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ARTICLE

Blockchain-Based Electronic Health Passport for Secure Storage and Sharing of Healthcare Data

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ABSTRACT: The growing demand for international travel has highlighted the critical need for reliable tools to verify travelers' healthcare status and meet entry requirements. Personal health passports, while essential, face significant challenges related to data silos, privacy protection, and forgery risks in global sharing. To address these issues, this study proposes a blockchain-based solution designed for the secure storage, sharing, and verification of personal health passports. This innovative approach combines on-chain and off-chain storage, leveraging searchable encryption to enhance data security and optimize blockchain storage efficiency. By reducing the storage burden on the blockchain, the system ensures both the secure handling and reliable sharing of sensitive personal health data. An optimized consensus mechanism streamlines the process into two stages, minimizing communication complexity among nodes and significantly improving the throughput of the blockchain system. Additionally, the introduction of advanced aggregate signature technology accommodates multi-user scenarios, reducing computational overhead for signature verification and enabling swift identification of malicious forgers. Comprehensive security analyses validate the system's robustness and reliability. Simulation results demonstrate notable performance improvements over existing solutions, with reductions in computational overhead of up to 49.89% and communication overhead of up to 25.81% in multi-user scenarios. Furthermore, the optimized consensus mechanism shows substantial efficiency gains across varying node configurations. This solution represents a significant step toward addressing the pressing challenges of health passport management in a secure, scalable, and efficient manner.

KEYWORDS: Blockchain; healthcare and machine learning; healthcare device data; health passport; computational overhead; signature verification

1 Introduction

With the continuous development of society, the demand for international travel, academic exchanges, and medical tourism has increased significantly. However, inconsistencies in healthcare regulations across countries have led to challenges in verifying travelers' health status. In recent years, fraudulent health passports [1] and medical data breaches have emerged as serious threats to public health and data privacy. For example, in 2021, Europol reported the dismantling of multiple fraudulent COVID-19 vaccine passport networks operating across Europe, where counterfeit certificates were sold on the black market to bypass travel restrictions. Similarly, in 2022, a massive healthcare data breach in the United States exposed sensitive patient records, affecting over 10 million individuals. These incidents highlight the vulnerabilities in current digital health documentation and the risks associated with central storage architectures, which are susceptible to cyberattacks and unauthorized data access [2]. Traditional paper-based health passports are prone to forgery, and digital records suffer from data silos and privacy issues. To address these challenges, we propose a blockchain-based health passport system integrating on-chain and off-chain storage, searchable encryption, and an optimized consensus mechanism for enhanced security, privacy, and efficiency.

However, there are huge differences in disease prevention measures and requirements in different countries and regions, resulting in differences in entry and exit health standards. In this context, many countries and regions have formulated strict Healthcare and machine learning policies to ensure public health and safety [3,4]. In this context, personal health passports have become a powerful tool that can be used to confirm the health status of travelers and meet the health entry requirements of different countries and regions. Personal health passports can contain Healthcare and machine learning information and vaccination records for effective management and monitoring of Healthcare and machine learning [5]. Traditional paper health passports can be traced back to the "health pass" issued during the European plague pandemic in the 15th century, which was intended to exempt travellers from quarantine measures. However, traditional paper health passports have the hidden danger of being easily forged and tampered with, leading to problems of insecurity and credibility. Especially in the digital age, the mobility and vulnerability of information further exacerbate these problems. In this context, some countries and international organizations have successively launched electronic health passports or health passports to allow work and travel abroad without compromising personal or Healthcare and machine learning. With the introduction of electronic health passports, the privacy leakage of personal information has become increasingly prominent. Traditional central storage architectures often Healthcare device data on third-party platforms. Once the third party is hacked or colluded with malicious attackers, the privacy and security of users will be difficult to guarantee [6]. Therefore, the protection of Healthcare device data and the management of privacy risks have become urgent issues to be addressed. At the same time, the Healthcare device data of various medical institutions and even countries are not interoperable, resulting in the formation of "information islands", which greatly limits the sharing of health passports around the world. Blockchain technology has been introduced into the field of smart medical care [7–9] by many scholars due to its inherent advantages such as difficulty in tampering, transparency and decentralization, bringing new possibilities for the management and verification of health passports [10]. However, the contradiction between the low throughput and efficiency of traditional blockchains and the high efficiency required by the actual application scenarios of health passports has not been resolved. Secondly, although searchable encryption technology allows users to Healthcare device data and upload it to the cloud server and retrieve ciphertext [11], users often use resource-constrained mobile devices, which cannot meet the large cryptographic computing burden brought by existing solutions. While cloud-based systems are widely used for health data storage, they rely on centralized architectures, making them vulnerable to single points of failure, unauthorized access, and large-scale data breaches. Additionally, centralized models struggle with interoperability, limiting seamless data exchange across healthcare institutions. In contrast, blockchain offers tamper-proof records through cryptographic hashing, decentralized control to eliminate reliance on third parties, and transparent yet privacy-preserving verification via smart contracts. Unlike cloud systems, blockchain ensures data integrity, where modifications are impossible without consensus, significantly reducing forgery risks in health passports. To address these difficulties, this article suggests a system for storing, sharing, and verifying personal health passports that is based on the blockchain. The main contributions of this work are as follows:

1. Hybrid On-Chain and Off-Chain Storage Optimization: The proposed approach integrates searchable encryption with a hybrid storage model, where only the index is stored on the blockchain while encrypted healthcare data is securely managed in the Interplanetary File System (IPFS). This

reduces on-chain storage overhead, enhances query efficiency, and enables scalable and privacy-preserving healthcare data management, addressing the limitations of conventional blockchain-based healthcare systems.

2. Efficient Multi-User Authentication via Optimized Aggregate Signatures: To support scalable and secure multi-user verification, the system employs an enhanced aggregate signature scheme, which reduces computational overhead for signature verification. Additionally, our approach introduces a rapid tracing mechanism for detecting malicious forgers, significantly improving security and fraud detection in healthcare data verification.
3. High-Throughput Two-Stage Weak Consensus Mechanism: The study optimizes the weak consensus algorithm to improve blockchain throughput and scalability. Unlike traditional PBFT-based consensus methods, our two-stage process significantly reduces communication complexity while maintaining strong security guarantees, making it more suitable for real-time healthcare applications.
4. Comprehensive Security and Performance Evaluation: The proposed system undergoes rigorous security validation, ensuring confidentiality, integrity, and resistance to forgery attacks. Extensive performance comparisons demonstrate up to a 49.89% reduction in computational overhead and a 25.81% decrease in communication costs, showcasing superior efficiency and robustness over existing blockchain-based healthcare frameworks.

The structure of this paper is as follows: Section 2 discusses review of existing research, highlighting strengths, identifying gaps. Section 3 represents essential concepts and theories needed to understand the proposed research. Section 4 describes the system architecture, components, and their interactions. Section 5 discloses the detailed design and implementation strategies of the proposed solution. In Section 6, evaluation of system security against vulnerabilities and potential threats is mentioned. Section 7 introduces the assessment of system performance using metrics and comparative results. Finally, Section 8 concludes with findings, research contributions, and future work suggestions.

