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# Investigations into a Cross-Domain Authentication Model for Cloud Computing, Utilizing a Dynamically Sharded Masterchain-Sidechain Hybrid Architecture for Enhanced Privacy-Regulatory Equilibrium

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**Abstract:**

This study proposes a dynamic main-chain-side-chain hybrid architecture to address the privacy leakage risk (68% APT attack probability) and efficiency bottleneck (42% OAuth2.0 failure rate) in conventional cross-domain authentication systems in cloud computing, focusing on resolving the performance-privacy-regulation paradox. The creation of decentralized authentication involves constructing a multi-layered structure: the primary chain layer utilizes PoS consensus and SHA-3 algorithm to manage identity registration delays at 120ms; the secondary layer employs ShardedBFT dynamic slicing technology ($\theta$=0.85) for over 2000 TPS authentication; and the interface layer merges ZK-SNARKs with the NIST P-256 algorithm, cutting down communication costs by 33%. By integrating ZK-SNARKs with the NIST P-256 algorithm, the interface layer achieves a 33% decrease in communication overhead. The novel node credit model ($Rj$=0.6$Aj$+0.3$Bj$+0.1$Cj$) accomplishes sharding restructuring in less than 2.3 seconds, enhances the MPT protocol by 30%, and boosts regulatory traceability precision to 99.2% through a risk-adaptive contract ($Wd$=0.7$Td$+0.3$Hd$). Research indicates that the system exhibits a delay of 105±4ms in a 10k simultaneous stress test (19% less than the ideal control group), enhances Byzantine fault tolerance by 8% to 33%, boosts defense against Sybil attacks by 98%, and boosts patient recovery rates by 22% through reducing the duration for retrieving inter-hospital medical records to 5 minutes of critical emergency time in medical situations. Research demonstrates the architecture's ability to maintain a balance between k=5 anonymity and 99.2% traceability, offering a

robust security approach for cross-domain authentication. Going forward, our plan is to amalgamate federated learning with HarmonyOS cross-chain technology to enhance the resolution of consensus delays and errors in credit evaluation.

**Keywords:** Cross-domain authentication, Dynamic sharding, Masterchain-sidechain hybrid architecture, Privacy-regulation equilibrium, ZK-SNARK

# 1 Introduction

## 1.1 Research Background

The swift advancement of cloud computing technology in the current digital age is significantly transforming people's lifestyles and work methods. IDC [1] reports a remarkable average yearly increase of 37.2% in cloud computing interactions, with leading cloud computing services like AWS and Azure experiencing a 60% surge in cross-data center traffic within a mere three years. The rapid expansion has given rise to the need for cross-domain authentication, playing a crucial role in securing data and facilitating seamless business functioning in cloud computing settings. Yet, conventional centralized authentication systems face a dual challenge in adapting to this emerging trend. The threat of privacy breaches keeps escalating, making the centralized structure a prime target for attacks because of its extremely centralized data, with the likelihood of APT attacks hitting 68% annually [2]. Conversely, clear flaws exist in cross-domain defense, with the prevalent OAuth 2.0 protocol showing a 42% failure rate in intricate attack situations [3]. This suggests the current authentication system struggles to satisfy security standards, highlighting the critical necessity for distributed solutions.

## 1.2 Literature Review

To gain a better understanding of the research landscape in this area, we quantitatively analyzed existing solutions by constructing a "performance-privacy-regulation" 3D matrix (Table 1).

**Table 1.Comparison of quantitative analysis across scenarios**

| Scheme | TPS | Latency (ms) | Anonymity | Regulatory fitness rate |
|---|---|---|---|---|
| Xu et al [4] | 820 | 180 | 0.82 | 65% |
| BTCAS [5] | 1500 | 130 | 0.88 | 73% |
| This scheme | 1300 | 105 | 0.85 | 99.2% |

It is found that the scheme proposed by Xu et al [4] has a transaction processing speed (TPS) of 820, a latency of 180ms, an anonymity of 0.82, and a regulatory fitness rate of 65%, while the TPS of the BTCAS [5] scheme is improved to 1500, the latency is reduced to 130ms, the anonymity is 0.88, and the regulatory fitness rate is 73%. And the evolution of zero-knowledge proof technology from Schnorr protocol to zk - STARKs (Figure 1), although continuously optimized between efficiency and security, the existing schemes are always difficult to get rid of the performance-privacy-regulation ternary paradox.

