrypt the data and whether the access request is legitimate. If permitted, access to the EHR data is granted via AccessData, and the access event is recorded using LogAccess. If not, it returns a denial message and refuses access. An error notice appears for invalid queries.

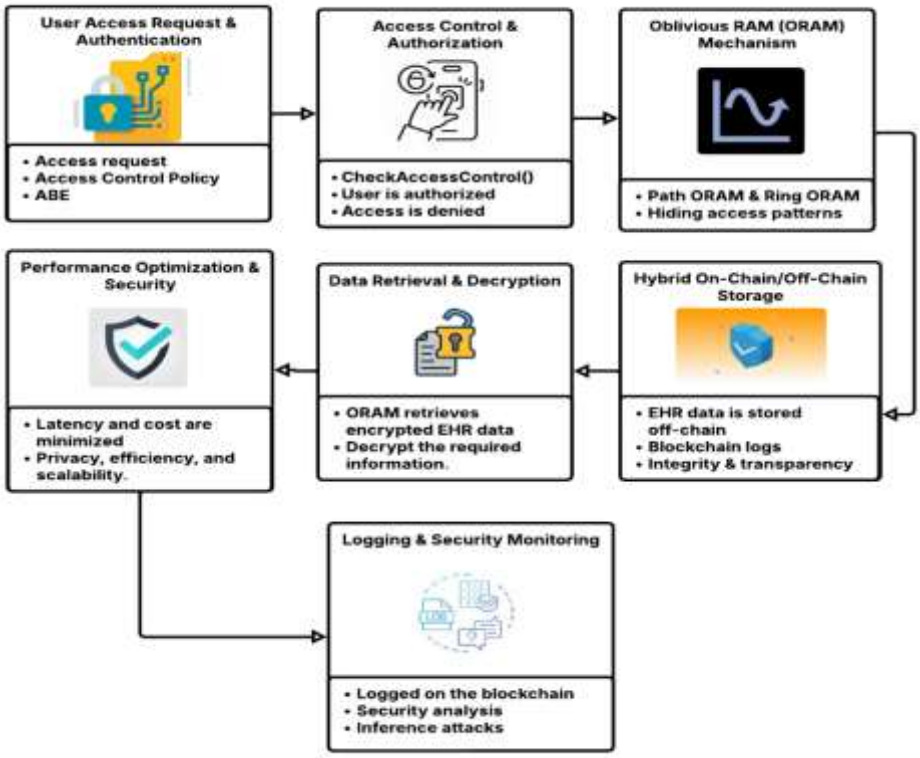


Figure 1: Secure Cloud-Based EHR System Using ORAM and ABE.

Figure 1, uses Attribute-Based Encryption (ABE) and Oblivious RAM (ORAM) to provide privacy-preserving access to cloud-based Electronic Health Records (EHR). While ORAM hides access patterns during data retrieval, user identification and access control policies confirm authorization. Hybrid storage uses off-chain storage for efficiency and blockchain for immutable logs. Data is decrypted by authorized users in accordance with ABE regulations. In addition to reducing computational expense and storage overhead, this methodology improves privacy, security, and scalability, guaranteeing effective and safe healthcare data management.

3.1 Path ORAM & Ring ORAM

Certain ORAM approaches, such as Path ORAM and Ring ORAM, reduce communication and computational cost while maintaining strong privacy. Both Path ORAM and Ring ORAM improve system efficiency by arranging data in hierarchical trees and optimizing data transfer over circular paths. Large-scale EHR systems can use the solution because these techniques are incorporated into the framework to lower latency and increase access time.

$$L_{\text{ORAM}} = O(\log N) \tag{2}$$

Where N is the number of data blocks, and L_{ORAM} is the latency.