2 Related Work

As a decentralized database [12], blockchain technology has been widely used in Healthcare and machine learning, financial services, and supply chain management [13]. In response to the sharing and verification of personal health passports, scholars have proposed many blockchain-based solutions. Demirbaga et al. [14] implement the Healthcare and Internet of Things (IoT) enable Healthcare device data management application GreenPass based on blockchain technology. Although the applications of Healthcare and machine learning status survey function was mentioned, its system model and detailed solution details were not introduced in depth. Jafari et al. [15] proposed a government-managed blockchain to store COVID-19 vaccination certificates, emphasizing the use of biometric authentication to enhance user anonymity and privacy protection. Ait Bennacer et al. [1] proposed a digital health passport based on a private chain, which contains antibody test results and timestamps, but private chains are not suitable for international entry and exit scenarios. Zarour et al. [16] proposed a solution VacciFi takes into account the general Healthcare device data protection regulation (GDPR), and the architecture is scalable. At the same time, the solution is committed to using a permissioned blockchain to ensure the availability, traceability, and integrity of Healthcare and machine learning information, but the solution fails to deal well with internal attacks. Guerar et al. [17] proposed a global architecture that uses blockchain to verify and distribute different health passports. Rajtar et al. [18] proposed an online passport system to report citizens' Healthcare and machine learning status. The scheme uses the user's biometric information (such as iris scan) to uniquely identify each user, while the blockchain stores the user's Healthcare and machine learning information such as historical medical records. A blockchain-based system for storing and exchanging immunization records was developed in this study [19]. Data traceability is ensured by storing the immunization records on the blockchain. Another benefit of mutual authentication is that it ensures the Healthcare device data's integrity and non-repudiation [20]. Consensus algorithms are an important component of blockchain systems and affect the overall operating efficiency of blockchain systems [21]. Among the most popular consensus algorithms currently in use are the Byzantine fault tolerance (BFT) protocol [22], proof of collateral [23], proof of assets [24], and proof of work [25]. When it comes to consortium chains, most consensus algorithms employ practical byzantine fault tolerance (PBFT) [21] consensus. Nevertheless, the network and the amount of time it takes for a message to reach agreement in the entire system are external elements that are bound to impact PBFT, being a strong consistency consensus mechanism. Consequently, wait times for individual nodes in a P2P network to reach consensus are similarly lengthened. Obviously, the global health passport information chain must have extremely high requirements for the throughput of the blockchain, which is difficult to meet with the traditional PBFT consensus mechanism. Therefore, it is very important to choose a consensus mechanism that is suitable for the current solution. Zhou et al. [26] proposed a weak consistency BFT consensus method by weakening the requirement for strong consistency in the consensus process. This method is based on an asynchronous BFT algorithm and only guarantees the relative position of the messages received and agreed upon by each node, without requiring the message order of each node to be completely consistent, thereby achieving consistency of the entire system, which also greatly improves the throughput of the entire blockchain. This solution improves the weak consistency BFT consensus method and further improves the efficiency. In summary, although scholars have proposed solutions to the sharing and verification problems of health passports, the existing solutions store a large amount of Healthcare device data in the blockchain, which increases the burden on blockchain nodes and reduces the efficiency of the overall solution. Especially in multi-user scenarios, frequent verification operations will further increase the time cost of the solution [27]. At the same time, for scenarios such as health passports that require frequent updates and verification of information, the existing solutions fail to fully consider the low throughput of traditional blockchains and cannot handle many user requests in a short period of time, thus affecting the real-time and accuracy of Healthcare and machine learning information. Therefore, there is an urgent need to seek a more efficient and sustainable method to improve the efficiency of the solution while ensuring security, and it should be able to take into account multiple dimensions such as confidentiality, integrity and multi-user scenarios. In order to more intuitively show the difference between our scheme and traditional schemes, our scheme is compared with some representative schemes [18] from multiple dimensions.

3 Preliminary Knowledge

3.1 Bilinear Mapping

Suppose that G_1 and G_2 are two prime-order multiplicative cyclic groups, with g being the generator of G_1. Then, G_2 is a bilinear map $e : G_1 \times G_1 \rightarrow G_2$, and it possesses the three attributes listed below [28,29].

1. Bilinearity: for all $u, v \in G_1$ and $a, b \in Z_p$, $e\left(u^a, v^b\right) = e(u, v)^{ab}$.
2. Non-degeneracy: $e(u, v) \neq 1$.
3. Computability: for all $u, v \in G_1$ can be efficiently computed.

If bilinear maps and group operations in G_1 are efficiently computable, then G_2 is said to be a bilinear group. It is worth noting that the mapping e is symmetric, that is, $e\left(g^a, g^b\right) = e(g, g)^{ab} = e\left(g^b, g^a\right)$.

3.2 Computing the Diffie-Hellman Problem

Given $P, xp, yp \in G$, and $x, y \in Z_q^*$, there is no feasible algorithm that can calculate xyp through P, x, y, that is, there is no algorithm that can complete the calculation task within an achievable time complexity [30].

3.3 Determine the Diffie-Hellman Problem

Given $P, xp, yp, Z \in G$, and $x, y \in Z_q^*$, there is no feasible algorithm that can determine whether the equation $Z = xyP(\text{mod p})$ is true through P, xp, yp and Z, that is, it is impossible to find an algorithm that can complete the calculation task within the achievable time complexity [31].

4 System Model

This section first focuses on the system model and entity functions, and then gives the threat model established in this paper and the security goals of the model.

4.1 System Model and Entity Functions

The solution model of this paper is shown in Fig. 1. It is assumed that each medical institution in each country acts as a consortium chain node and cooperates to maintain a consortium chain. The scheme includes six entities: users, medical institutions, IPFS, consortium chain, customs, and key generation center (KGC). Here is the key process of the interaction: The system initialization is the first thing that KGC finishes and distributes the public and private key pairs of each entity; then, the medical institution generates a health passport for the user; finally, the health passport ciphertext is uploaded to IPFS, and the keyword index and signature are uploaded to the consortium chain as a transaction. When the user needs to visit the doctor again or go abroad, the user generates a query trapdoor and initiates a request to the consortium chain. The consortium chain returns the document storage identifier to IPFS or provides the verification result to the customs, thereby completing the passport update and verification operation.

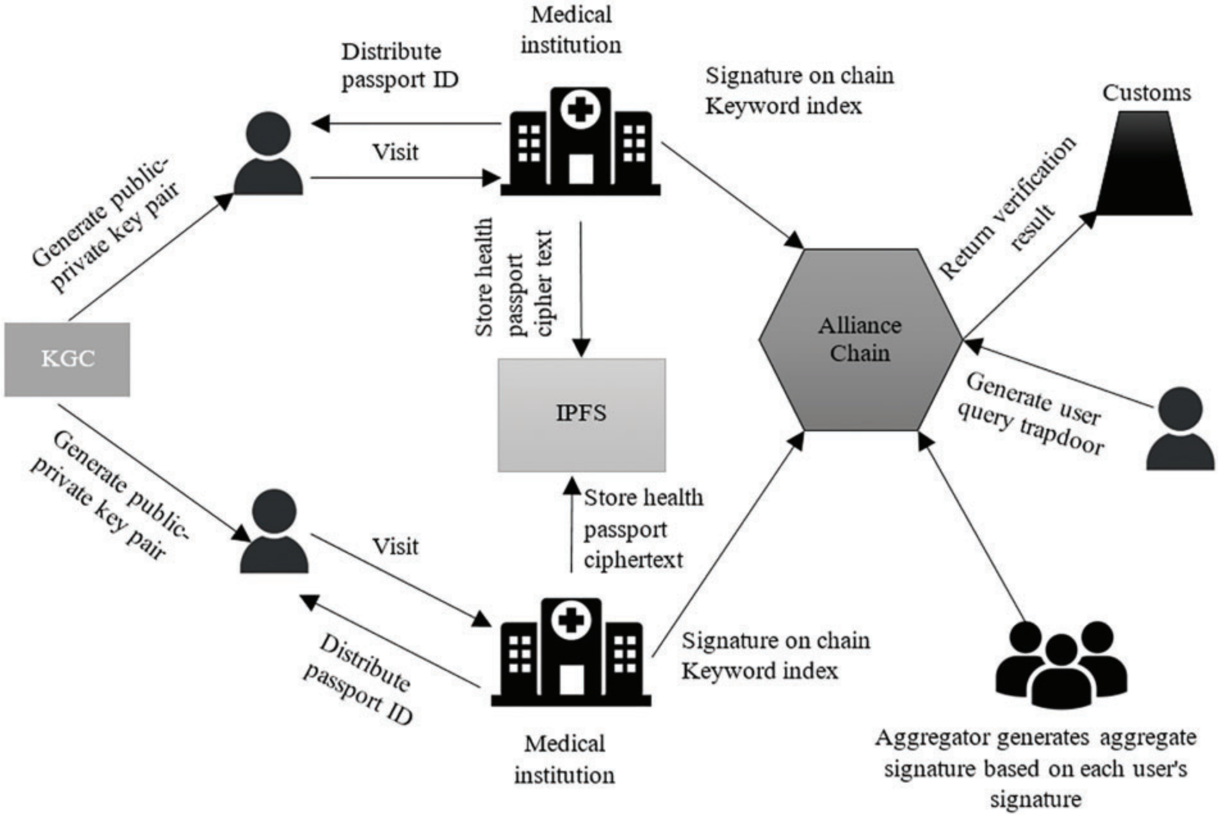

Medical institution
Distribute passport ID
Visit
Signature on chain
Keyword index
Customs
Generate public-private key pair
Store health passport cipher text
Return verification result
KGC
Alliance Chain
IPFS
Generate user query trapdoor
Generate public-private key pair
Store health passport ciphertext
Visit
Distribute passport ID
Signature on chain
Keyword index
Medical institution
Aggregator generates aggregate signature based on each user's signature

