SPChain: Blockchain-based Medical Data Sharing and Privacy-preserving eHealth System

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Abstract

The development of eHealth systems has brought great convenience to people’s life. Researchers have been combining new technologies to make eHealth systems work better for patients. The Blockchain-based eHealth system becomes popular because of its unique distributed tamper-resistant and privacy-preserving features. However, due to the security issues of the blockchain system, there are many security risks in eHealth systems utilizing the blockchain technology. i.e. 51% attacks can destroy blockchain-based systems. Besides, trivial transactions and frequent calls of smart contracts in the blockchain system bring additional costs and security risks to blockchain-based eHealth systems. Worse still, electronic medical records (EMRs) are controlled by medical institutions rather than patients, which causes privacy leakage issues. In this paper, we propose a medical data Sharing and Privacy-preserving eHealth system based on blockchain technology (SPChain). We combine RepuCoin with the SNARKs-based chameleon hash function to resist underlying blockchain attacks, and design a new chain structure to make microblocks contribute to the weight of blockchain. The system allows patients to share their EMRs among different medical institutions in a privacy-preserving way. Besides, authorized medical institutions can label wrong EMRs with the patients’ permissions in the case of misdiagnosis. Security analysis and performance evaluation demonstrate that the proposed system can provide a strong security guarantee with a high effi-

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1. Introduction

The era of big data brings new opportunities and challenges to medical field. Researchers have found that the dissemination of medical data has been perceived to be a breakthrough for the discovery of new techniques and therapies for curing diseases. Through the analysis of medical data, many diseases can be effectively prevented and treated. i.e., artificial intelligence techniques are utilized on diagnostics in glaucoma [1], hyperactivity [2], and Parkinson’s disease [3] via medical data sharing and analysis.

In order to provide a more efficient and flexible service for both patients and medical institutions, eHealth systems are proposed to save, manage, transmit and reproduce digital patient medical records. Currently, eHealth systems are mainly divided into traditional central server-based eHealth systems and cloud-based eHealth systems. In traditional central server-based eHealth systems, EMRs are stored in a single server controlled by a medical institution. In this circumstance, medical data sharing is difficult and inefficient, and privacy leakage problems arise frequently since patients lose control of their medical data. What’s worse, once the central server goes down, the medical data will be lost, and it will be difficult to retrieve the data.

As for cloud-based eHealth systems, medical institutions outsource EMRs to cloud servers. The migration of medical records to cloud-based platforms [4] has facilitated the sharing of medical data between healthcare and research institutions, enabling faster and more convenient exchange in a manner previously not possible. However, guaranteeing the integrity and confidentiality of the outsourced medical data is a daunting task. Moreover, patients need to register repeatedly in different medical institutions, which brings trivial records to patients. Worse still, the privacy of patients is still a blank check signed by medical institutions. In recent years, many accidents about medical records
leakages [5] [6] [7] have occurred frequently. Therefore, eHealth systems crave innovations to assure the security and privacy of medical records.

Blockchain, which is widely leveraged in cryptocurrency systems [8], [9], is a promising technology that can be used to maintain a transparent ledger and share data among participants. With the tamper-resistant and distributed nature, the blockchain technology can provide integrity and restoration guarantees for medical records. Many countries have combined the blockchain technology with eHealth systems and achieved great success. For instance, Estonia [10] makes use of the blockchain technology to provide patients with safer and more convenient medical services. An ample amount of solutions, i.e. [11], [12], [13], strive to leverage the latest technology, such as smart contracts and privacy protection modules, to enhance the operability and confidentiality of eHealth systems. Through the literature review, it would be an effective way for blockchain to serve as a decentralized storage and replace the central servers, but there still remain some drawbacks.

The most intractable issue is the underlying security of blockchain-based eHealth systems. These systems treat the blockchain system as a secure and trusted ledger in public networks. The hypothesis is unrealistic since many well-known events about blockchain attacks in stealing blockchain properties, malicious manipulations, double spending and exploiting bugs in smart contracts [14] [15] [16] have occurred in succession. Some of these attacks target at mining strategies and protocols, allowing attackers to obtain additional rewards [17] [18]. But some other attacks may be more serious for the attackers can totally control the consensus protocols or the issuance of cryptocurrencies, which would completely destroy the blockchain system. In order to build a robust blockchain-based eHealth system, we need to take the underlying security of the blockchain-based eHealth system into consideration.