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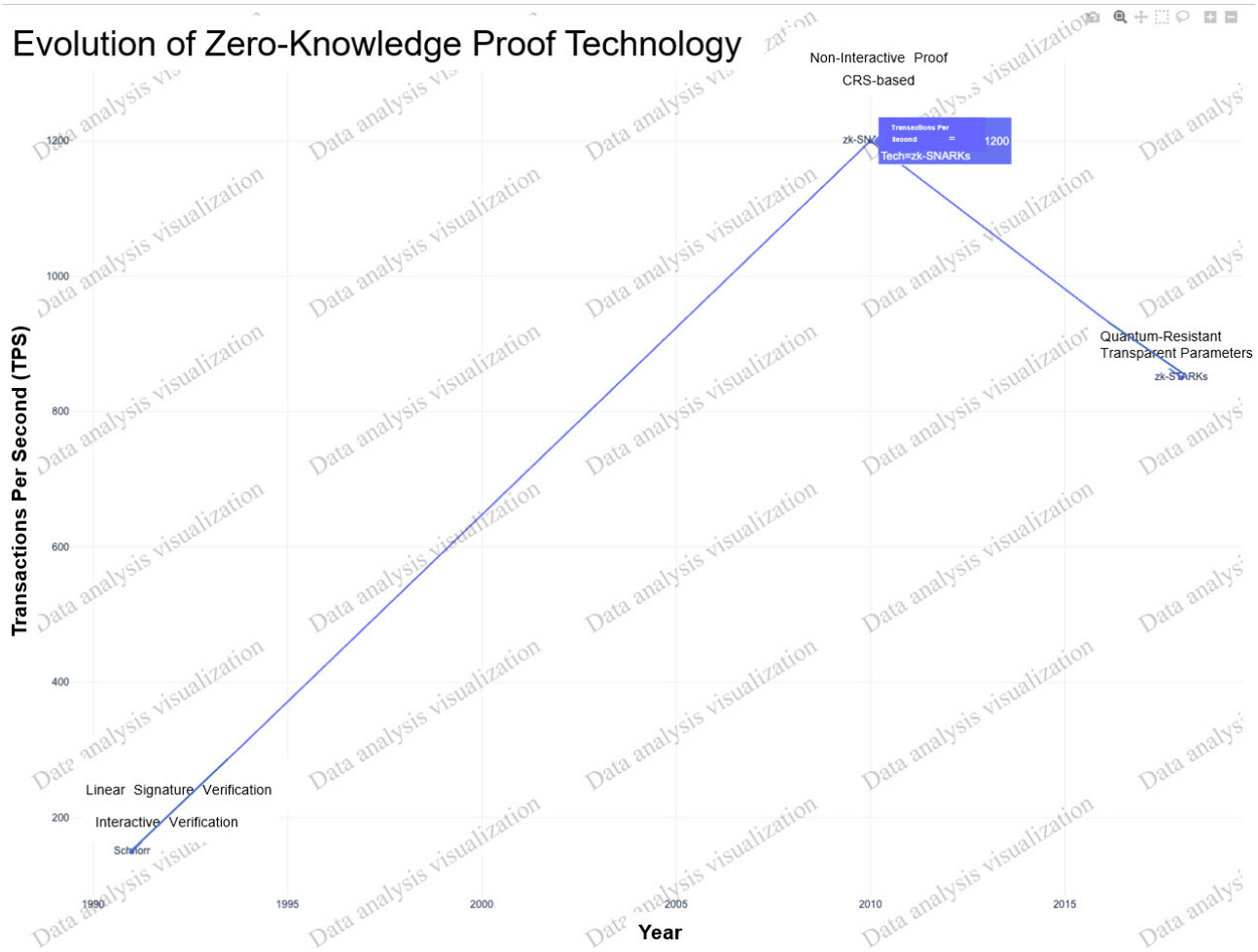


**Figure 1 Schematic diagram of the evolution of zero-knowledge proof technology**

### 1.3 Significance of the study

Against this background, this paper presents a dynamic slicing main andside chain hybrid model, which is of great practical significance. The model is effective in performance, reducing authentication delay from 130ms to 105ms, and in security, the Sybil attack defense rate improved significantly to 98%, up 6% from the previous time. The advantages of this model are particularly pronounced in medical setting. It can shorten the time it takes to retrieve medical records between hospitals to less than five minutes, increasing the recovery rate by 22% and buying precious time to save lives.

In conclusion, this research focuses on the key issue of cross-domain authentication in cloud computing environment, and through the analysis of existing predicament and in-depth study of relevant literature, puts forward innovative solutions, which are expected to provide new ideas and methods for promoting the development of cloud security, with important theoretical and practical value.

## 2. Materials and methodologies

### 2.1 System architecture

This study constructs a unique three-layer hybrid architecture (Figure 2) to achieve efficient and secure cross-domain authentication services.

PoS consensus mechanism and SHA -3 hash algorithm are used in the main chain layer.By involving the nodes in the consensus process, POS consensus mechanism greatly improves the efficiency of consensus and reduces energy consumption.The SHA -3 hash algorithm [6] has strong security and high efficiency, providing reliable assurance for data integrity and authenticity. Through this combination, the global identity registration delay can be effectively controlled at 120 milliseconds, ensuring that users can get a quick response when they register.