Figure 1: System model

1. **User:** The user registers a personal health passport to go to a medical institution for treatment or go abroad for customs inspection. At the same time, multiple users can form a travel group or academic exchange group to complete multi-user verification during the inspection.
2. **Medical institution:** Generate or update a personal health passport after providing medical services to the user, and encrypt the Healthcare device data and store it in IPFS. Finally, generate a keyword index for the passport and upload it to the consortium chain as a transaction.
3. **IPFS:** IPFS is a decentralized file storage network used to store the encrypted Healthcare device data of personal health passports generated by medical institutions.
4. **Alliance chain:** Each country selects medical institution representatives to form alliance chain nodes to jointly complete the release and consensus of transactions. Furthermore, it is the responsibility of the alliance chain to return the result of the passport verification process to customs or to query the ciphertext storage index using the user-generated trapdoor.
5. **Customs:** Customs staff need to obtain the verification results of the alliance chain on the user's passport.
6. **KGC:** In charge of creating all entities' partial private keys and system settings.

4.2 Threat Model

The threat model established in this paper is as follows.

1. The alliance chain node may send invalid search results to the user after receiving a search request to save computational resources.
2. The IPFS storage network is forthright and inquisitive. Although it can faithfully carry out the user's commands, it will use data like keyword indexes supplied by the user to make assumptions.

4.3 Security Goal

Assuming that all blockchain nodes and customs inspectors are semi-honest parties, attackers may eavesdrop on communications between users and other entities. Based on this assumption, this paper proposes the following security goals.

1. **Confidentiality:** Health passport data contains users' personal privacy information, and there may be a risk of leakage during sharing. Therefore, ensuring the confidentiality of health passport of Healthcare device data becomes one of the goals of this scheme.
2. **Traceability and non-repudiation:** In order to resolve disputes between doctors and patients and possible liability issues after medical treatment, the scheme should be able to effectively prevent malicious attackers from tampering with health passport data records. Therefore, the scheme is required to have traceability (non-repudiation after tracing) and the characteristics of being difficult to tamper with.
3. **Non-forgeability:** When customs conduct epidemic prevention inspections, malicious attackers may forge the health passports of legitimate users to deceive inspectors. Therefore, the scheme is required to prevent attackers from forging health passports.

5 Solution Design

In order to solve the privacy leakage problem faced by the current health passport in the process of sharing and verification, as well as the problem that the blockchain throughput is low and cannot match the real-time performance of smart medical care, this section gives a specific solution design. The solution considers the multi-user scenario where users travel in groups, and divides the solution into two scenarios: single user and multi-user. The solution mainly includes four stages: system initialization, health passport encryption and storage, health passport update, and health passport verification. The symbols are shown in Table 1.

Table 1: Explanation of symbols

Parameter	Meaning
SK	Master key
CP	Public parameters
(pk_i, sk_i)	User public and private key pair
$passport_i$	Personal health passport
c_{P_i}	Health passport ciphertext
δ_i	User signature
$PUID_i$	Health passport number
I_k	Keyword index
$index_f$	Ciphertext retrieval identifier
T_c	Transaction
SToken	Search trapdoor
δ	Aggregate signature
index	Block sequence number
OID	Block node number
M	Packaged transaction
D	Message summary
NID	Node Identifier

5.1 System Initialization

In this stage, the key generation center generates system parameters and public and private key pairs of each entity.

5.1.1 System Establishment

Input security parameter λ, the Key Generation Center (KGC) selects two multiplicative cyclic groups G_1 and G_2 of order p, defines bilinear map $e : G_1 \times G_1 \rightarrow G_2$, where the generator of G_1 is g. Randomly select $s \in \mathbb{Z}_p^*$, set the master key $SK = s$, and calculate:

$$P_{\text{pub}} = g^s. \tag{1}$$

Select six collision-resistant hash functions $H_0 : \{0,1\}^* \times G_1 \rightarrow \mathbb{Z}_p^*$, $H_1 : \{0,1\}^* \times G_1^2 \rightarrow \mathbb{Z}_p^*$, $H_2 : \{0,1\}^* \rightarrow \mathbb{Z}_p^*$, $H_3 : \{0,1\} \rightarrow G_1, H_4 : G_2 \rightarrow \{0,1\}$, $H_5 : G_2^2 \times \{0,1\}^* \rightarrow \{0,1\}^n$, and publish the public parameter CP as follows:

$$CP = \{p, g, e, SK, P_{\text{pub}}, H_0, H_1, H_2, H_3, H_4, H_5\}. \tag{2}$$

5.1.2 Generate Partial Keys

Based on the master keySK and user identity $ID \in \{0,1\}^*$, KGC randomly selects $r_i \in \mathbb{Z}_p^*$, and calculates:

$$R_i = g^{r_i}, \quad k_i = H_0(ID_i \parallel R_i), \quad d_i = g^{r_i + k_i}. \tag{3}$$

KGC sends the partial private key $D_i = (R_i, d_i)$ to user i through a secure channel.

5.1.3 Generate a Complete Public-Private Key Pair

User i randomly selects $x_i \in \mathbb{Z}_p^*$, and calculates:

$$X_i = g^{x_i}. \tag{4}$$

Generate a complete public key $pk_i = (R_i, X_i)$ and a private key $sk_i = (x_i, d_i)$.

5.1.4 Other Entities in the System

Other entities in the system generate their own public-private key pairs according to the above steps. The public-private key pairs of hospital h and alliance chain node C are represented as:

$$pk_h = (R_h, X_h), \quad sk_h = (x_h, d_h), \tag{5}$$

$$pk_c = (R_c, X_c), \quad sk_c = (x_c, d_c). \tag{6}$$

5.2 Health Passport Encryption and Storage

After the user's first visit, the medical institution generates a health passport for the user and stores the passport ciphertext of Healthcare device data on IPFS. Then, the relevant keyword index, user signature, and ciphertext retrieval identifier are uploaded to the alliance chain as a transaction. The alliance chain node is responsible for packaging these transactions and executing the improved weak consensus mechanism to ensure that the transaction is successfully recorded on the chain.

