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Enhancing Cloud Healthcare Security Using Fine-Grained Access Control with Weight-Improved Particle Swarm Optimization and Zero-Knowledge Proofs

Rajababu Budda
IBM, California, USA
RajBudda55@gmail.com

Aravindhan Kurunthachalam
Associate Professor
School of Computing and Information Technology
REVA University
Bangalore
Aravindhan03@gmail.com

ABSTRACT

Background Information: The improved security framework for cloud healthcare systems presented in this research combines Zero-Knowledge Proofs (ZKP), Weight-Improved Particle Swarm Optimization (WIPSO), and fine-grained access control. By improving privacy and data security, the framework guarantees safe access to private medical data.

Objectives: Using WIPSO and ZKP to provide fine-grained access control will improve cloud healthcare security by reducing unwanted access and protecting user privacy, data integrity, and confidentiality.

Methods: By optimizing access control policies, a WIPSO algorithm increases the effectiveness of security. ZKP provides safe, private access to cloud-stored medical data by ensuring user authentication without disclosing private information.

Results: Significant gains in access control efficiency and security are made possible by the suggested framework, which also lowers computing costs and prevents unwanted access attempts while safeguarding private medical information.

Conclusion: A strong, scalable solution for cloud healthcare security is offered by the combination of WIPSO and ZKP, which offers efficient, privacy-preserving, and fine-grained access control over sensitive medical data.

Keywords: Secure cloud access, user authentication, healthcare information systems, fine-grained access control, Weight-Improved Particle Swarm Optimization (WIPSO), Zero-Knowledge Proofs (ZKP), data privacy, privacy preservation, access control optimization, and healthcare data protection.

1. INTRODUCTION

The optimization algorithm Particle Swarm Optimization (PSO), which draws inspiration from fish and bird social behavior patterns, is a novel method for improving Fine-Grained Access

Control (FGAC) [1][2]. Healthcare businesses dynamically optimize user access privileges in response to evolving requirements and risk levels by utilizing Weight-Improved PSO (WIPSO) to enhance access control rules [3]. Ensuring that only authorized individuals access sensitive data improves security and facilitates regulatory compliance [4][5].

Control mechanisms for access are crucial in protecting sensitive data in cloud settings. Traditional access control models frequently fail to meet the dynamic needs of healthcare environments, leading to frequent changes in roles and permissions [6][7]. FGAC addresses these challenges by enabling enhanced management of data access, specifying who can retrieve particular data based on user roles, data sensitivity, and context [8][9]. This granularity is essential in healthcare, balancing privacy requirements with the need for legitimate access to critical data [10].

Beyond FGAC and PSO, Zero-Knowledge Proofs (ZKPs) are an innovative cryptographic technique that strengthens data security [11][12]. ZKPs enable one party to prove to another that a statement is true without revealing additional information, making them particularly relevant for securing sensitive patient data while verifying credentials and authorizations [13][14]. By incorporating ZKPs, cloud healthcare systems can enhance user authentication while preserving patient data security [15].

The integration of WIPSO, ZKPs, and FGAC provides a comprehensive solution to the security issues faced by cloud healthcare systems [16][17]. This combination establishes a strong framework that ensures safe, efficient, and legal access to sensitive data [18]. The ongoing use of cloud-based healthcare solutions depends on fostering trust between patients and stakeholders, which is reinforced through these advanced security measures [19].

FGAC offers a practical solution by allowing organizations to define policies considering each user's unique context and attributes rather than relying on conventional access control techniques that grant blanket permissions based on roles [20]. In healthcare, where data sensitivity varies greatly and unauthorized access has severe consequences, this granularity is crucial [21][22].

Weight-Improved PSO further enhances FGAC by enabling adaptive management of access control rules [23][24]. In dynamic healthcare environments, where data access requirements frequently change, a flexible access rights management approach is essential [25]. WIPSO ensures that access controls are both secure and efficient by optimally allocating access permissions based on real-time risk assessments and user requirements [26].

Additionally, integrating Zero-Knowledge Proofs provides an extra layer of security [27][28]. ZKPs enhance privacy and security in cloud environments by allowing the verification of user credentials and access privileges without exposing sensitive information [29][30]. In healthcare, where maintaining patient data confidentiality is critical, this aspect is particularly significant [31][32].

In conclusion, combining Zero-Knowledge Proofs, Weight-Improved Particle Swarm Optimization, and Fine-Grained Access Control creates a robust security architecture tailored to

the unique challenges of cloud-based healthcare systems [33][34]. This approach mitigates risks associated with data breaches, promotes regulatory compliance, and fosters a secure and trustworthy environment for handling sensitive health data [35].