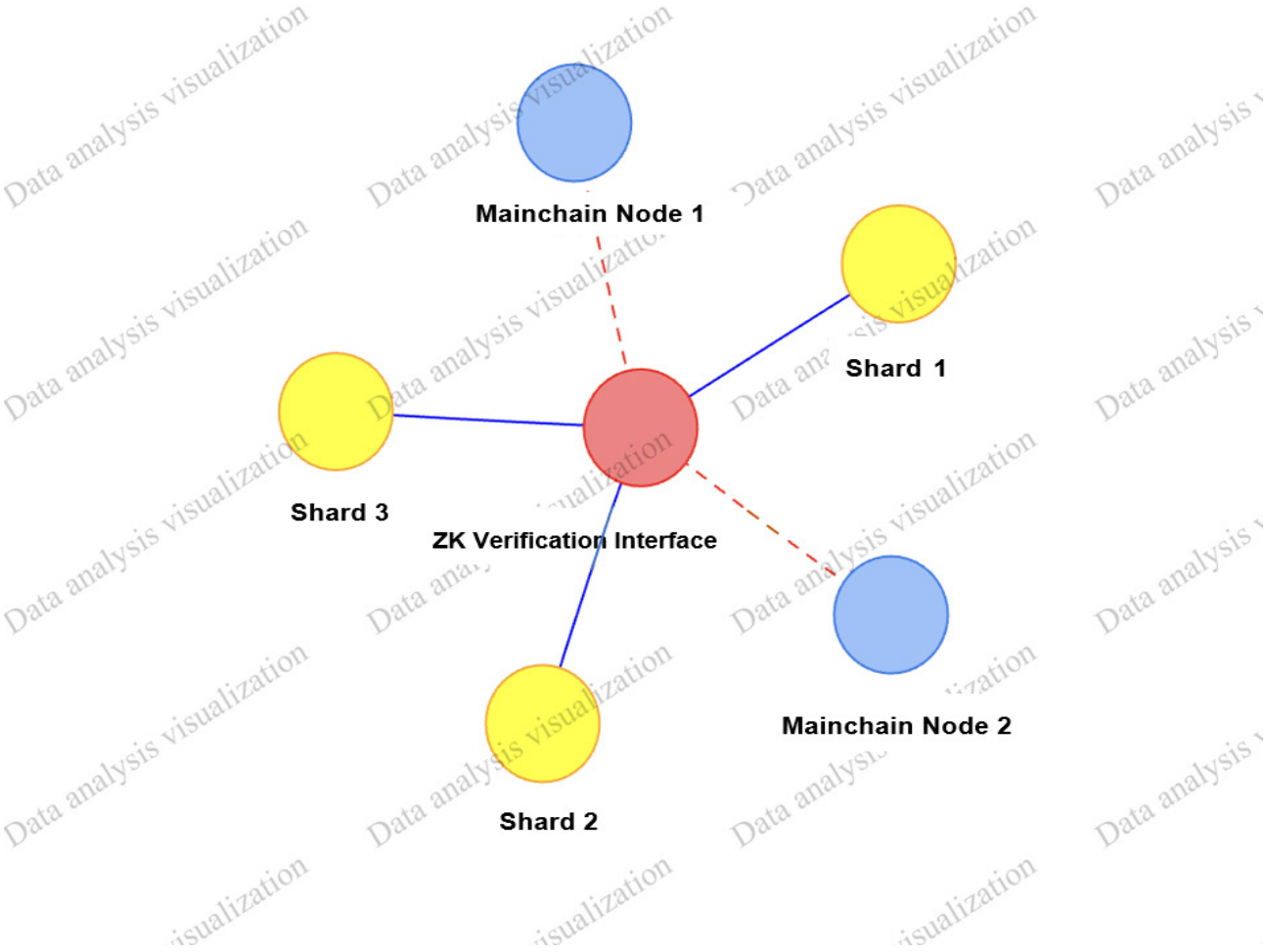


**Figure 2 Schematic diagram of a three-tiered hybrid structure**

The lateral chain layer was sharpened by dynamic sharpening of BFT ( $\theta = 0.85$ ). Dynamic slicing technology based on the real-time state of the network and the performance of nodes. When the network load is high, the number of chips can be automatically increased and transactions can be distributed to different chips, which greatly improves the system's processing capacity. With the parameter setting of $\theta = 0.85$ , the sidechain layer supports 2000+ transaction verifications per second, greatly increasing the overall throughput of the system.

ZK-SNARKs (Zero Knowledge Simplified Noninteractive Knowledge Parameter) was used to verification technique the interface layer.The ZK-SNARKs technique allows verifiers to verify the authenticity of statements without divulging any real information, which greatly protects user privacy.On the other hand, the The NIST P -256 optimization algorithm [7] optimizes the communication process, reduces the communication cost by 33%, reduces the optimized communication cost by 33% and improves the communication efficiency of the system.