1. **User Visit:** After user i visits hospital h, hospital h generates a health passport for user i, including the user's personal information, health passport number $PUID_i$ and visit information. The visit information includes the visit time, visit location, and personal medical records.
2. **Passport Encryption:** Hospital h randomly selects a secret value $\theta_i \in \mathbb{Z}_p^*$, calculates:

   $$A_i = X_i^{\theta_i}, \quad e(g^{\theta_i}, H_3(PUID_i)) = B_i, \tag{7}$$

   where $B_i = k \cdot$ passport, and the ciphertext of the health passport is:

   $$C_{P_i} = (A_i, B_i). \tag{8}$$

3. **Passport Storage:** The passport ciphertext C_{P_i} is uploaded to IPFS, and the corresponding ciphertext retrieval identifier $index$ is returned.
4. **Passport Signature:** The user randomly selects $u_i \in \mathbb{Z}_p^*$, and calculates the private key (x_i, d_i) of user i. The user signature $\delta_i = (U_i, V_i)$ is computed as the signature of user i on the passport.
5. **Transaction Upload:** Hospital h uses the health passport number $PUID_i$ to generate the keyword index $I_k = H_5(e(H_3(PUID_i), g) \parallel PUID_i)$, combines the signature δ_i and the ciphertext retrieval identifier index, and constructs the transaction:

   $$T_c = \{\delta_i, I_k, index_f. \tag{9}$$

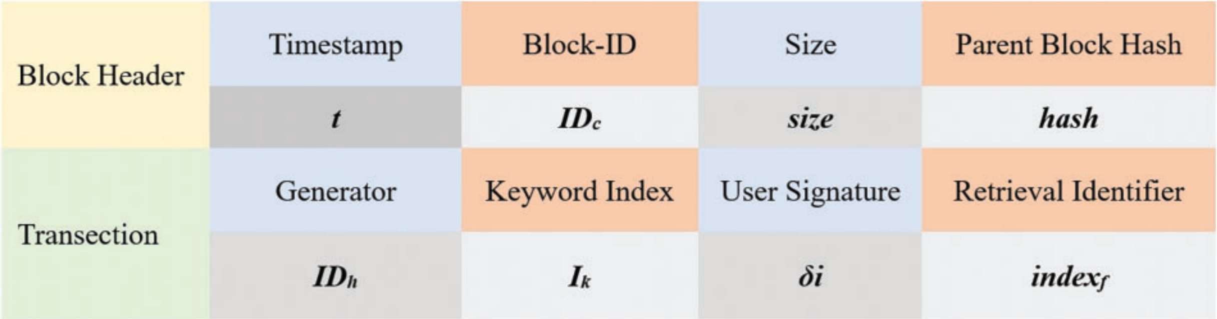
   Finally, the hospital uploads the transaction T_c to the consortium chain. The transaction structure is shown in Fig. 2.
6. **Alliance Chain Consensus:** The alliance chain nodes receive the transaction T_c uploaded by the hospital, reach consensus on it through the improved weak consensus mechanism, and package it on the chain. The specific scheme of the improved consensus mechanism is as follows:

(a) Transaction T_c is submitted to the alliance chain and broadcast in the P2P network composed of each hospital node.

(b) When a node A receives the transaction T_c sent by the client, the node first verifies the signature and integrity of T_c, and then stores the transaction in the local transaction pool. When the number of transactions to be stored reaches the preset interval, the node packages the transaction and writes it into a new block, generating a prepare message $\langle \text{Prepare}, \text{index}, \text{OID}, M, D, \text{proof} \rangle$ for the new block, and broadcasts the `Prepare` message to the P2P network. Among them, index is the ordered sequence number of the block generated by the current node, OID is the node number that generates this block, M is the packaged transaction, D is the message digest, and Proof is the proof that node A has inserted the block into the local chain.

(c) Assume that another random node B receives the `Prepare` message from node A that generated this message. The node will check that the `Prepare` message is authentic and signed. Once the validation is approved, a `commit` message $\langle \text{Commit}, \text{index}, D, \text{OID}, \text{NID} \rangle$ is generated. Only the summary D of the message is broadcast, and NID is the node that communicated with the P2P network by sending a `Commit` message.

(d) When node B receives $2f + 1$ messages sent by other nodes, it indicates that the transaction has reached a consensus within the consensus node and can be put on the chain. In addition to adding the latest block to its local chain, the node verifies that the index of blocks and the block numbers generated by other nodes are incremented in order to achieve relative consistency between the blocks generated by each node.



Block Header	Timestamp	Block-ID	Size	Parent Block Hash
	t	***ID_c***	***size***	***hash***
Transection	Generator	Keyword Index	User Signature	Retrieval Identifier
	ID_h	***I_k***	***δi***	***index_f***

Figure 2: Transaction structure

5.3 Update of Health Passport

When users visit the doctor again, they need to obtain passport data, which is updated and stored by the medical institution. The steps are as follows:

1. **Generate Trapdoor:** User i randomly selects the secret value $l_i \in \mathbb{Z}_p^*$, and (τ_1, τ_2) as the query trapdoor. User i submits $SToken$ to the alliance chain node and initiates a search request.
2. **Data Retrieval:** After receiving the request, the alliance chain node C verifies whether the conditions $I_K - H_5\left(e\left(\frac{\tau_1}{\tau_2^{x_c}}, X_i\right) \parallel PUID_i\right)$ holds. The node extracts the index f in the corresponding transaction, searches for the ciphertext C_{P_r} from IPFS, and returns it to the user.
3. **Decryption and Verification:** The user calculates the Healthcare and machine learning document data as:

$$passport_i = \frac{B_i}{e(A_i, H_3(PUID_i))^{\frac{1}{x_i}}}. \tag{10}$$

4. **Medical Treatment and Update:** After the medical institution provides medical services, it updates the user's health passport of Healthcare device data and stores it back on the chain.

5.4 Verification of Health Passport

5.4.1 Single User Verification

To address the higher computational overhead in single-user scenarios, we propose optimizations to enhance efficiency while maintaining security.

1. **Generate a Trapdoor:** The user generates a query trapdoor based on the health passport number *PUID* and initiates a request to the alliance chain to retrieve the user's signature.
2. **Obtain Signature:** Upon receiving the request, the alliance chain node verifies the keyword index *IK* in the transaction T_c using:

   $$IK = H_5\left(e\left(\frac{\tau_1}{\tau_2^{x_c}}, X_i\right) \parallel PUID_i\right) \tag{11}$$

   If valid, the node retrieves and returns the corresponding user signature δ_i.
3. **Optimize Signature Verification:** Instead of performing full bilinear pairing operations, which are computationally expensive, we optimize single-user verification by:
   - **Precomputing Pairing Results:** Frequently used cryptographic values are cached to reduce redundant computations.
   - **Lightweight Hash-Based Authentication:** Combining a lightweight hash function with elliptic curve signatures to minimize verification overhead.
   - **Hybrid Storage Strategy:** Leveraging off-chain verification for certain non-critical attributes while keeping essential verification on-chain to reduce transaction load.
4. **Verify Signature:** The alliance chain node calls the verification smart contract and computes:

   $$H_2(e(V_i, g)) = H_2\left(e\left(R_i \cdot P_{pub}^{k_i} \cdot X_i^{k_i}, g\right) \cdot e\left(U_i^{k_i}, g\right)\right) \tag{12}$$

   If the condition holds, the user's passport status is validated and returned to the customs staff.

While hybrid on-chain and off-chain storage has been explored in previous studies, our approach introduces key optimizations that enhance efficiency and security. Unlike conventional models that rely on basic off-chain storage, we integrate searchable encryption with IPFS, ensuring that only encrypted data is stored off-chain while a lightweight index remains on-chain for efficient retrieval. This design reduces on-chain storage overhead, minimizes blockchain transaction costs, and accelerates query response times. Additionally, our approach optimizes multi-user verification and retrieval, as demonstrated in our experimental results, showing lower communication overhead and improved scalability in contrast to existing hybrid storage techniques.

5.4.2 Multi-User Verification

To improve verification efficiency, when group users (such as international travel groups, academic exchange groups, etc.) plan to travel abroad or conduct international exchanges, the team aggregates signatures to accept the customs Healthcare and machine learning status check.

5.4.3 Obtaining Personal Signatures

n users in the group generate query traps based on their passport numbers to retrieve their respective signatures δ_i $(1 \le i \le n)$. The process is consistent with Section 4.1.