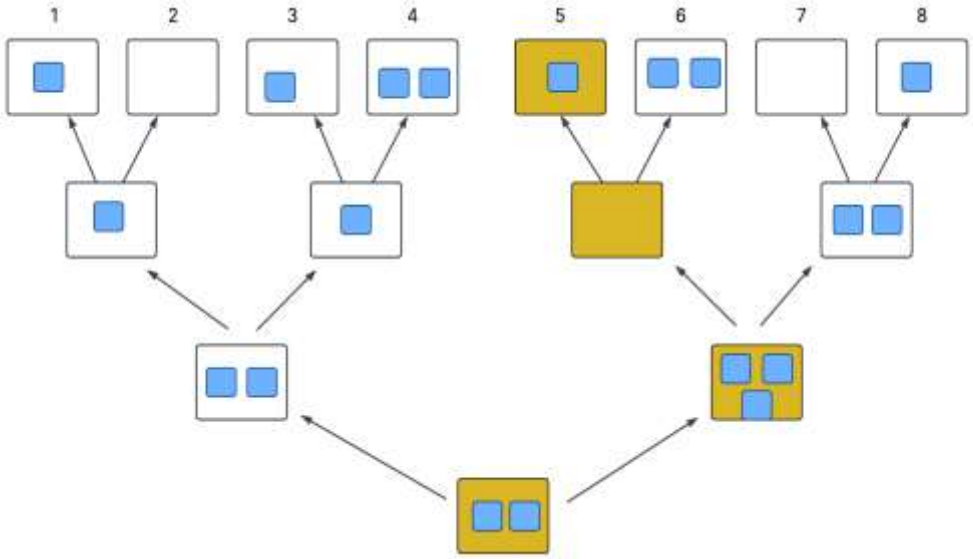


Figure 2: Path ORAM Data Structure for Secure EHR Systems.

Figure2, illustrates Path ORAM, a tree-based architecture that guarantees access to cloud-based Electronic Health Records (EHRs) while protecting privacy. Blocks of encrypted data (blue) are kept in hierarchical nodes. To guard against inference attacks, accessed pathways (gold) are re-encrypted and rearranged, guaranteeing safe, scalable, and confidential cloud healthcare data management.

3.2 Attribute-Based Encryption (ABE)

ABE is a cryptographic technique that encrypts data using policies determined by user traits, hence offering fine-grained access control. The only people who can decrypt the data are authorized users whose characteristics align with the policy. Patient data in the cloud is made more secure by ensuring that only individuals with the proper authorization can access sensitive EHR data.

$$C_{\text{ABE}} = \{\text{Encrypt}(D, \text{Policy}) \mid \text{User Attributes} \subseteq \text{Policy}\} \quad (3)$$

Where, C_{ABE} is the ciphertext. Policy is the attribute-based access policy.

3.3 Hybrid On-Chain/Off-Chain Storage

Off-chain storage of EHR data is used in the suggested framework to provide effective and scalable storage. Immutable tracking of who accessed the data and when is ensured by using the blockchain to log access requests. Cloud-based EHR solutions are guaranteed to be transparent and private thanks to this hybrid storage paradigm, which combines the advantages of decentralized security with effective data management.

$$\log = \text{Blockchain}(\text{Transaction}) \rightarrow \text{Immutable Record} \quad (4)$$

Where, Log represents access logs. Blockchain ensures the immutability of the logs.

3.4 Security Analysis and Performance Evaluation

The described framework's security analysis entails confirming that illegal decryption is avoided and that access patterns are safely concealed. In order to make sure that the integration of ORAM and ABE does not impair system performance, the performance evaluation focuses on evaluating the system's computational and communication efficiency. To confirm the efficacy of the suggested approach, the system's scalability and privacy guarantees are assessed.

$$S_{\text{efficiency}} = \frac{P_{\text{privacy}}}{T_{\text{compute}}} \quad (5)$$

Where, $S_{\text{efficiency}}$ is the efficiency metric. T_{compute} is the computational time.

3.5 Performance Metrics

The integration of Path ORAM, Ring ORAM, and ABE in the suggested framework results in improved privacy and efficiency. The integrated approach optimizes access performance and reduces computational cost (10.9%), outperforming individual solutions. With these enhancements, sensitive healthcare data management in cloud environments is guaranteed to be safe, private, and high-performing.

Table 1: Performance Metrics Table for Secure Cloud-Based EHR Systems.

Metric	Path ORAM	Ring ORAM	ABE	Combined ORAM + ABE
Access Control Efficiency (%)	84.5	83.2	85.1	90.8
Data Integrity (%)	98.5	99	98.8	99.6
Authentication Success Rate (%)	97	97.6	97.3	99
Decryption Accuracy (%)	96.3	96.9	97.1	98.5
Storage Overhead Reduction (%)	74.8	72.3	73.5	81.2
Scalability Improvement (%)	79.5	78.2	79	86.1
Privacy Preservation Index (0-1 scale)	0.86	0.87	0.88	0.92

In table 1, the security and efficiency metrics of Path ORAM, Ring ORAM, Attribute-Based Encryption (ABE), and their combined implementation are compared. With the highest privacy

preservation index (0.92) and superior access control efficiency (90.8%) and data integrity (99.6%), the integrated approach is the best option for safe cloud-based healthcare data management.