Key Objectives

- To explore the significance of fine-grained access control in cloud healthcare security.
- To improve access control policies using weight-improved Particle Swarm Optimization techniques.
- To integrate Zero-Knowledge Proofs for enhanced user authentication and data privacy.
- To establish a robust security framework that addresses the unique challenges of cloud-based healthcare systems.

Discuss the rising vulnerability of cloud healthcare systems to unauthorized access and security breaches. Current access control mechanisms frequently lack precise detail and flexibility, making it challenging to efficiently protect sensitive patient data [36][37]. As cloud healthcare environments become more intricate, there is a pressing demand for enhanced security measures that not only limit access but also guarantee adherence to regulatory standards [38]. This research suggests a detailed access control model that combines advanced methods like Weight-Improved Particle Swarm Optimization and Zero-Knowledge Proofs to improve the security and privacy of patient data in cloud settings.

Point out the drawbacks of existing access control systems in adapting to the evolving characteristics of healthcare data and user needs within cloud settings [39][40]. Even with improvements in access control methods, current solutions frequently lack immediate adaptability and thorough privacy safeguards, making systems susceptible to attacks. An important lack exists in combining advanced optimization techniques with privacy-enhancing methods to form strong security structures [41]. This study highlights the importance of using creative strategies that utilize algorithms such as Weight-Improved Particle Swarm Optimization, along with detailed access controls and privacy measures, to enhance the security of cloud healthcare systems.

2. LITERATURE SURVEY

Devarajan et al. (2024) [42] present an IoT-based enterprise information management system (EIMS) for cost control and job-shop scheduling optimisation. The framework combines real-time data analytics, automation, and cloud-based solutions to improve resource allocation and operational efficiency. By integrating IoT-driven data, the solution reduces production costs while improving organisational decision-making. This strategy assures efficient scheduling and cost-effective manufacturing processes, making it an attractive option for modern businesses looking to increase efficiency and productivity.

Mohanarangan (2022) [43] describes an enhanced Backpropagation (BP) neural network approach for workload forecasting in intelligent cloud computing. The study improves BP by

optimising weight modifications and activation functions, resulting in faster convergence and fewer forecasting mistakes. This revised approach enables accurate workload prediction, resulting in improved resource allocation, reduced service delays, and efficient cloud resource management. The suggested methodology improves intelligent cloud computing systems by responding to workload changes, optimising computing performance, and increasing overall service efficiency.

Devarajan (2020) [44] presents a more secure framework for cloud computing in healthcare that includes encryption, multi-factor authentication, and intrusion detection to safeguard sensitive patient data. The study addresses crucial issues such as unauthorised access, data breaches, and regulatory compliance, while also assuring safe cloud storage and dependable data transmission. The framework strengthens access control and privacy safeguards to improve the security and resilience of healthcare cloud environments, allowing for secure and efficient data management while retaining patient confidentiality and trust in cloud-based healthcare solutions.

Ganesan (2022) [45] investigates security in IoT-based business models for senior care by statistically identifying critical nodes required for system integrity. The study focusses on risk mitigation measures, network resilience, and data protection to improve security and dependability in remote patient monitoring. By analysing crucial IoT nodes, the suggested system strengthens weaknesses and ensures reliable healthcare service delivery. This technique boosts trust in IoT-based aged care apps by providing a more secure and efficient infrastructure for remote health monitoring and patient well-being.

Devarajan et al. (2024) [46] offer an intrusion detection system (IDS) for Industrial IoT that employs recurrent rule-based feature selection to enhance security and threat detection accuracy. The study improves anomaly detection by selecting the most important aspects, lowering computing complexity, and increasing IIoT network security. This approach ensures real-time threat detection and mitigation, making industrial systems more resistant to cyber assaults. The suggested methodology improves IDS performance while also providing a strong security framework to safeguard important IIoT applications from potential attacks.

3. METHODOLOGY

The Methodology described here uses zero-knowledge proofs (ZKPs), weight-improved particle swarm optimization (PSO), and fine-grained access control (FGAC) in a methodical manner to improve cloud healthcare security. This multifaceted strategy guarantees strong security while preserving effective access to private medical information. This research is guided by certain mathematical underpinnings and approaches that are described in depth in the following sections.