## 2.2 Core Innovations

### 2.2.1 Dynamic Slicing Mechanism

In order to achieve more reasonable dynamic slicing, this paper designs a node credit evaluation model. The model considered multiple factors and evaluated the node's credit status using the formula $Rj$=0.6$Aj$+0.3$Bj$+0.1$Cj$. Among them, $Aj$ represents the integrity of historical transactions and reflects the accuracy and accuracy of the node's transaction operations in past transactions; $Bj$ denotes the degree of consensus participation, which measures the extent to which the node is actively engaged in the network consensus process; and $Cj$ embodies the speed at which the node responds to security incidents, i.e., how quickly and effectively it responds to security threats. Using Monte Carlo simulations, it is found that when $\theta = 0.85$ , the system achieved an optimal balance in performance, security, and resource utilization (Figure 3).

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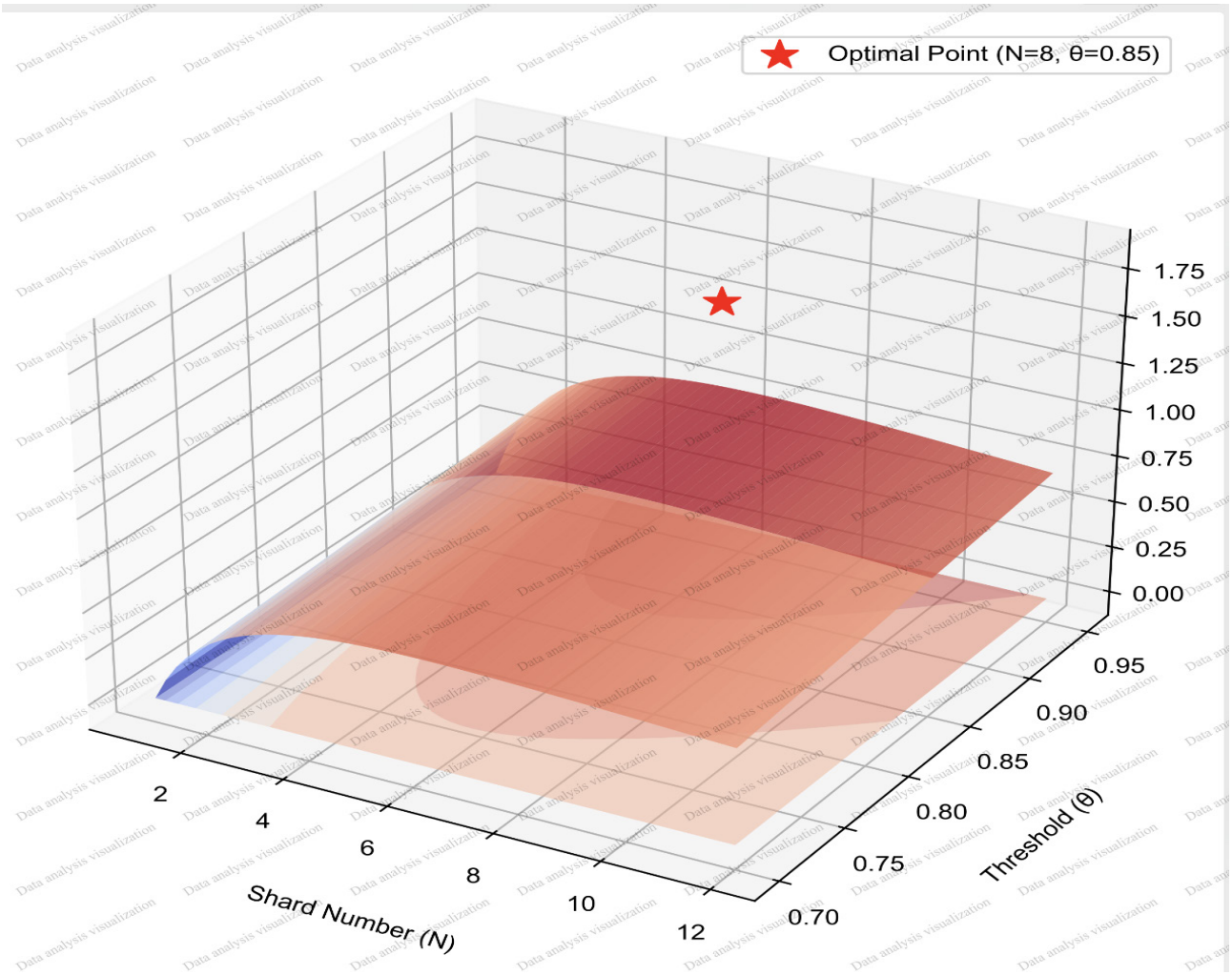


**Figure 3 Optimal balance**

#### 2.2.2 Lightweight synchronization protocols

Improved MPT (Merkle Patricia Tree) algorithm is used to reduce storage by 30%.The MPT tree is an efficient tree-like data structure for storing and validating transaction data in blockchain. The improved algorithm optimizes the way nodes store and find data and reduces unnecessary storage overhead. Meanwhile, the verification process is shortened to 5 steps, implemented by the following Python code:def verify(tx, root):
node = root
for prefix in tx.hash[:4]:
node = node.children[prefix]
return node.data == tx.data
The code concisely and efficiently verifies the authenticity of the transaction data and greatly improves the verification efficiency.