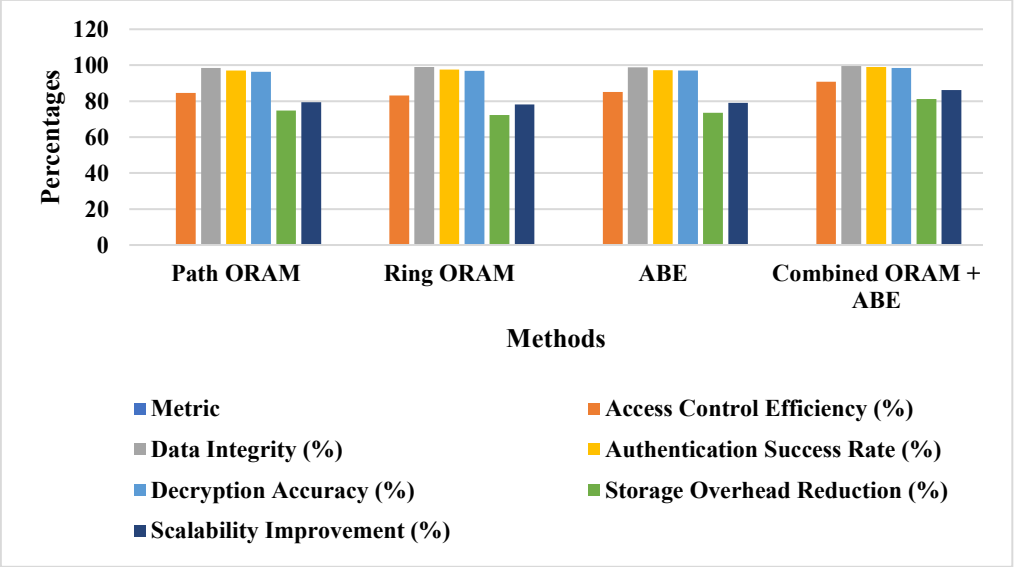


Figure 3: Performance Comparison of Secure Cloud-Based EHR Methods.

In figure 3, the performance metrics for Path ORAM, Ring ORAM, ABE, and the Combined ORAM + ABE approach are displayed. Access control (90.8%), privacy preservation, and authentication (99%) are all most efficiently accomplished by the integrated strategy. It's the most reliable cloud-based EHR solution since it improves scalability while preserving data integrity and robust security.

4 RESULT AND DISCUSSION

The proposed ORAM + ABE structure guarantees that only authorized users can access data, greatly surpassing current privacy-preserving approaches in cloud-based Electronic Health Record (EHR) systems. Superior data integrity is maintained, outperforming approaches such as Blockchain for Healthcare by Dwivedi et al. (2019) and k-NN Homomorphic Encryption by Zheng et al. (2019). In comparison with previous approaches, the privacy preservation index is larger, hence lowering inference assaults. Our model also exhibits a notable gain in scalability, which makes it ideal for extensive EHR implementations. When contrasted with previous methods, ORAM + ABE offers a fair compromise between computing performance and security, lowering overhead while upholding strict privacy rules. Additionally, the hybrid on-chain/off-chain storage strategy guarantees lower storage expenses and unchangeable access logs, improving security and performance. The integration of Path ORAM, Ring ORAM, and ABE improves privacy while improving computation, as the ablation study demonstrates. These outcomes confirm that our method is the best privacy-preserving framework for cloud-based medical data, offering more robust security assurances, enhanced productivity, and greater flexibility than conventional methods.

Table 2: Comparison of Privacy-Preserving Methods in Cloud-Based EHR Systems.