5.4.4 Generate Aggregate Signature

The aggregator in the team calculates the hash set Hash $= \{\text{hash}_1, \text{hash}_2, \ldots, \text{hash}_n\}$ based on the signature set $\{\delta_1, \delta_2, \ldots, \delta_n\}$, where $\text{hash}_i = H_2(\text{hash}_{i-1} + e(V_i, g)), \quad 1 \le i \le n$. Let $t = \text{hash}_n$, and get the aggregate signature $\delta = (U_1, U_2, \ldots, U_n, t)$, and initiate a verification request to the consortium chain.

5.4.5 Verify the Aggregate Signature

The consortium chain node calls the verification smart contract and calculates k_i and h_i for all $1 \le i \le n$. It verifies that

$$\begin{aligned} t = H_2\Bigg(H_2\Bigg(H_2\Bigg(H_2\Bigg(e\big(R_2 \cdot P_{pb}^{t_1} \cdot X_1^{b_1}, g\big) \cdot e\big(U_1^{k_1}, g\big)\Bigg) + \\ e\big(R_2 \cdot P_{pb}^{k_1} \cdot X_2^{k_2}, g\big) \cdot e\big(U_2^{h_2}, g\big)\Bigg) + \cdots + e\big(R_n \cdot P_{pab}^{k_n} \cdot X_n^{h_k}, g\big)\Bigg)\Bigg), \end{aligned} \tag{13}$$

holds. If true, it means that the passport status of the users in the group is normal, and the result is returned to the customs staff; if not, it means that there are malicious users in the group and someone has forged the health passport. To find malicious users, for $1 \le i \le n$, calculate

$$t_i = H_2\left(\text{hash}_{i-1} + e(R_i \cdot P_{\text{pub}}^{k_i} \cdot X_i^{n_i}, g) \cdot e(U_i^{h_i}, g)\right), \tag{14}$$

in sequence. Determine whether $t_i = \text{hash}_i$ is true. If the equation is not true, the passport status of user i is abnormal.

6 Security Analysis

6.1 Correctness

1. **Retrieval Correctness:** For the equation $I_K = H_5\left(e\left(\frac{\tau_1}{\tau_\lambda^*}, X_i\right) \| \text{PUID}_i\right)$ in step (2) in Section 4.3, the derivation process is shown in Eq. (15):

$$\begin{aligned} &H_5\left(e\left(\frac{\tau_1}{\tau_2 x_4}, X_4\right) \| \text{PUID}_i\right) = \\ &H_5\left(e\left(\frac{H_3(\text{PUID}_i)^{\frac{1}{x_i}} \cdot X_c^{t_i}}{(g^t)^{x_t}}, g^t\right) \| \text{PUID}_i\right) = \\ &H_5\left(e\left(\frac{H_3(\text{PUID}_i)^{\frac{1}{x^2}} \cdot (g^x)^t}{(g^i)^{x_t}}, g^x\right) \| \text{PUID}_i\right) = \\ &H_5(e(H_3(\text{PUID}_i), g) \| \text{PUID}_i) = I_\kappa. \end{aligned} \tag{15}$$

2. **Decryption Correctness:** For step (3) in Section 5.3, where the passport is given as $\frac{B_i}{e\left(A_i, H_3(\mathrm{PUID})^{\frac{1}{x_i}}\right)}$ in step (3) of Section 5.3, the derivation process is shown in Eq. (16):

$$\begin{aligned}
\mathrm{passport}_i &= \frac{B_i}{e\left(A_i, H_3\left(\mathrm{PUID}_i\right)\right)^{\frac{1}{x_i}}} = \\
&\frac{k \cdot \mathrm{passport}_i}{e\left(X_i^{\theta_s}, H_3\left(\mathrm{PUID}_i\right)\right)^{\frac{1}{x_i}}} = \\
&\frac{k \cdot \mathrm{passport}_i}{e\left(X_i^{\theta_i}, H_3\left(\mathrm{PUID}_i\right)\right)^{\frac{1}{x_i}}} = \\
&\frac{e\left(g^{\theta_i}, H_3\left(\mathrm{PUID}_i\right)\right)}{e\left(\left(g^{x_i}\right)^{\theta_i}, H_3\left(\mathrm{PUID}_i\right)\right)^{\frac{1}{x_i}}} \cdot \mathrm{passport}_i.
\end{aligned} \tag{16}$$

3. **Signature Correctness:** For the equation in Section 5.4.1, $H_2\left(e\left(V_i, g\right)\right) = H_2\left(e\left(R_i \cdot P_{\mathrm{pub}}^{k_i} \cdot X_i^{k_i}, g\right) \cdot e\left(U_i^{k_i}, g\right)\right)$, the detailed derivation and proof are shown in Eq. (18):

$$\begin{aligned}
&e\left(V_i, g\right) = e\left(g^{k_i x_i + k_i \alpha_i} \cdot d_i, g\right) = \\
&e\left(g^{k_1 + k_1 \mu_1} \cdot g^{r_j + k_s}, g\right) = \\
&e\left(g^{\prime_H} \cdot g^{\hbar_{x_2}} \cdot g^{k_{,\mu_1}} \cdot g^{k_s}, g\right) = \\
&e\left(g^{r_i} \cdot \left(g^{x_j}\right)^{k_i} \cdot \left(g^{v_j}\right)^{k_i} \cdot \left(g^{s_i}\right)^{k_i}, g\right) = \\
&e\left(R_i \cdot X_i^{k_i} \cdot U_i^{k_i} \cdot P_{\mathrm{p}i}^{k_i}, g\right) = \\
&e\left(R_i \cdot P_{\mathrm{pub}}^{k_i} \cdot X_i^{h_i}, g\right) \cdot e\left(U_i^{\alpha_i}, g\right).
\end{aligned} \tag{17}$$

4. **Aggregate Signature Correctness:** For the equation in Section 5.4.2:

$$\begin{aligned}
t = H_2\Bigg(H_2\Bigg(H_2\Bigg(H_2\Bigg(&e\left(R_1 \cdot P_{\mathrm{pub}}^{k_1} \cdot X_1^{k_1}, g\right) \cdot e\left(U_1^{k_1}, g\right)\Bigg) \\
&+ e\left(R_2 \cdot P_{\mathrm{pub}}^{k_3} \cdot X_2^{k_{t_4}}, g\right) \cdot e\left(U_2^{k_z}, g\right)\Bigg) \cdots \\
&+ e\left(R_n \cdot P_{\mathrm{pub}}^{L_n} \cdot X_n^{k_n}, g\right) \cdot e\left(U_n^{n_n}, g\right)\Bigg),
\end{aligned} \tag{18}$$

The proof process is similar to the verification of signature correctness.

6.2 *Confidentiality*

In this scheme, the user's public key is used to encrypt the health passport data, and only those with the corresponding private key can decrypt the data. The encrypted health passport data is stored on IPFS, ensuring that even if IPFS is compromised by hackers, the attackers cannot obtain valid data. Additionally, the KGC only retains part of the private key $D_i = (R_i, d_i)$, while the complete private key $\mathrm{sk}_i = (x_i, d_i)$ is generated by the user, enhancing data confidentiality.

6.3 Traceability and Non-Repudiation

This scheme relies on the immutable nature of blockchain. The index and signature of the user's passport are uploaded to the consortium blockchain, and each transaction includes the identity identifier of the transaction creator, ID_k. If there is an issue with the user's health status, it can be traced back to the relevant medical institution. Moreover, the hospital's signature sig_b included in the transaction prevents the hospital from denying the facts.

6.4 Unforgeability

Before uploading the transaction to the consortium blockchain, the user signs the health passport using their private key. Malicious attackers cannot obtain the user's private key, making it impossible to forge valid signatures. Invalid signatures cannot pass the verification equation: $e\left(V_i, g\right) = e\left(R_i \cdot P_{\mathrm{pub}}^k \cdot X_i^{k_i}, g\right) \cdot e\left(U_i^{k_i}, g\right)$, thereby ensuring the unforgeability of the health passport.

7 Performance Analysis

This section first compares the functions of this scheme with related health passport schemes; then analyzes the computational overhead of this scheme from a theoretical perspective and compares it with existing schemes; finally, evaluates the performance of the scheme through simulation experiments.