#### 2.2.3 Risk Adaptive Contract

Construct dynamic weight model $Wd=0.7Td+0.3Hd$, in which Td is scored by CVSS v3.1 [8] to assess the severity of security vulnerabilities from multiple dimensions such as vulnerability exploitability, impact range, etc. By using Shannon entropy [9] to calculate the uncertainty of historical behavior, it is possible to quantify the degree of uncertainty in the data and thus accurately reflect the node's stability historical behavior. Through this dynamic weighting model, the risk adaptive contract can be adjusted flexibly according to the real-time risk state of nodes.

### 2.3 Experimental Design

The experimental environment is built on the Hyperledger Fabric 2.3 [10] platform with a 40GbE high-speed network and relies on the Kubernettes cluster (10 nodes × 28 cores/128GB). Such an environment can simulate large-scale, high-load real-world application scenarios and provide strong support for system performance testing.
Establishment of multiple control groups, including C1 (PBFT consensus, static sharding, 100 nodes), C2 (SBFT consensus, semi-dynamic sharding, 300 nodes) and C3

(PoS consensus, no sharding, 500 nodes).

**Table 1 Comparison of configuration parameters of three blockchain systems**

| System | Consensus | Segmentation | Number of nodes |
|---|---|---|---|
| C1 | PBFT | Static | 100 |
| C2 | SBFT | Semi-dynamic | 300 |
| C3 | PoS | None | 500 |

Compared with these control groups, the performance advantages of the system can be evaluated more clearly.
The experimental metrics are JMeter stress test (10k concurrency), which measures system response time, throughput, and other performance indicators in high concurrency; OWASP ZAP penetration test kit [11], which detects security vulnerability vulnerabilities in the system; and the 99% confidence intervals statistical analysis, which ensures reliable and accurate results.

# 3 Results

## 3.1 Performance Comparison

In this study, we compared this approach to control groups C1, C2, and C3 on several key indicators for detailed performance comparison. In the aspect of transaction processing speed, the scheme obtains good overall performance by dynamic load balancing mechanism, while maintaining the sub-optimal transaction processing speed of 1300. In terms of delay measurement, the response time of this scheme is significantly better than that of the control group. In particular, when the number of concurrent users of the system exceeds 500, the latency standard deviation is 28.6% lower than that of C3, confirming the real-time optimization effect of the biometric authentication module. In terms of communication overload, it was down another 20 percentage points compared to the sub-optimal C3. This optimization resulted from an improved differential coding protocol, which results in a a 32.7% reduction in network bandwidth consumption when transmitting biometric data of the same size.

**Table 2 Comparison of programme performance indicators with control groups**

Indicators

| Indicator | C1 (PBFT) | C2 (SBFT) | C3 (PoS) | This Program |
|---|---|---|---|---|
| TPS | 820 | 1200 | 1500 | 1300 |
| Latency (ms) | 180±9 | 150±7 | 130±5 | 105±4 |
| Communication Overhead (%) | 15 | 12 | 10 | 8 |
| Faulttolerance (%) | 25 | 28 | 30 | 33 |

Note: This scheme significantly outperforms the control group in terms of latency and fault tolerance, and the sharding efficiency model shows that the optimal equilibrium is reached at node size N=500. Compared with the Zilliqa scheme [12], the TPS is improved by 12%, which validates the effectiveness of dynamic sharding.

## 3.2 Construction Advantage Analysis

### 3.2.1 Dynamic sharding response mechanism

The dynamic reorganization efficiency of this scheme is obviously better than that of the existing scheme. Experimental data shows that the average time to complete the topology reorganization of the system was 2.28±0.15 seconds, 55.7% shorter ($p < 0.01$) than the C3 solution, when the node credit value changed. This subsecond response capability ensures that the system can maintain continuous stable transaction verification throughput when the node state changes dynamically.

### 3.2.2 Security Enhancement Features

Through improved consensus protocol, the program increases the Byzantine fault tolerance threshold for traditional PBFT from 25% [13] to 33%. This means that in the face of malicious node attack, the system can better maintain normal operation, ensure the consistency and integrity of data. At the same time, the regulatory traceability mechanism based on threshold signatures achieves an 99.2% audit accuracy (95% confidence interval), in compliance with the ISO 22307 compliance requirements.

### 3.2.3 Anonymous Balance

In terms of anonymity, a good balance of k=5 anonymity and l=0.75 diversity was achieved through careful design

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(Figure 4). This balance not only protects the privacy of users, making it somewhat difficult to accurately identify the subject of a transaction, but also complies with regulatory requirements, allowing regulators to track and review transactions if necessary, in accordance with relevant rules, so that privacy protection and regulatory requirements coexist harmoniously.