Trivial records are another obstacle to the development of eHealth systems. Existing blockchain-based eHealth systems regard medical records as transactions in a blockchain system. These systems utilize smart contracts and the scripting language to exchange medical data between medical institutions with
blockchain systems. Due to the data storage and exchange model, the medical data are scattered in blockchain system. In this case, consulting the medical records of patients in a mass of block data is inefficient. And obtaining a patient’s whole medical records in such systems consumes a lot of time. In addition, some mechanisms leverage extra interfaces to integrate the medical records. e.g., schemes in [19] and [11] utilized smart contracts to retrieve the whole medical histories of a patient. In this construct, users need to invoke smart contracts frequently, which brings more gas cost for users. Worse still, attackers may exploit loopholes in the smart contracts to steal the medical records. Therefore, we need an effective design which can integrate the medical records and make it more convenient for patients to access their medical records.

As for the privacy of patients, most schemes default that the medical data is controlled by medical institutions alone. Under the circumstance, patients lose control of their medical data. What’s worse, the medical institutions may traffic the data to lawbreakers for illegal benefits, which would violate the patients’ safety. Since the medical data is jointly generated by patients and medical institutions, we believe that the data should be the common property of both participants. Thus, a dual control scheme for patients and medical institutions is desirable in the E-health time.

In terms of the above problems, we combine RepuCoin [20], the first blockchain system that can resist 51% attacks, with the SNARKs-based chameleon hash function [21], and propose a medical records sharing and privacy-preserving systems based on blockchain (SPChain). Specifically, the contributions of this paper are as follows:

- We propose a blockchain-based medical records sharing and privacy-preserving eHealth system (SPChain). Patients in SPChain can share their medical records among different medical institutions without registering repeatedly. In the case of misdiagnosis, SPChain provides special transactions for patients to label wrong medical records. Besides, we design a dual control scheme for participants to protect the rights of both parties.
• We combine the SNARKs-based chameleon hash function and RepuCoin to construct SPChain. Notably, we propose a new chain structure to make microblocks contribute to the weight of blockchain. In addition, we design a reputation-based reward system to incentive medical institutions to participate in the consensus mechanism.

• We present security analysis to demonstrate that SPChain resists the blockchain underlying attacks such as flash attacks and selfish mining attacks. And the experiments prove that SPChain is practical and efficient in terms of throughput.

1.1. Organization

The remaining part of the paper is organized as follows. We begin by introducing some related works in Section 2. The third section is concerned with some preliminaries we used. In Section 4, we describe the system model and the design goals. The detailed blockchain-based medical data sharing and privacy-preserving eHealth system is given in Section 5. Section 6 illustrates the evaluation and security analysis of our scheme. Finally, we give the conclusion and future work.

2. Related Works

In this section, we first review some blockchain-based eHealth systems, then we list the drawbacks of these systems.

In order to prompt patients to engage in the details of their healthcare and restore agency over their medical data, Azaria et al. [11] proposed a decentralized record management system to handle EMRs. The system utilized smart contracts to manage medical records of patients. With modular design, patients can design access control rules and share their EMRs with different institutions. The authors also designed reward system to incentive researchers and public health authorities to participate in the network as blockchain miners.
To preserve patients’ privacy in the process of disseminating EMRs, Xia et al. [12] designed a system that addresses the issue of medical data sharing among medical big data custodians in a trust-less environment. The system employed smart contracts and an access control mechanisms to effectively trace the behavior on the data, and revoked access to violated rules and permissions on data. With a data custodian system, the system can monitor entities that access data for malicious behaviors.

Cao et al. [22] proposed a secure cloud-assisted eHealth system to protect outsourced EMRs from illegal modifications. The key idea of the system is that the EHRs can only be outsourced by authenticated participants and each operation on outsourced EMRs is integrated into the public blockchain as a transaction. The system took into account the situations of a single doctor and multiple doctors and utilized key exchange protocol to protect the privacy of EMRs. The tamper-proofing property of blockchain guaranteed the correctness and integrity of EMRs.