7.1 Functional Comparison

The functional comparison between the proposed scheme and other health passport schemes [10] is shown in Table 2. As can be seen from Table 2, all schemes achieve confidentiality and integrity. The schemes in reference [32] cannot guarantee the non-repudiation of data; the scheme in reference [18] does not consider the problem of health passport forgery; the schemes in reference [33] achieve the above functions well, but cannot provide efficient health passport verification in multi-person scenarios. The proposed scheme achieves these functions well.

Table 2: Feature comparison

Function	[10]	[32]	[33]	[18]	[34]	Proposed solution
Confidentiality	√	√	√	√	√	√
Traceability	√	√	√	√	√	√
Integrity	√	√	√	√	√	√
Non-repudiation	×	×	√	√	√	√
Unforgeable	√	√	√	×	√	√
Multi-person scenario	×	×	×	×	×	√

7.2 Computational Overhead

To compare the computational overhead, we conducted simulation experiments using a desktop PC equipped with Windows 10, an Intel Core i3-10100 CPU running at 3.60 GHz, and 16 GB of RAM. The evaluation focuses on health passport retrieval and signature verification, which are the primary computationally intensive stages in our proposed scheme. Table 3 presents the execution time for key cryptographic operations.

We benchmarked our approach against existing blockchain-based healthcare authentication schemes, specifically those in references [18,33,34]. The computational overhead comparison is provided in Table 4, where n represents the number of users. Reference [32] was excluded from this comparison as it does not provide detailed computational metrics.

Table 3: Execution time of the operation

Symbol	Operation	Execution time/ms
T_k	Hash function operation	0.04
T_s	Point multiplication operation	0.07
T_s	Exponential operation	10.56
T_s	Bilinear operation	4.98

Table 4: Computational cost comparison

Scheme	Computational overhead of retrieval phase	Computational overhead of signature verification phase	Total
Zero-knowledge [24]	$3nT_h + 5nT_m + 3nT_e + 2nT_p$	$3nT_h + 5nT_m + 3nT_e + 2nT_p$	$6nT_h + 10nT_m + 6nT_c + 4nT_p$
Hierarchical Attribute [11]	$nT_h + 3nT_e + nT_p$	$2nT_h + 3nT_m + 3nT_e + 3nT_p$	$3nT_h + 3nT_m + 4nT_e + 4nT_p$
Single user (Proposed)	$2nT_h + nT_m + 4nT_e + nT_p$	$4nT_h + 3nT_m + 3nT_e + 3nT_p$	$5nT_h + 3nT_m + 4nT_c + 4nT_p$
Multi user (Proposed)	$2T_h + T_m + 4T_e + T_p$	$3nT_h + 3nT_m + 3nT_e + 2nT_p$	$(3n+2)T_h + (3n+1)T_m + (3n+4)T_c + (2n+1)T_p$

Figs. 3–5 compare the computational overhead at several levels. Fig. 3 shows the computational overhead during the health passport retrieval stage. The x-axis represents the number of users, while the y-axis shows the time taken (in milliseconds) for data retrieval. The comparison includes our proposed scheme against prior methods [34] and [33]. Lower computational overhead indicates a more efficient retrieval process.

The systems mentioned in reference [34] have lower computational overheads than the scheme in the single-user case, but they aren't as good as the method in the multi-user situation. The difference will widen as the number of users increases. Unlike earlier techniques, which necessitate retrieving each user's health passport individually, the aggregate signature technology introduced in this paper's scheme simply requires one retrieval. The retrieval stage's computing overhead increases with the number of users. During the signature verification stage, Fig. 4 shows the computational overhead of the technique. In the single-user scenario, the computational cost of the signature verification in this paper's technique is higher than in reference [33], but it's about the same as in reference [18]. This paper's approach, which is applicable to both single- and multiple-user scenarios, has lower computing cost during the signature verification stage compared to the scheme in reference [33]. Reason being, compared to the scheme in reference [18], the signature verification procedure of the scheme in reference [34] and this paper's scheme reduces one bilinear operation, slightly lowering the computational overhead of signature verification. Also, the suggested technique has a small benefit over the solution in the literature [33] since it reduces 2 multiplication processes.