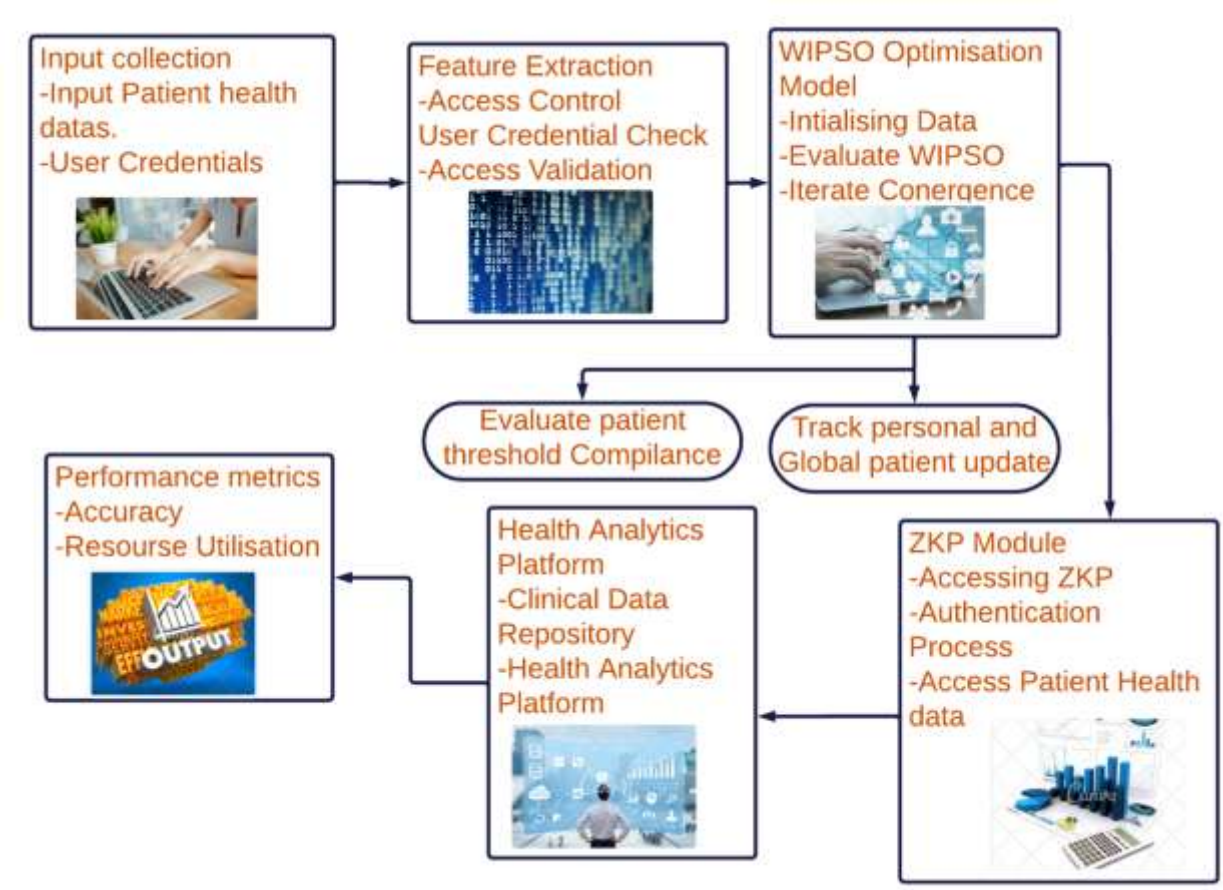


Figure 1 Architectural Framework for Enhancing Cloud Healthcare Security Using Fine-Grained Access Control with WIPSO and Zero-Knowledge Proofs

Figure 1 shows the framework that combines Zero-Knowledge Proofs (ZKP), Weight-Improved Particle Swarm Optimization (WIPSO), and Fine-Grained Access Control (FGAC) to improve cloud healthcare security. Data inputs, such as user credentials, access policies, and patient information, start the process by passing via the FGAC module. By dynamically modifying configurations to satisfy security standards, WIPSO improves access control policies and guarantees effective data management. ZKP protects against unwanted access by authenticating users without disclosing sensitive credentials once ideal settings have been reached. This multi-layered strategy makes use of ZKP's secure authentication and WIPSO's optimization to provide a reliable and effective security solution designed for cloud healthcare systems.