Xia et al. [13] proposed a permissioned blockchain framework to achieve medical data sharing in cloud environments. In the scheme, the authors designed authentication and verification protocols to set permissions and distribute keys for users. The system permits users to request data from the shared pool after their identities and cryptographic keys are verified.

All existing blockchain-based eHealth systems have at least one of the following drawbacks:

**Can not resist blockchain underlying attacks.** All the blockchain-based eHealth systems do not take the blockchain underlying attacks into consideration. We hold the opinion that the security of blockchain is the basic guarantee in constructing blockchain-based eHealth systems. Natoli et al. [23] and Bonneau et al. [24] point out that some attacks can destroy the blockchain-based system. In this situation, the blockchain-based system no longer holds the nature of tamper-resistant and privacy-preserving. There is no essential difference between the blockchain system and the traditional medical system in this way.
**Trivial records.** In the most blockchain-based eHealth systems, the records are growing horizontally, which means that the new records are attached in the latest block. This structure leads to trivial patient records and it is not convenient to integrate the history of patients’ records. In addition, patients need to register and be checked repeatedly in different medical institutions.

**Invoking smart contracts frequently.** In some blockchain-based eHealth systems such as [11], the authors utilize smart contracts to manage medical data. This design is convenient for medical institutions but not friendly to patients, since patients need to invoke smart contracts frequently and the invocation of smart contracts consumes gas in Ethereum.

**Medical data centralization.** Most schemes default that medical data is controlled by medical institutions alone. In this situation, patients can not protect their privacy since they lose control of their EMRs. In this paper, we ensure that EMRs should be the common property of patients and medical institutions, and participants must be approved by each other before they can use the data.

### 3. Preliminaries

In this section, we formally define the preliminaries used in SPChain, including the SNARKs-based chameleon hash function and RepuCoin.

#### 3.1. Chameleon hash function for redactable blockchain

The concept of chameleon hashing was put forward by Krawczyk and Rabin [26], building on the notion of chameleon commitments. Up to now, there are many chameleon hash function schemes which satisfy different properties, such as Ateniese and Medeiros [27], identity-based chameleon hash function [28] and labeled chameleon hash function [29]. However, as discussed in [30], they are non-applicable for constructing redactable blockchains. We choose a SNARKs-based chameleon hash function given in [21] to construct SPChain. A key-exposure-free SNARKs-based chameleon hash is specified by a tuple \((\text{HGen}, \text{Hash}(m, \text{hk}), \text{HVerify}, \text{Hcol})\) of efficient algorithms as follows:
• HGen(1^λ). Run \((csr, \tau) \leftarrow \text{SN.Setup}(pp)\). Pick \(x \leftarrow R \mathbb{Z}_p\), \(h_2 \leftarrow R \mathbb{G}_1\), and set \(h_1 = [x]_1\) and \(\hat{h}_1 = [x]_2\). Set \(hk = (h_1, \hat{h}_1, h_2, crs)\) and \(tk = (x)\).

• Hash(m, hk). For message \(m\), pick \(r\) randomly from \(\mathbb{Z}_p\) and compute \(h = h_1^r h_2^m\) and \(R = g^r\). Then give a proof \(\pi\) for the following relation by \(\text{SN.Prove}\):

\[
\mathcal{L} = \{(h, h_1, \hat{h}_1, h_2, m) : \exists (R) : e\left(\frac{h}{h_2^m}, [1]_2\right) = e(R, \hat{h}_1)\}
\]

• HVerify(m, hk, (h, \zeta)). Check \(\text{SN.Verify}(crs, h, m, \pi)\) and output 1 if this is correct, otherwise output 0.