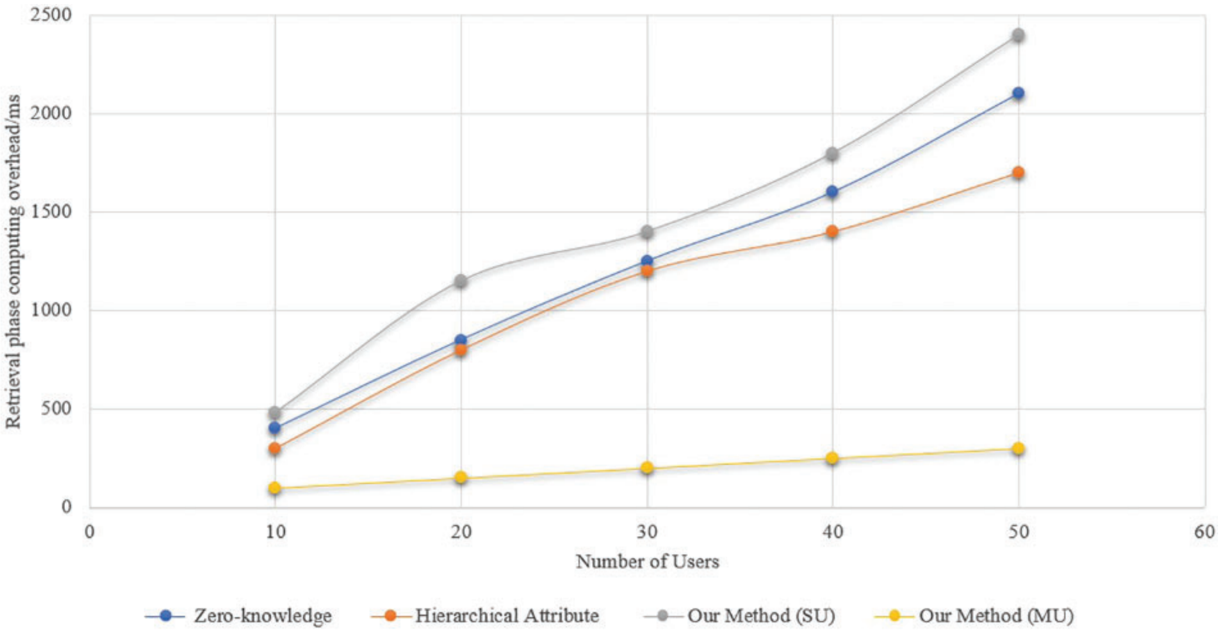


Figure 3: Computational overhead at the retrieval stage

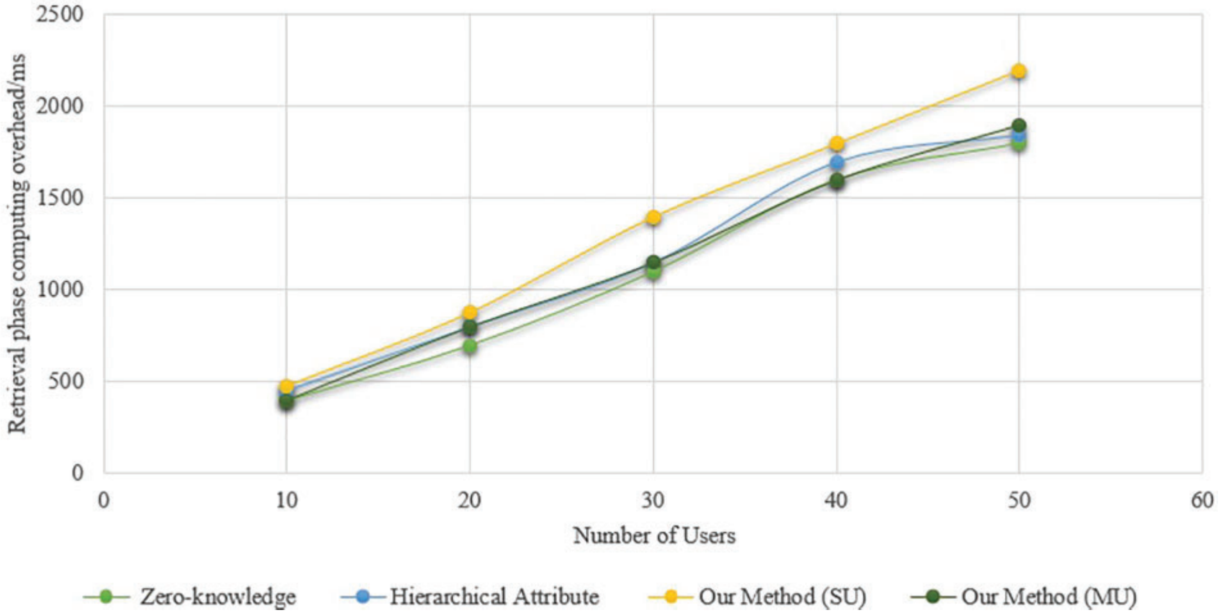


Figure 4: Computational overhead at the signature verification stage

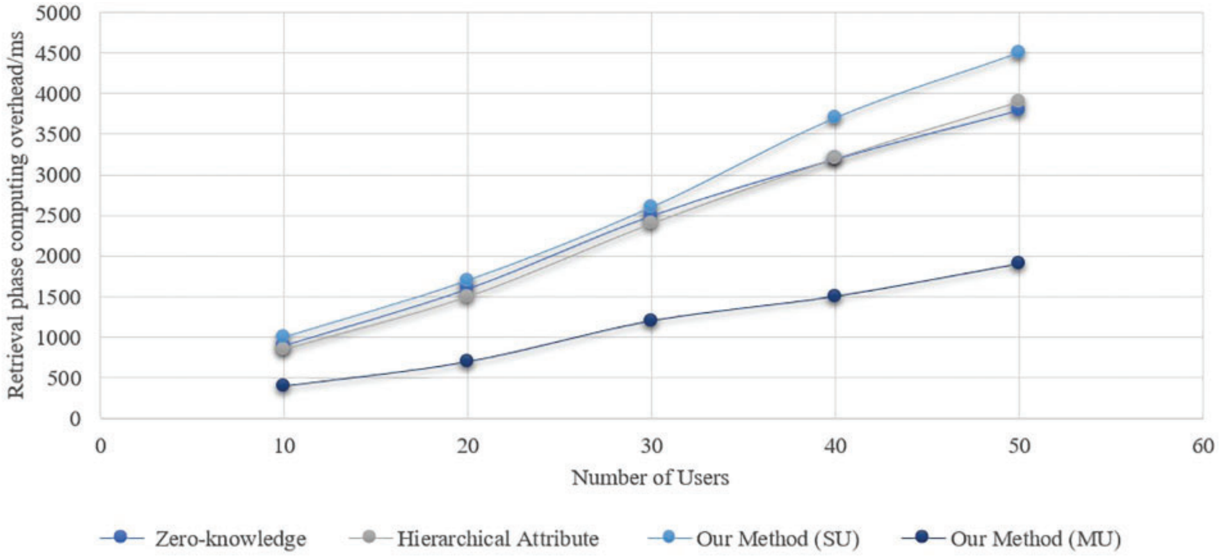


Figure 5: Total computational overhead

Fig. 5 is for the scheme's total computing cost. With a maximum optimization of 49.89%, the suggested method clearly outperforms the current system in terms of overall computing cost in the multi-user situation. The reason behind this is that the suggested system takes into account the possibility of merging complex calculations (like bilinear mapping and exponential operations) when the user group performs retrieval and verification, in contrast to the present scheme. Combining the calculation processes for a single user with those for a multi-user scenario allows for the realization of calculation merging in the latter. Despite this, in the single-user scenario, the computational cost of the proposed scheme will be higher than other existing schemes. However, in the multi-user scenario, from the Healthcare device data retrieval stage to the verification stage, other existing schemes clearly have higher computational costs than the proposed scheme (Figs. 3–5). Consequently, the suggested approach is better suited to situations involving international communication or foreign travel due to its greater efficiency advantage in real applications. An adversarial actor might potentially falsify a valid user's health passport within the scheme, rendering the signature verification ineffective. Finding the malicious forger after signature verification fails requires re-obtaining and confirming each user's signature individually.

7.3 Consensus Overhead

To evaluate the efficiency of the improved weak consensus algorithm proposed in this paper, simulations of the PBFT algorithm [35], the weak consensus algorithm, and the improved weak consensus algorithm were conducted using Java as the programming language. The simulations modeled a P2P network environment with 4~64 nodes communicating via different WebSocket ports. Each experiment was repeated 10 times, and the average result was taken as the final outcome. The experiments were performed on a laptop computer running Windows 11, equipped with an AMD Ryzen 7 5800H CPU and 16 GB of RAM. The throughput of the blockchain was measured in terms of the number of transactions per second (TPS), which is the number of transactions that can be added to the chain per second. TPS is defined as:

$$\mathrm{TPS} = \frac{N_{T_t}}{t}, \tag{19}$$

where t represents the time and N_{T_t} is the number of transactions added to the chain within time t. This paper compares the traditional PBFT algorithm, the weak consensus algorithm, and the improved weak consensus algorithm. The comparison of consensus efficiency is shown in Fig. 6. The throughput of the PBFT consensus algorithm drops as the number of nodes grows, as shown in Fig. 6. In this research, we present an improved weak consensus algorithm that outperforms the PBFT method [21] and the weak consensus algorithm [18] in terms of throughput at low node densities. While doing so, it still performs well when the number of nodes is large. The improved weak consensus algorithm only needs two stages to reach consensus, which greatly reduces the communication complexity of reaching consensus between nodes and improves the throughput of the entire blockchain system.