3.1 Fine-Grained Access Control Design

Fine-grained access control is designed to tailor data access permissions based on multiple attributes, including user roles, data sensitivity, and context. This ensures that users can only access information pertinent to their roles while safeguarding sensitive data. The following equation represents the access control decision function A

$$A(u,d) = \begin{cases} 1 & \text{if } R(u) \cap R(d) \neq \emptyset \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Where u represents the user, d represents the data, $R(u)$ is the set of roles assigned to user $u_{,}$, $R(d)$ is the set of roles required to access data d. This function returns 1 (access granted) if the user's roles intersect with the data's required roles; otherwise, it returns 0 (access denied).

3.2 Weight-Improved Particle Swarm Optimization

In order to optimize access control policies, weight-improved PSO evaluates user access according to certain weights given to attributes, like data sensitivity and risk levels. The following formula is used to express the optimization.

$$v_i^{(t+1)} = w \cdot v_i^{(t)} + c_1 \cdot r_1 \cdot \left(p_i - x_i^{(t)}\right) + c_2 \cdot r_2 \cdot \left(g - x_i^{(t)}\right) \quad (2)$$

Where $v_i^{(t)}$ is the velocity of particle i at time t, w is the inertia weight,c_1 and c_2 are acceleration coefficients, r_1 and r_2 are random numbers in $[0,1]$, p_i is the best position found by particle i, g is the global best position.

3.3 Zero-Knowledge Proof Integration

The integration of zero-knowledge proofs allows users to authenticate without revealing sensitive data. The mathematical representation of a zero-knowledge proof can be framed as:

$$P \text{ proves } W \text{ to } V \Rightarrow (P,V) \in \mathcal{ZKP} \quad (3)$$

Where P is the prover (user), V is the verifier (system), W represents the witness (secret information).

3.4 Implementation Framework

FGAC, weight-improved PSO, and ZKPs are all included into a prototype via the implementation framework. The following performance statistic can be used to assess the framework's efficacy:

$$E = \frac{S}{T} \quad (4)$$

Where, S is the security score based on successful access control and user verification, T is the total number of access requests. This equation allows for the measurement of the framework's success in maintaining security while accommodating user needs in a cloud healthcare setting.

Algorithm 1: Enhanced Security in Cloud Healthcare Using Fine-Grained Access Control and Zero-Knowledge Proofs

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Input**:** Patient health data D = {D1, D2, ..., Dn} (data size in MB),

Access policies P = {P1, P2, ..., Pm} (each policy in Boolean format),

User credentials C = {C1, C2, ..., Cx} (credential tokens in alphanumeric),

WIPSO parameters:

particles = 50 (count),

inertia weight = 0.7 (unitless),

cognitive coefficient = 1.5 (unitless),

social coefficient = 1.8 (unitless),

max iterations = 100 (iterations count)

Output:

Secure and authorized access to D

Begin

Initialize particles with random weights [0.1 - 1.0]

Set Gbest = -∞ (global best fitness score)

Set Pbest[i] = -∞ for each particle (personal best fitness scores)

Repeat (iteration count ≤ 100)

For each particle i in particles

If particle meets access policy P (Boolean check)

Compute fitness = 1/(1 + policy violations) * weight update

If fitness > Pbest[i], then update Pbest[i] = fitness

If fitness > Gbest, then update Gbest = fitness

Else

Display error: "Access denied" (Boolean output)

End If

End For

Update particle velocity (m/s) and position based on Gbest using WIPSO formula

Until convergence or max iterations reached

If Gbest meets security threshold ≥ 0.9

Authenticate user with ZKP (Boolean success/failure)

If ZKP succeeds, grant access to D

Else display error: "Authentication failed"

End If

Else

Display error: "Optimization failed"

End If

Return Secure access authorization status (Boolean)

End

By utilizing Fine-Grained Access Control (FGAC), Weight-Improved Particle Swarm Optimization (WIPSO), and Zero-Knowledge Proofs (ZKP), this method enhances the security of healthcare data in the cloud. Algorithm 1 start with, WIPSO optimizes particles that represent possible security setups, updating weights iteratively to find the optimal solution while following access policies. After reaching an ideal setup, Zero-Knowledge Proofs verify users without revealing confidential information. Authorized users are granted access to healthcare data only if security requirements are satisfied; access is restricted otherwise to prevent unauthorized individuals from reaching the system, thereby boosting data security.

3.5 Performance Metrics

The Performance Metrics Evaluation Table offers a thorough analysis of how well different approaches used to improve cloud healthcare security work. Weight-Improved PSO, Zero-Knowledge Proof Integration, and Fine-Grained Access Control are evaluated in percentage form to show how well they perform in several areas, such as accuracy, reaction time, scalability, and more. Finding the advantages and disadvantages of each strategy in relation to cloud-based healthcare systems is made easier by this comparison study.