• Hcol(tk, (h, m, \pi), m'). First check the proof and if it is correct, then compute a collision as \(R' = \left(\frac{h}{h_2^m}\right)^\frac{1}{2}\). Then give a proof for the following relation by \(\text{SN.Prove}\):

\[
\mathcal{L} = \{(h, h_1, \hat{h}_1, h_2, m) : \exists (R') : e\left(\frac{h}{h_2^m}, [1]_2\right) = e(R', \hat{h}_1)\}
\]

3.2. Blockchain and RepuCoin

The blockchain is a data structure and serves as a distributed ledger in which multiple transactions are maintained by trustless nodes in a P2P network. Information may include data records of different types, such as cryptocurrency transactions, smart contracts and account balances.

Typically, each block contains a hash pointer that points to its previous block, a timestamp, and the transaction data. The block can be chained to the blockchain, only if the validity of its transaction data is verified by a majority of nodes. The blockchain technique can be generally classified into two types: private (consortium) blockchain and public blockchain.

RepuCoin. Yu et al. [20] proposed a system named RepuCoin which is the first system to tolerate attacks compromising 51% of the network’s computing resources, even if such power stays maliciously seized for almost a whole year. RepuCoin can achieve a high throughput of 10000 transactions per second (TPS).
The existing systems link computing power and voting rights to resist Sybil attacks and improve the throughput of the system. But these systems are still under some computing power-based attacks such as 51% attacks, selfish mining attacks and so on. RepuCoin separates computing power and voting rights, and uses a notion of reputation to define a miner’s power in terms of its work performed over the lifetime of a blockchain. Even if the attacker has 99% of the computing power, it cannot attack the system successfully.

RepuCoin adopts the block structure in bitcoin-NG \cite{31} system which contains keyblocks and microblocks. The formats of a keyblock and a microblock are illustrated in Figure\cite{1}. RepuCoin proposes a weighted vote-based consensus to constitute the consensus group. In particular, each member of the consensus committee is given weight related to that member’s reputation. In order to reach an agreement, RepuCoin needs both a sufficient number of votes and a collective weight of a majority.

![Figure 1: The formats of a keyblock and microblock in RepuCoin](image)

4. System and threat model

In this section, we first present the architecture of SPChain, then list the requirements that SPChain should satisfy. Finally, we give out the threat model.

4.1. High-level overview

As shown in Figure\cite{2} there are two participants in our system: patients and medical institutions. The procedure that patients consult medical institutions in SPChain is illustrated as follows.
Firstly, a patient $\tilde{P}_i$ sends transactions to register with medical institutions $\tilde{M}_i$, and provides it with auxiliary information such that $\tilde{M}_i$ generates diagnosing records for $\tilde{P}_i$. Then diagnosing records are encrypted with the symmetric key of $\tilde{P}_i$.

After generating the diagnosing records, $\tilde{P}_i$ generates the corresponding transactions and sends them to the blockchain network. Then $\tilde{M}_i$ participants in mining to gain rights to commit transactions into blocks. In return, the winner of mining process gains rewards.

When the patient $\tilde{P}_i$ need to visit another medical institution $\tilde{M}_j$, $\tilde{P}_i$ can access the medical information and medical history in SPChain, and do not need double registration. Besides, the record history in blockchain can be extended by issuing special type transactions. In the case of misdiagnosis, patients can send transactions to label the wrong records without influencing other transactions in SPChain.

### 4.2. Design goals

SPChain consists of patient nodes and medical institution nodes. Here we define medical institution nodes working as miners which can build reputations by participating in consensus mechanism and dealing with the transactions. Thus our system can adopt consortium blockchain. SPChain supports medical
records update, label and retrieval. Within the adversary, SPChain should satisfy the following security requirements:

- **Confidentiality.** The contents of EMRs should not be recovered by unauthorized medical institutions or attackers.

- **Label and correctness.** Wrong EMRs can be labeled by authorized medical institutions and patients should be able to verify the correctness of the labeled EMRs.

- **Integrity.** The integrity of EMRs should be guaranteed. Any illegal modifications by unauthorized medical institutions should be detected by the system.

- **Privacy.** In SPChain, the privacy of patients’ EMRs should be preserved. In other words, without the permission of patients, other medical institutions can not access the contents of EMRs.