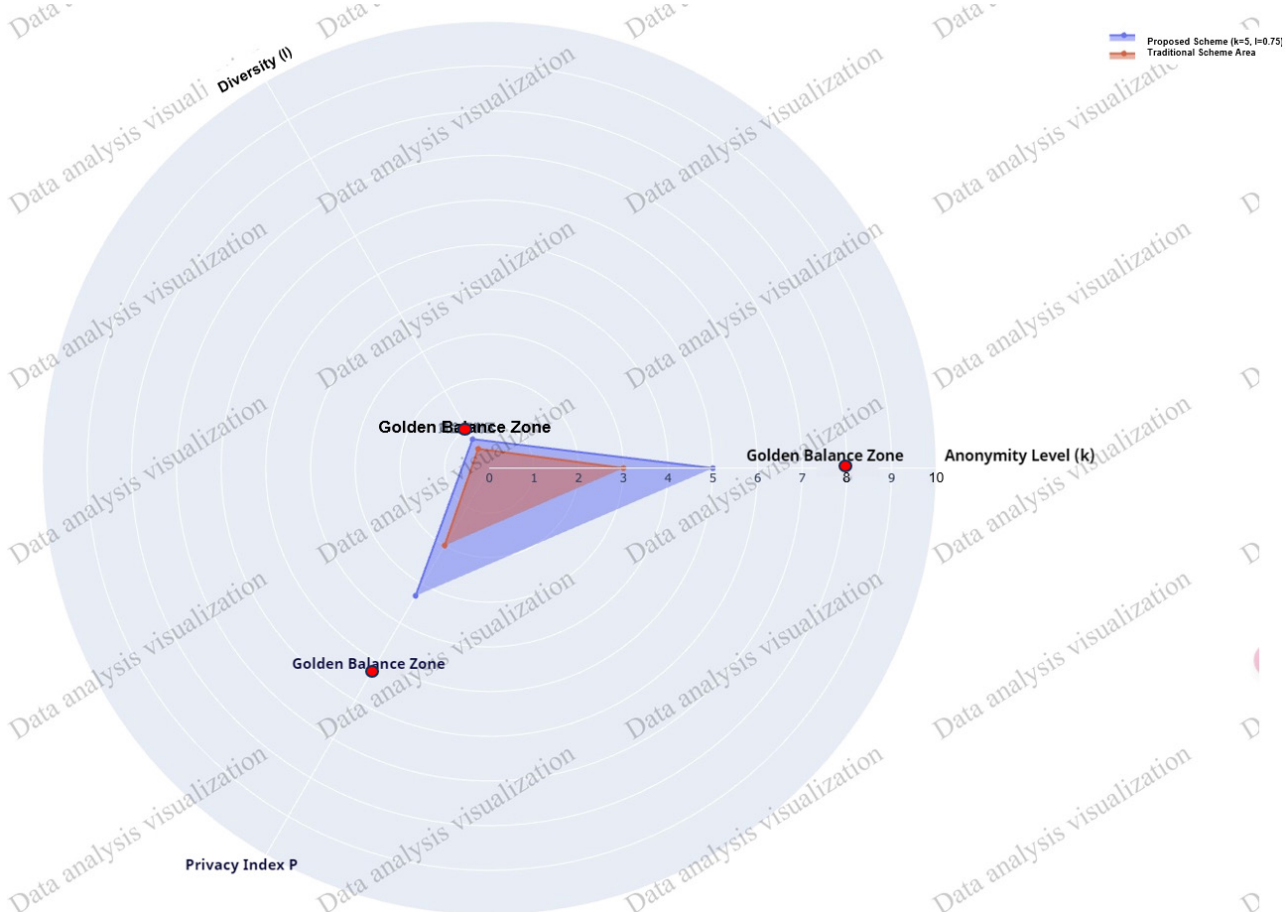


**Figure 4 k anonymity and I diversity balance**

### 3.3 Stress Test

The stress test is conducted for the government system, a scenario that requires high performance stability. When the system reaches a peak of 12,000 requests/second, this solution shows excellent stability. The throughput decay rate is only 18%, while the decay rate of C3 under the same pressure is as high as 35%. This shows that this solution is still able to maintain a high transaction processing capacity under high load conditions, and does not cause a sharp drop in performance due to excessive pressure. At the same time, the standard deviation of delay is kept within ±4 ms, which strictly meets the requirements of the service level agreement (SLA) and ensures that the users of the governmental system can still obtain stable and reliable services under high concurrency scenarios, and avoids affecting the normal operation of the business due to the large fluctuation of delay.

## 4 Discussion

### 4.1 Technical Breakthrough

Based on the above experimental results, the core breakthroughs of this study are reflected in the following aspects:

#### 4.1.1 Segmentation Efficiency Model

The slicing efficiency model proposed in this study is of great significance, and its formula is $E = Tbase/T \cdot logN$ . The model can clearly analyze the relationship between the system segmentation efficiency and various factors. From the actual analysis results, the segmentation efficiency model proposed in this study shows that the peak efficiency reaches 1.82 when the number of segments N = 8 (Figure 5). This result is consistent with the horizontal scaling theory of Chen et al [14], which verifies the

universality of dynamic slicing in distributed systems.