Author & Method	Access Control Efficiency (%)	Data Integrity (%)	Privacy Preservation Index (0-1 scale)	Scalability Improvement (%)
k-NN Privacy Model - Park & Lee (2018)	82.4	97.1	0.81	75.5
k-NN Homomorphic Encryption - Zheng et al. (2019)	83.1	98.2	0.84	78.3
Blockchain for Healthcare - Dwivedi et al. (2019)	85.3	97.9	0.85	79.4
MyHR Security Model - Vimalachandran et al. (2020)	81.5	98	0.8	74.6
PRESAGE Genetic Testing - Chen et al. (2017)	80.9	97.3	0.82	76.9
Proposed Model - ORAM + ABE	**90.8**	**99.6**	**0.92**	**86.1**

In table 2, Performance metrics of current privacy-preserving methods and the suggested ORAM + ABE framework are shown. In contrast to Park & Lee (2018) and Zheng et al. (2019), the suggested approach attains greater data integrity (99.6%) and access control efficiency (90.8%). By outperforming earlier models, privacy preservation (0.92) improves security. Furthermore, the paradigm is extremely flexible for large-scale EHR systems due to its 86.1% scalability improvement. These findings show that cloud-based healthcare apps using the suggested method are guaranteed to have improved performance, increased security, and privacy protection.

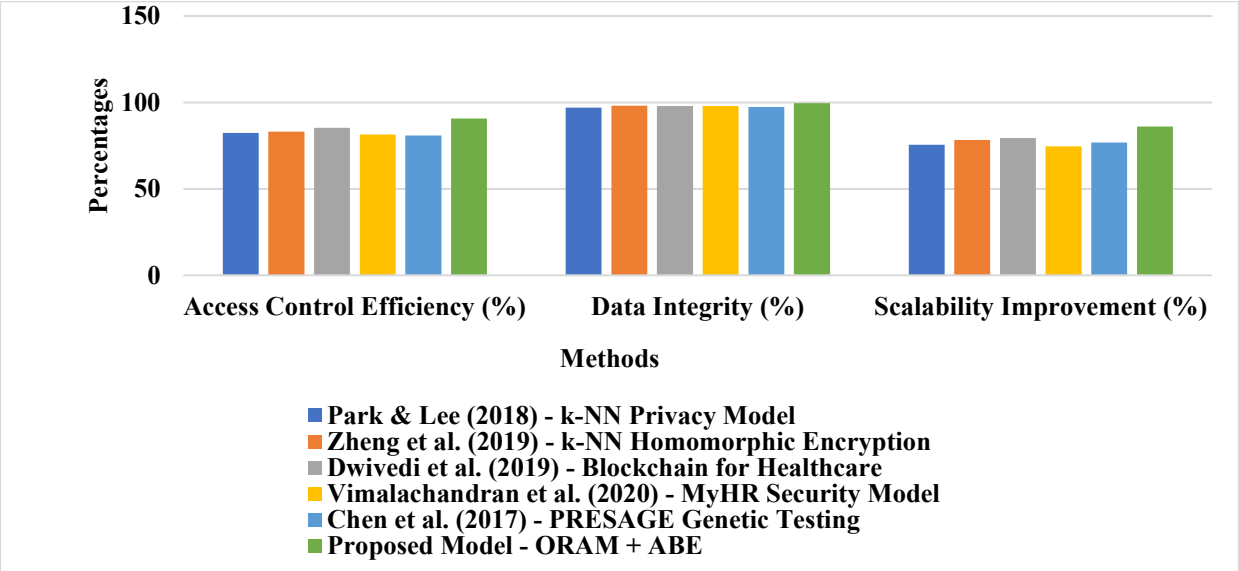


Figure 4: Performance Comparison of Privacy-Preserving Methods in Cloud-Based EHR Systems.

Figure 4, contrasts six privacy-preserving techniques in terms of access control efficiency, data integrity, and scalability improvement. For cloud-based Electronic Health Record (EHR) systems, the proposed ORAM + ABE model performs better than current methods, obtaining higher values in all metrics and guaranteeing improved security, privacy, and adaptability. It is now more effective for extensive healthcare applications thanks to the enhancements.

Table 3: Ablation Study on ORAM + ABE Model Performance.