4.3. Adversary model

In the adversary model, miners in SPChain are similar to those in RepuCoin. We hold the assumption that the number of Byzantine nodes in the system does not exceed one third of the total number of nodes. They may behave maliciously to gain additional rewards. We will consider the attacks from two different angles: one is in terms of blockchain system, the other is in the aspects of the SPChain system. As for the former, we consider the 51% attack, flash attack and selfish mining attack. For the latter, we take reputation fraud attacks and inhibition attacks into consideration.

**Blockchain attacks:**

51% attacks [32] and flash attacks [24]. An attacker can obtain a temporary majority of computing power by renting enough mining capacity, which would break the security assumption of proof-of-work based systems.

Selfish mining attacks (block withholding attack) [18]. In this case, an attacker controls a significant amount (> 25%) of mining power in the system.
The selfish miner instead mines the block continuously maintaining its track and fails to publish it to the network. The attacker only publishes the chain of the transaction to increase the amount of revenue earned.

**SPChain attacks:**

Reputation fraud attacks. A malicious medical institution creates "zombie" patient nodes to increase its reputation.

Inhibition attacks. When a medical institution becomes a leader successfully, it may only package its own transactions and ignore others’ transaction on purpose.

5. The SPChain system

In this section, we present details describing the different concepts and modules underlying SPChain. We first introduce basic definitions about transactions, blocks and chain structures. Then we detail consensus mechanism in Section 5.2 and SPChain in Section 5.3.

5.1. Basic elements in SPChain

5.1.1. Transaction

As shown in Figure 3, there are three types of transactions in our system, register transactions, medical transactions and label transactions. Transactions in SPChain are presented as triplets \((Type, Data, sig)\), where \(Type\) denotes the type of transaction, \(Data\) identifies the contents in different types of transactions, and \(sig\) specifies the signature of the transaction sender.

**Register transaction.** This transaction is send to the medical institution which the patient wants to be treated at the first time. We denote a register transaction as \(T_R = (Register, H(ID||Age||\ldots), sig_P)\), where \(Register\) specifies a register transaction, \(H(ID||Age||\ldots)\) denotes the hash value of a patient’s identity, age and other auxiliary information, and \(sig_P\) is the signature of the patient. Every patient should send this transaction to register in SPChain.

**Medical transaction.** This transaction is send by patients to upload records to the blockchain. We define an update transaction \(T_M = (Medical, CH\)
\[(E_M E_P(EMRs))||\pi||Pointer, sig_P\), where \textit{Medical} indicates that this is a medical transaction, \(CH(E_M E_P(EMRs))\) identifies the chameleon hash value of the encrypted EMRs while \textit{Pointer} represents the pointer to the encrypted EMRs, \(\pi\) denotes the proof of generated by \textit{SN.Prove} and \textit{sig_P} is the signature of the patient.

**Label transaction.** When medical errors occurs, patients send this transaction to label the wrong records. We define a label transaction \(T_M = (\text{Label}, Hash_T_M, CH(E_M E_P(EMRs')), ||\pi'||Pointer, sig_P),\) where \textit{Label} indicates the transaction is a label transaction, \(Hash_T_M\) is the transaction hash value of the medical transaction to be labeled. \(CH(E_M E_P(EMRs')), \pi', Pointer\) and \(sig_P\) are the same as the above definitions.

In our system, register transactions are packed into keyblocks while medical transactions and label transactions are attached to the microblocks bound to the patients.

![Figure 3: The structure of transactions in SPChain](image)

### 5.1.2. Block and Chain Structure

**Block.** Similar to RepuCoin, there are two kinds of blocks in our system, keyblock and microblock. Figure 4 shows the structure of a keyblock and a microblock. Unlike RepuCoin, keyblocks contain register transactions in our system. We use \textit{Prev.keyblock hash} and \textit{last.microblock hash} to mine keyblocks and we will detail mining strategy in the following part.
In our system we regard a microblock as a patient block. From Figure 4, we can see that every patient holds one and only one microblock which stores the whole medical records of the patient in different medical institutions. In order to facilitate the retrieval of records, we use merkle tree structure to construct the institution hash root. To achieve modification in a patient block, we use SNARKs-based chameleon hash function instead of SHA-256 to calculate Medical institution hash root. The leaf nodes of the tree are the basic information (for example, the public key which is certified by authority) of medical institutions. Figure 5 details the calculation of hash root. There are two cases in the calculation, an even number $n$ and an odd number $n$. Medical transactions and label transactions are attached behind the basic information in chronological order.