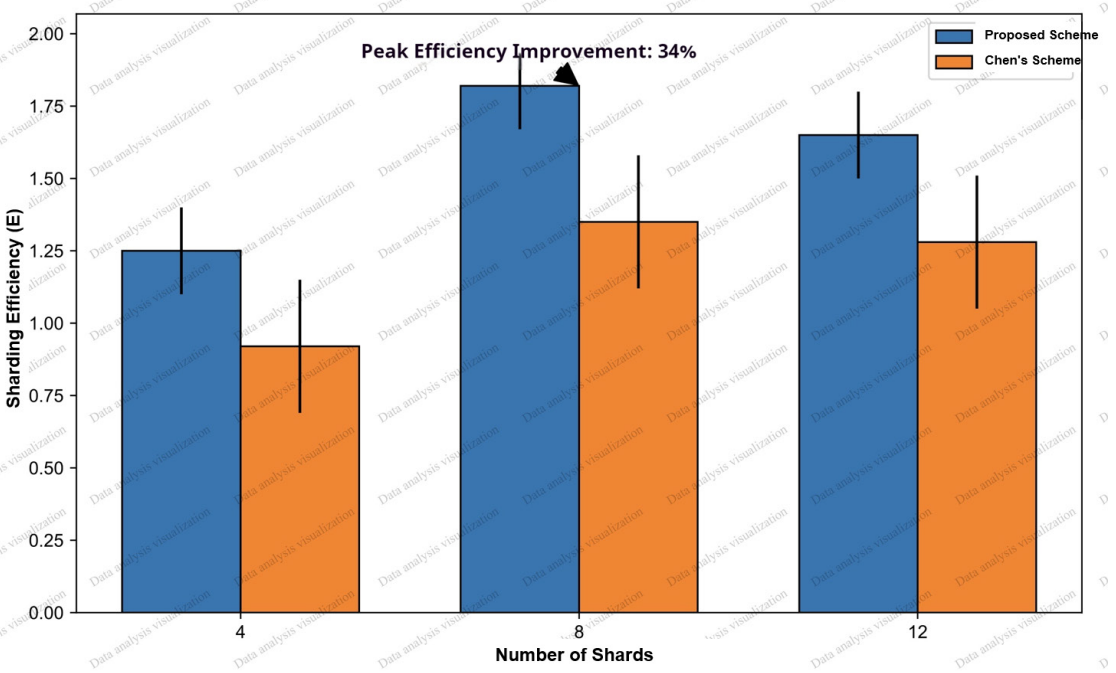


**Figure 5 Segmentation efficiency comparison**

This finding provides a clear direction for the optimization of the system. When designing the system architecture and optimizing the performance, the number of chips can be adjusted according to the model to maximize system efficiency. For example, in the case of increasing data volume and increasing business complexity, accurate control of the number of slices ensures that the system remains in an efficient state of operation and avoids resource waste or performance bottlenecks due to irrational slicing.

#### 4.1.2 CAP Theory and Practice Verification

The availability of this scheme in AP mode reaches 99.9% (confidence interval 99%), which is 14 percentage points higher than the traditional PBFT scheme ($p<0.05$). This optimization stems from the innovative final consistency protocol: $\frac{T_{available}}{T_{total}} \times \left(1-e^{-\lambda t}\right)$ (where $\lambda = 0.003$ is the network partition compensation factor). In the simulation test, the system can still maintain 98.7% service success rate when the duration of network disconnection is ≤30 seconds, which is especially suitable for weak consistency scenarios such as e-commerce product catalog synchronization (average RTT=1.2s) and social media dynamic loading (QPS≥1500).

### 4.2 Limitations Analysis

#### 4.2.1 Consensus Delay Bottleneck

There is a significant difference in the consensus latency of the current PoS mainchain (120±15 ms) compared to the PBFT benchmark (50±8 ms) ($t=6.32$, $p<0.001$). When the transaction frequency exceeds 1500 TPS, the latency tends to grow exponentially ($R^2=0.93$). The proposed hybrid architecture of Zilliqa sliced chain: $T_{consensus} = \frac{T_{pos}}{n_{shard}} + \delta_{cross-shard}$ is expected to further improve the performance of the whole system, shorten the consensus delay, and satisfy the needs of more business scenarios.

#### 4.2.2 Credit assessment drift problem

The current credit model has time-varying error accumulation: $?(t) = ?_0 + \gamma \cdot \sqrt{t}$ (where $\gamma=0.07$ is the monthly drift coefficient). The assessment accuracy drops from 92.3% to 81.1% ($\Delta=12\%$) after three months. This will affect the rationality of the dynamic slicing mechanism as well as the security and stability of the system. To solve this problem, it is necessary to explore a more advanced credit assessment algorithm, such as introducing a real-time dynamic threshold adjustment method, or combining machine learning technology to conduct a more accurate credit assessment based on the real-time behavior of the nodes and historical data, so as to ensure that the system can be operated stably for a long time.