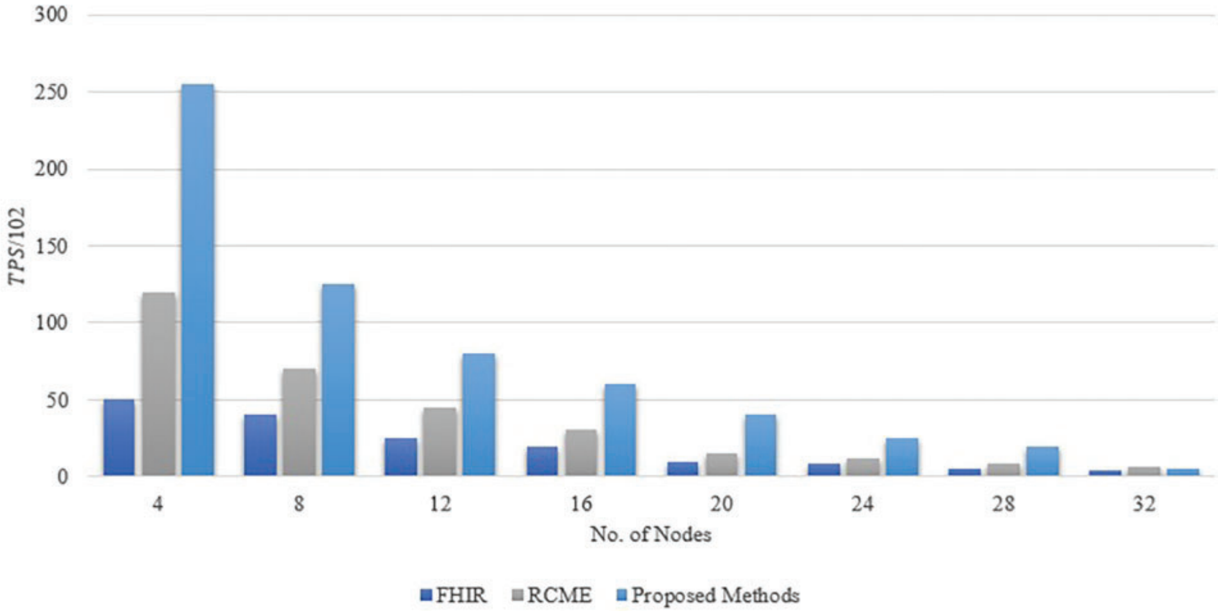


Figure 6: Comparison of consensus efficiency

7.4 Communication Overhead

Assuming that the length of the index, trapdoor, hash value, and key pair is 256 bits, the length of the health passport data ciphertext is 512 bits, the length of the signature is 1024 bits, the length of the ID is 128 bits, and the length of the timestamp is 64 bits, the communication overhead in the storage phase is shown in Fig. 7. In the health passport data storage phase, the solution in reference [34] needs to send 1984 bits, the solution in reference [33] needs to send 1792 bits, and the solution in this paper only needs to send 1664 bits; in the retrieval phase, the communication overhead is shown in Fig. 8. The solution in reference [34] needs to send 1984 bits, the solution in reference [33] needs to send 1536 bits, and the solution in this paper only needs to send 1280 bits. Compared with the solutions in reference [34], the communication overhead of the solution in this paper is smaller, with the highest optimization of 25.81%, which is attributed to the reduction of unnecessary transmission (such as timestamps and keys).

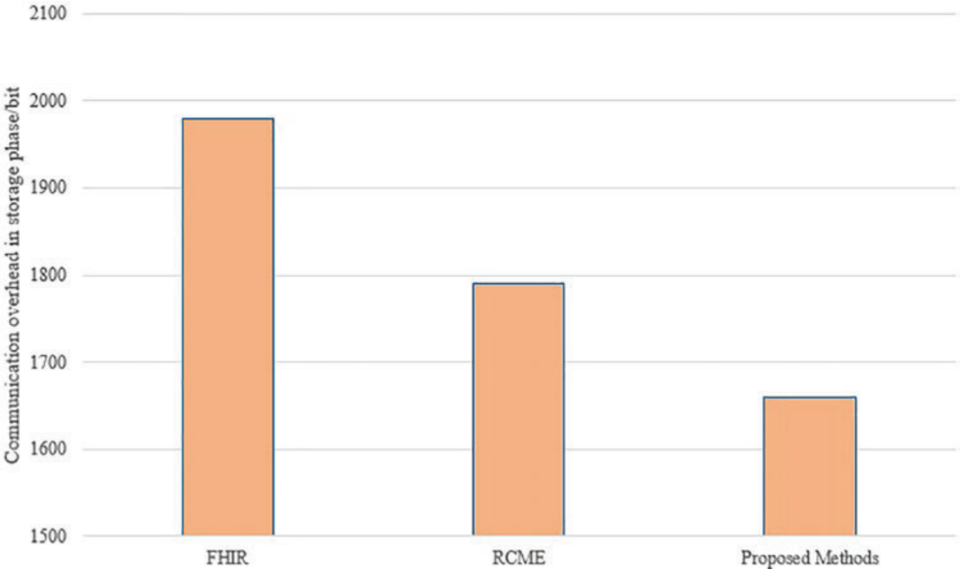


Figure 7: Comparison of communication overhead in storage phase

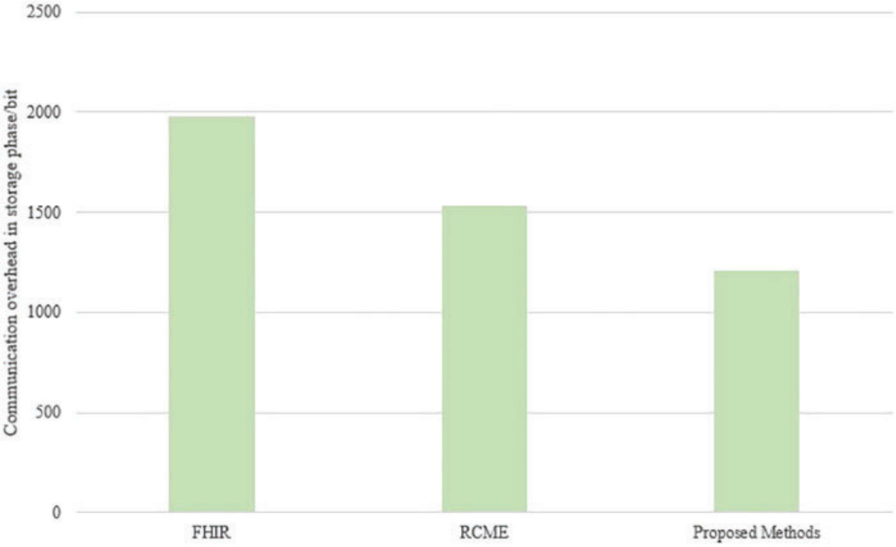


Figure 8: Comparison of communication overhead in the retrieval phase

7.5 Real-World Deployment

While our proposed blockchain-based health passport system offers significant security and efficiency advantages, real-world deployment presents several challenges:

1. **Cost and Infrastructure Requirements:** Implementing blockchain-based solutions requires computational resources for consensus mechanisms, storage, and encryption operations. Healthcare institutions must invest in compatible hardware and software, which may pose financial constraints, especially in resource-limited regions.

2. **Energy Consumption:** Blockchain networks, particularly those using consensus mechanisms like PBFT, can be computationally intensive. Although our optimized weak consensus algorithm reduces communication overhead, further work is needed to explore energy-efficient blockchain frameworks suitable for large-scale healthcare adoption.
3. **Regulatory Compliance:** Ensuring compliance with healthcare data protection laws (e.g., GDPR, HIPAA) is critical. Blockchain's immutability raises challenges for data modification or removal requests, necessitating privacy-preserving mechanisms such as zero-knowledge proofs.
4. **User Adoption and Usability:** Medical professionals and travelers may require training to interact with blockchain-based health passport systems. A user-friendly interface and integration with existing electronic health record (EHR) [36] systems will be essential for seamless adoption.

Future research will focus on optimizing energy efficiency, cost-effectiveness, and regulatory adaptability to facilitate real-world deployment in healthcare environments.

8 Conclusion

This paper addresses critical challenges in the global sharing of personal health passports, including "information islands," inadequate privacy protection, and risks of forgery. To overcome these, a blockchain-based solution for health passport storage, sharing, and verification is proposed, integrating searchable encryption technology with blockchain to ensure secure, efficient, and scalable data management. The proposed scheme introduces an innovative combination of on-chain and off-chain storage using IPFS, enhancing storage optimization while maintaining reliability. Additionally, an improved aggregate signature mechanism is employed to facilitate efficient multi-user verification, while a two-stage weak consensus algorithm significantly improves blockchain throughput and reduces communication complexity. Through comprehensive security analysis and experimental validation, the scheme demonstrates notable advantages, achieving up to 49.89% optimization in computational overhead and up to 25.81% reduction in communication overhead in multi-user scenarios. However, challenges remain in single-user cases, where retrieval and signature verification overheads are higher than existing solutions. To address this, future research will explore lightweight cryptographic operations and hybrid storage mechanisms to enhance efficiency in low-volume transactions. Furthermore, ethical and legal considerations are paramount in blockchain-based healthcare systems. Our approach ensures compliance with GDPR and HIPAA by utilizing off-chain storage for sensitive data while maintaining secure on-chain references. To address blockchain immutability challenges, potential solutions include zero-knowledge proofs, revocable encryption, and hybrid blockchain governance models to uphold user privacy and the right to data modification. Future research will refine privacy-preserving techniques, regulatory adaptability, and energy-efficient consensus mechanisms to enhance scalability and real-world applicability. By addressing key concerns in security, privacy, efficiency, and ethical compliance, this work presents a robust and adaptable framework for secure health passport management, with significant potential for global healthcare data interoperability and secure international travel.

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Ethics Approval: Not applicable.

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