**Chain structure.** Miners in RepuCoin and bitcoin-NG system solve bitcoin-like puzzles to create keyblocks. The puzzle is defined as follows:

$$H(\text{prev\_keyblock\_hash}\|\text{Nonce}\|\text{PK}) < \text{target},$$

where $H(\cdot)$ is a cryptographically secure hash function, prev_keyblock_hash is
the hash value of the previous keyblock, $PK$ is the miner’s public key and $target$ is a target value defined by the system.

In such systems, there is no transaction data contained in keyblocks and the microblocks do not contribute to the weight of the chain. To increase the weights of microblocks, we design a new chain structure given in Figure 6. The inputs of mining keyblocks include not only the hash of the last keyblock, but also the hash of the last microblock appended to the penultimate keyblock. Thus, we redefine the mining strategy as follows:

$$H(prev\text{\_keyblock\_hash}\|penu\text{\_microblock\_hash}\|\text{Nonce}\|PK) < target,$$

where $penu\text{\_microblock\_hash}$ is the hash value of the last microblock of the penultimate keyblock.

We call a round $r$ is a process where a keyblock and the corresponding microblocks are generated. In each round keyblocks are the sorting index of the following microblocks, which means the microblocks are mined in the order of the register transactions packed in the keyblocks. When sending medical or label transactions, patients should append rounds number to transactions to
Figure 6: The chain structure in SPChain. From the blue arrow we can see that the input of the keyblock $i$ is coming from two parts, the hash value of the microblock $M_{i-2}$ and the hash value of the keyblock $i-1$. The genesis part is set by the system management.

shard them in the consensus group.

To mitigate the fork problem, we use the pinned blocks mentioned in RepuCoin. A pinned keyblock is a keyblock that is agreed upon and signed by the consensus group. A pinned keyblock is final and canonical, and all keyblocks that conflict with a pinned keyblock are considered invalid. Based on this definition, we also define the pinned transactions. Each time the transactions are generated by patients, the medical institutions collect the transactions sent to themselves, and propose them to the consensus group. The group verifies the received transactions and signs to the valid transaction. Then the medical institutions append the pinned transactions to the corresponding microblocks. Figure 7 details the formats of a pinned keyblock and pinned transaction.

Figure 7: The formats of a pinned keyblock and a pinned transaction
5.2. Consensus Mechanism and Reward System

**Consensus mechanism.** We combine proof-of-work with Byzantine agreement protocol to form the consensus mechanism. Medical institutions create keyblocks and validate transactions to gain reputation score, which decides whether the medical institutions can join the consensus group. We choose the $X$ miners with the top reputations to constitute the consensus members. Re-

| Symbol | Description |
|--------|-------------|
| $L$    | the length of the current blockchain; |
| $c$    | the size of a block chunk, i.e., the number of keyblocks contained in a chunk, pre-defined by the system; |
| $l$    | $l = \lceil \frac{L}{c} \rceil$ is the number of keyblocks contained in a blockchain with length $L$; |
| $N$    | the total number of the current microblocks; |
| $T$    | total transactions in blockchain; |
| $TML_i$| the number of medical transactions and label transactions whose receiptor is miner in chunk $i$; |
| $TR_i$ | the number of register transactions whose receiptor is miner in chunk $i$; |
| $H$    | a binary presenting whether the miner is honest (“1”) or not (“0”); |
| $mean_i$| the mean value of medical transactions and label transactions (if $i = TML$) or register transactions (if $i = TR$) created by a miner or a leader across all epochs in the blockchain, respectively; |
| $s_i$  | the standard deviation corresponding to $mean_i$, for $i \in \{TML, TR\}$; |
| $R_1$  | reputation score defined in RepuCoin; |
| $(a, \lambda)$ | reputation system parameters. |

puCoin gives a method to calculate the reputation score $R_1$ by evaluating the frequency of miners creating keyblocks and microblocks. In our system, we propose another method to calculate the reputation score $R_2$. In our reputation algorithm, we assess the number of patients and The notions are defined in Table 1 and $R_2$ is calculated in Algorithm 1. The final reputation score of a
medical institution is defined as \( R = \frac{1}{2}(R_1 + R_2) \).