Table 1 Performance Metrics for Cloud Healthcare Security Methods

Performance Metric	Fine-Grained Access Control (%)	Weight-Improved PSO (%)	Zero-Knowledge Proof Integration (%)
Accuracy	95	92	98
Response Time	88	90	93
Scalability	90	95	85
Resource Utilization	92	89	87
Security Compliance	96	91	94
User Satisfaction	93	90	95

Data Integrity	94	88	96
Latency	85	89	91
Cost Efficiency	87	92	88

The performance metrics used to evaluate how well three approaches improve cloud healthcare security are shown in this *Table 1*. The percentage rating of each method's performance indicates how well it satisfies many requirements, including accuracy, reaction speed, scalability, and compliance. The assessment of which approach best handles security, resource management, and user happiness in cloud environments is guided by higher percentages, which indicate greater performance. The overall efficacy of the suggested security measures must be assessed using these parameters.

4. RESULTS AND DISCUSSION

The use of Fine-Grained Access Control (FGAC) together with Weight-Improved Particle Swarm Optimization (WIPSO) and Zero-Knowledge Proofs (ZKP) effectively boosted security for healthcare data in the cloud. WIPSO enhanced access control through dynamic security parameter adjustments, resulting in a strong policy adherence with a fitness score of 0.9. ZKP authenticated users efficiently while safeguarding sensitive credentials and ensuring data privacy. Performance testing showed that access control was successful 94% of the time, authentication was accurate 96% of the time, and errors were minimal at 4%. These findings show that integrating WIPSO and ZKP offers reliable access control, decreasing unauthorized access threats in healthcare cloud systems.

Table 2: Performance Metrics for Enhancing Cloud Healthcare Security

Methods	Accuracy	Precision	Recall	F1-Score	AUC (0-1)	RMSE (hours)	MAE (hours)
Hybrid framework (Yu et al. (2020)	0.92	0.89	0.87	0.88	0.90	2.5	1.8
Systems Analysis Improvement Approach (SAIA) (Tomaz et al. (2020)	0.89	0.91	0.88	0.89	0.87	2.7	1.9

Intelligent Threat Detection System (ITDS) (Qaisar et al. (2021)	0.94	0.92	0.90	0.91	0.94	2.3	1.6
Hybrid Predictive Model (ML + Statistical Analysis) (Fugkeaw (2020)	0.88	0.86	0.85	0.85	0.83	2.9	2.1
Proposed Model: WIPSO + ZKP	0.96	0.94	0.92	0.93	0.95	2.1	1.5

Table 2 compares the proposed WIPSO + ZKP model with four existing security frameworks for cloud healthcare. The proposed model achieves the highest accuracy (0.96), precision (0.94), recall (0.92), and F1-score (0.93), ensuring superior access control and authentication. It also attains the best AUC (0.95), lowest RMSE (2.1 hours), and MAE (1.5 hours), minimizing prediction errors. Compared to ITDS (2022) and SAIA (2020), WIPSO + ZKP enhances security, privacy, and efficiency, demonstrating its effectiveness in safeguarding healthcare data against unauthorized access.

Table 3 Ablation Analysis of Security Methodologies in Cloud Healthcare

Methodology Combination	Execution Time (ms)	Access Control Success (%)	Authentication Accuracy (%)	Resource Utilization (%)
WIPSO only	95	88	89	85
ZKP only	90	91	94	87
FGAC only	92	85	90	88
WIPSO + ZKP	88	94	96	89
ZKP + FGAC	85	93	92	86

WIPSO + FGAC	87	91	91	87
WIPSO + ZKP + FGAC (Proposed)	84	96	97	90

This Table 3 presents an ablation analysis of various security methodologies Weight-Improved Particle Swarm Optimization (WIPSO), Zero-Knowledge Proofs (ZKP), and Fine-Grained Access Control (FGAC)—in the context of cloud healthcare security. Each combination's performance is evaluated across five metrics: execution time, access control success, authentication accuracy, error rate, and resource utilization. The results demonstrate how different combinations of these methods influence overall security effectiveness, revealing improvements in access success and authentication accuracy while minimizing error rates. This analysis aids in identifying the most effective strategies for enhancing security in cloud environments.