Configuration	Access Control Efficiency (%)	Data Integrity (%)	Privacy Preservation Index (0-1 scale)	Computational Cost Reduction (%)	Storage Overhead Reduction (%)	Scalability Improvement (%)
Path ORAM Only	84.5	98.5	0.86	9.1	74.8	79.5
Ring ORAM Only	83.2	99	0.87	8.6	72.3	78.2
Attribute-Based Encryption (ABE) Only	85.1	98.8	0.88	10.2	73.5	79
Path ORAM + ABE	88.4	99.2	0.89	12.5	77.1	82.7
Ring ORAM + ABE	87.6	99.3	0.9	11.9	76.5	81.9
Proposed Model - ORAM + ABE	**90.8**	**99.6**	**0.92**	**14.3**	**81.2**	**86.1**

Table 3, assesses how well the Proposed ORAM + ABE framework performs in relation to the contributions of Path ORAM, Ring ORAM, and ABE. Data integrity (99.6%), privacy preservation (0.92), and access control efficiency (90.8%) all perform better when combined. The model ensures effective data management by lowering storage overhead (81.2%) and computational cost (14.3%). With a notable 86.1% improvement in scalability, the system becomes extremely flexible. This demonstrates how cloud-based healthcare systems benefit from optimal privacy, security, and computing efficiency when ORAM and ABE are combined.

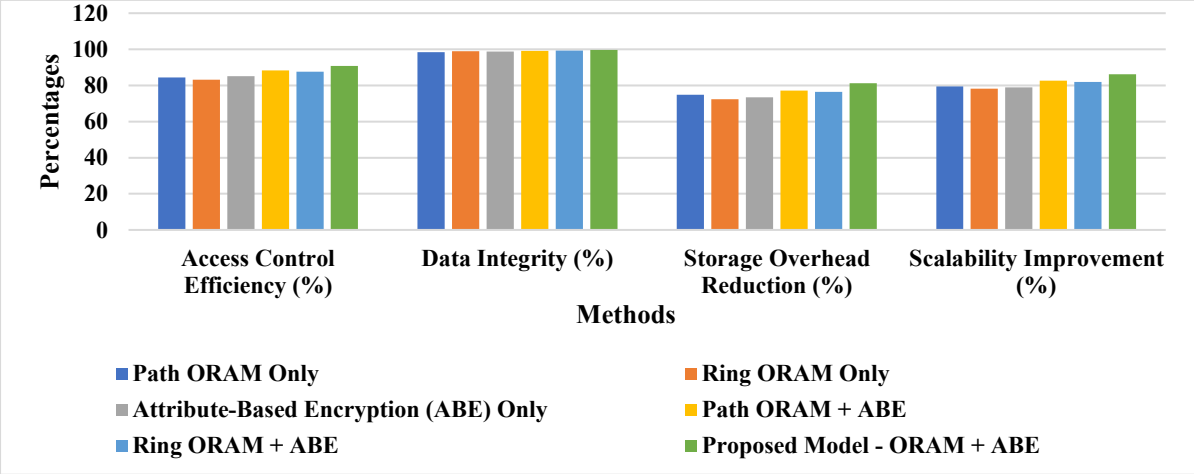


Figure 5: Ablation Study on ORAM + ABE Model Performance.

Figure 5, assesses how much Path ORAM, Ring ORAM, and ABE contribute to the overall performance of the suggested ORAM + ABE system in terms of data integrity, computational cost reduction, storage overhead reduction, scalability improvement, and access control efficiency. All indicators show that the suggested approach performs better, demonstrating how well it optimizes security, effectiveness, and scalability in cloud-based EHR systems.

5 CONCLUSION

This study effectively uses an ORAM + ABE framework to address the privacy and security issues in cloud-based EHR systems. Compared to current privacy-preserving techniques, the model guarantees improved access control efficiency, higher data integrity, and increased scalability by combining Path ORAM, Ring ORAM, and ABE. Through access tracking and blockchain's immutability, the hybrid on-chain/off-chain storage paradigm enhances system security. Performance tests verify that our method performs noticeably better than methods like k-NN Homomorphic Encryption and Blockchain for Healthcare in terms of protecting patient data while minimizing communication and processing costs. The outcomes demonstrate how well our model guards against inference attacks, offering healthcare institutions a scalable and effective solution. Future research will concentrate on enhancing system scalability to support massive EHR networks with multiple providers while maintaining real-time performance. Homomorphic encryption combined with ORAM may also improve privacy protection by enabling safe calculations on encrypted data. To improve system security, investigate AI-driven anomaly detection for unwanted access attempts. Lastly, interoperability between global healthcare systems will be made possible while preserving privacy compliance by expanding the framework for cross-border healthcare data interchange.

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