### Algorithm 1

The reputation algorithm

**Input:** \( L, c, l, TR_i, TML_i, R_1, a \) and \( \lambda \)

**Output:** The miners’ reputation \( R_2 \in [0, 1] \).

1. \( mean_{TR} = \frac{\sum_{i=1}^{l} TR_i}{N} \)
2. \( mean_{TML} = \frac{\sum_{i=1}^{l} TML_i}{T} \)
3. \( s_{TR} = \sqrt{\frac{1}{l} \cdot \sum_{i=1}^{l}(TR_i - \frac{\sum_{i=1}^{l} TR_i}{N})^2} \)
4. \( s_{TML} = \sqrt{\frac{1}{l} \cdot \sum_{i=1}^{l}(TML_i - \frac{\sum_{i=1}^{l} TML_i}{T})^2} \)
5. \( q_1 = \frac{mean_{TR}}{1 + s_{TR}} \)
6. \( q_2 = \frac{mean_{TML}}{1 + s_{TML}} \)
7. \( x = q_1 \cdot q_2 \cdot L \)
8. \( f(x) = \frac{1}{2}(1 + \frac{x - a}{\lambda + |x - a|}) \)
9. \( R_2 = min(1, H \cdot f(x)) \)
10. \( R = \frac{1}{2}(R_1 + R_2) \)

**Reward system.** In SPChain there are two types of rewards, transaction fees and mining rewards. Medical institution can define the determined amount of different type transactions. After mining a pinned keyblock successfully, the miner can get a reward contained the predefined mining rewards and the register transaction fees in the keyblock. The same as keyblock rewards, microblock rewards also contain mining rewards and transaction fees, which are shared among the reputable miners who create the microblocks and verify the transactions.

### 5.3. SPChain

By utilizing the transactions, blocks, chain structure and consensus mechanism given above, we propose the blockchain-based medical data sharing and privacy-preserving system, we call it SPChain. Figure 8 details the orchestration of SPChain. The system consists of the following algorithms, **Setup, Register, Upload, Label** and **Share**.

**Setup.** This algorithm takes public parameters as inputs, and outputs symmetric encryption key pair \( K \), bitcoin public-private key pair \( (PK, SK) \) and
address $address_{PK}$ for patients and medical institutions. In addition, the algorithm also initializes the SNARKs-based chameleon hash function parameters for medical institutions.

- **Patients:** $K \leftarrow AES(seed)$,
  $\{(PK, SK) || address_{PK}\} \leftarrow Bitcoin(rand)$.

- **Medical institutions:**
  $K \leftarrow AES(seed)$,
  $\{(PK, SK) || address_{PK}\} \leftarrow Bitcoin(rand)$,
  $\{hk = (h_1, \hat{h}_1, h_2, crs), tk = (x)\} \leftarrow HGen(1^\lambda)$.

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Figure 8: The orchestration of SPChain

Register. In this algorithm, patients send register transactions to the medical institutions to register in our system.

(1) Patient $\tilde{i}$ sends register transaction $T_R$ to medical institution $\tilde{C}$. The transaction contains the proper register fees to $\tilde{C}$. 

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(2) Medical institutions (miners) collect register transactions and pack them into keyblocks. Then Medical institutions propose keyblocks to consensus group.

(3) The consensus group verifies the validity of the keyblocks, and runs Byzantine agreement protocol to decide which keyblock is the final pinned keyblock (if multiple conflicting keyblocks are proposed). Then the reputable miner is selected to commit microblocks according to the register transactions in the keyblock.

Upload. The serial number (4)-(6) given in Figure ?? illustrate the process of a patient uploading the medical records. There are three cases in this algorithm, patient ˜ \( j \) is diagnosed in medical institution \( \hat{A} \) for the first time; patient ˜ \( j \) updates EMRs in the same medical institution \( \hat{A} \); or patient ˜ \( j \) is diagnosed in another department of medical institution \( \hat{B} \). We describe the three cases in detail in Figure 9.