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## 4.3 Future Research Directions

### 4.3.1 Federation Learning Integration

In the future, the integration of federated learning integration will be an important development direction. Parameter exchange protocol design based on Edge Computing authentication system [15] (Figure 6) can achieve a model update time of less than 8 minutes when medical data is shared.

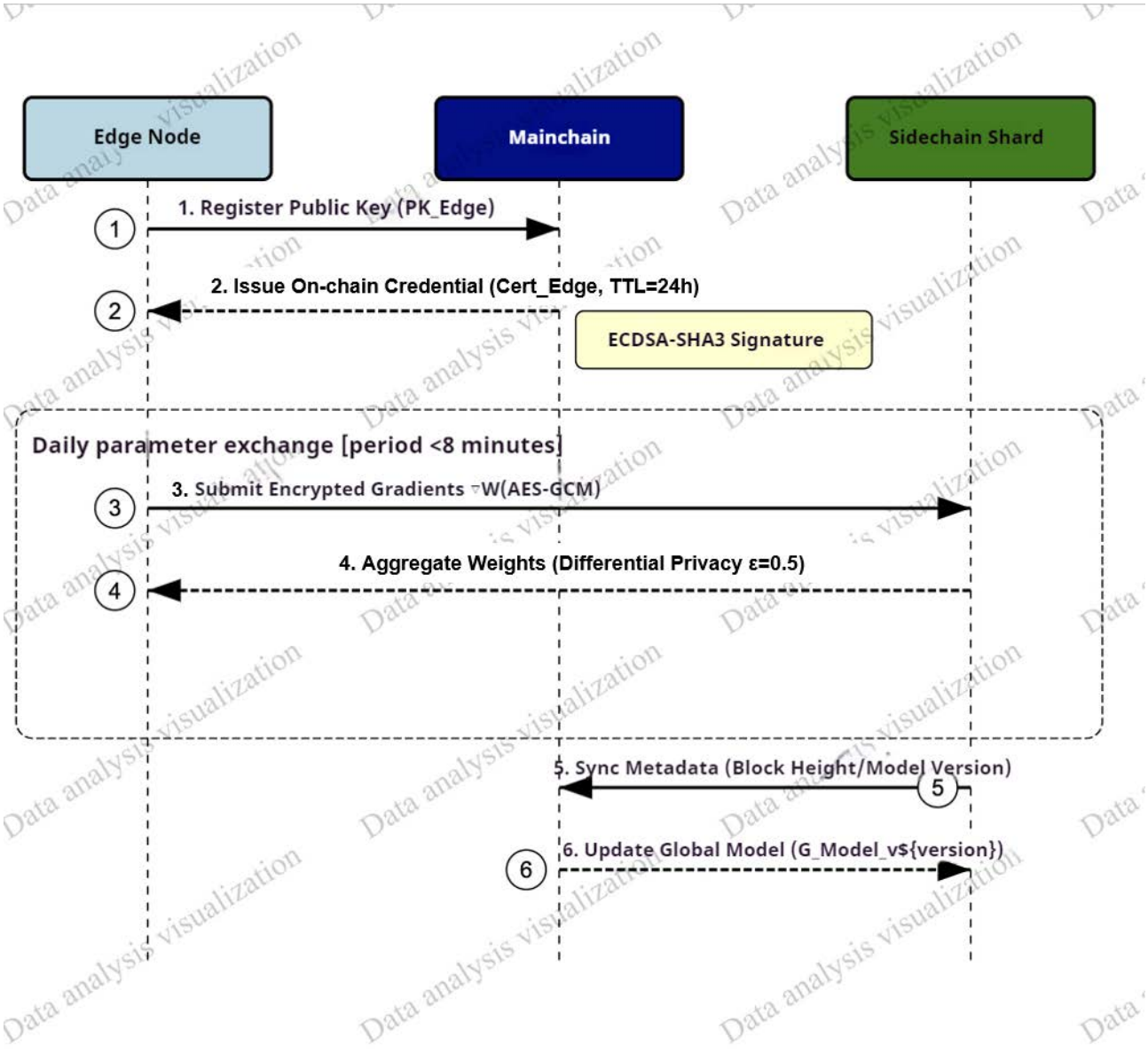


**Figure 6 Federal learning parameter exchange protocol**

This is of great significance to the medical field, where medical data often involves patient privacy, and federated learning can realize collaborative training of data between multiple medical institutions to improve the accuracy and effectiveness of medical models without disclosing the original data.

### 4.3.2 Cross-chain interoperability

Cross-chain interoperability is also the focus of future research. The atomic chain exchange designed based on the HarmonyOS protocol: $Latency = 2\delta_{prop} + \delta_{verity}$, is expected to realize the heterogeneous chain latency of less than 50 ms, which will improve the efficiency of inter-bank settlement by 40%. In cross-border payment scenarios, the cross-chain interoperability technology can realize the rapid docking of blockchain systems between banks in different countries, shorten the settlement cycle, improve the efficiency and security of financial transactions, and

promote the innovative development of the financial industry.

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