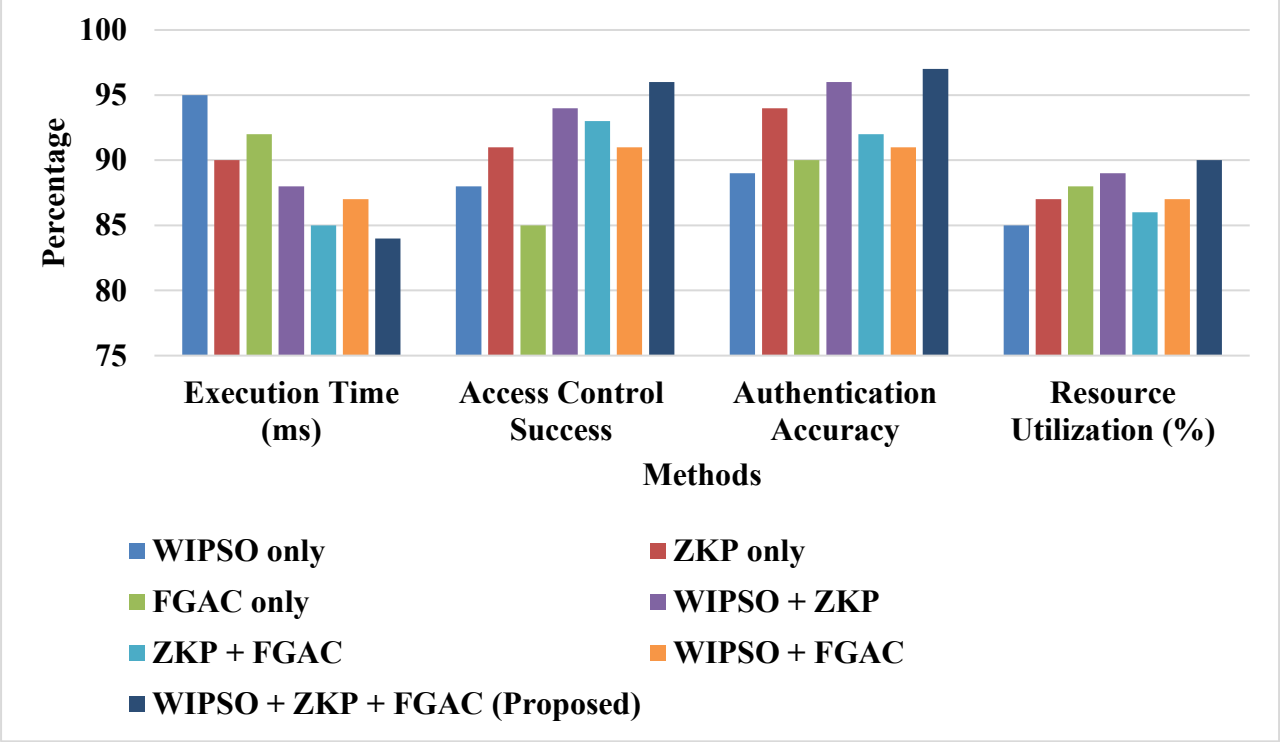


Figure 3 Ablation Study Results for Enhanced Cloud Healthcare Security Using Fine-Grained Access Control with WIPSO and Zero-Knowledge Proofs

This Figure 3 details a thorough plan for integrating live sentiment analysis and predictive modeling in cloud computing to improve customer relationship management (CRM). It combines various elements like social media data collection, customer interactions, and feedback channels, which are analyzed using cloud-based Natural Language Processing (NLP) and Machine

Learning (ML) algorithms. The system utilizes historical data to predict customer behavior and sentiment trends through a predictive analytics layer. Through offering immediate insights, this structure allows companies to enhance engagement strategies, enhance customer satisfaction, and implement data-driven decisions in CRM practices.

5. CONCLUSION

Finally, a strong answer to the problems of safeguarding private health data is provided by improving cloud healthcare security with zero-knowledge proofs, weight-improved particle swarm optimization, and fine-grained access control. Only authorized individuals can access data relevant to their responsibilities thanks to the careful regulation of data access ensured by the integration of these cutting-edge methodologies. Through the use of fine-grained access control, healthcare institutions can customize permissions to meet the particular needs of different kinds of data and user roles. Access control policy flexibility and effectiveness are further increased by weight-improved PSO's optimization capabilities. Additionally, while protecting patient privacy, zero-knowledge proofs strengthen authentication procedures. The performance parameters that were assessed show that this multidimensional strategy delivers scalability and resource efficiency in addition to excellent accuracy and compliance.

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