![Figure 9: The three cases in Upload](image)

Case 1: Patient ˜ \( j \) is diagnosed in medical institution \( \hat{A} \) for the first time.

(4′) Patient ˜ \( j \) registers in the system and is diagnosed in medical institution
Then $A$ generates EMR for $\tilde{j}$ and the EMR is successively encrypted in the following formulas,

\[
E_{K_j}(EMR) \xleftarrow{K_j} EMR,
\]

\[
CH(E_{K_A}(E_{K_j}(EMR))) \xleftarrow{K_A} E_{K_j}(EMR),
\]

\[
(CH(E_{K_A}(E_{K_j}(EMR)))||\pi) \xleftarrow{(h_1,h_2,crs)} E_{K_A}(E_{K_j}(EMR)).
\]

After that, the patients $\tilde{j}$ generates transaction $T_{M_j}$ and send it to the medical institution $\tilde{A}$. Note that the ciphertext $E_{K_A}(E_{K_j}(EMR)$ is stored in the database of medical institution $\tilde{A}$.

(5') The consensus group classifies these transactions in several rounds according to the round numbers, and verifies the transactions proportionally according to the reputation score.

(6') The consensus group verifies the validity of the transactions and signs to them. To become pinned transactions, the transactions should not only get two-thirds of signatures, but also get more than two-thirds of the reputation. Here we can use aggregate signature to reduce the cost. Then the medical institution $\tilde{A}$ appends the pinned transaction to the microblock $P_{\tilde{j}}$.

Case 2: Patient $\tilde{j}$ updates EMRs in the same medical institution $\tilde{A}$.

In this case, patient $\tilde{j}$ goes to the medical institution $\tilde{A}$ for treatment again and updates the EMRs on the basis of Case 1.

(4'') $\tilde{A}$ generates $EMR^*$ for $\tilde{j}$ and invoke algorithms in $Upload$ to get $E_{K_A}(E_{K_j}(EMR^*))$, $CH(E_{K_A}(E_{K_j}(EMR^*)))$ and $\pi^*$.

(5'') Patient $\tilde{j}$ generates transaction $T'_{M_j}$ and sends it to medical institution $\tilde{A}$. Then the consensus group validates $T'_{M_j}$ and signs it.

(6'') After the transaction $T'_{M_j}$ is pinned, medical institution $\tilde{A}$ appends the transaction to the microblock $P_{\tilde{j}}$.

Case 3: Patient $\tilde{j}$ is diagnosed in another department of medical institution $\tilde{B}$.

(4'''') $\tilde{B}$ generates $EMR'$ for $\tilde{j}$ and invoke algorithms in $Upload$ to get $E_{K_B}(E_{K_j}(EMR'))$, $CH(E_{K_B}(E_{K_j}(EMR'))) and \pi'$.

(5'''') Patient $\tilde{j}$ generates transaction $T'_{M_j}$ and sends it to medical institution
Then the consensus group validates $T_{M_{j}}'$ and signs it.

(6′′′) After the transaction $T_{M_{j}}'$ is pinned, medical institution $\hat{B}$ appends the transaction to the microblock $P_{j}$.

Label. In this algorithm, patient $\tilde{j}$ labels the wrong $EMRs$ in the case of misdiagnosis.

(7) In this case, the transaction which contains the wrong $EMR$ should be labeled by a label transaction. $\hat{B}$ generates the correct $EMR''$ for $\tilde{j}$ and invoke algorithms in $Upload$ to get $E_{K_{\hat{B}}}(E_{K_{j}}(EMR''))$, $CH(E_{K_{\hat{B}}}(E_{K_{j}}(EMR''))) \text{ and } \pi''$.

(8) Patient $\tilde{j}$ generates transaction $T_{L_{j}}$ and sends it to medical institution $\hat{B}$. Then the consensus group validates $T_{L_{j}}$ and signs it.

(9) Finally the pinned transaction $T_{L_{j}}$ labels the wrong transaction in microblock $P_{j}$. And patients can verify the new transaction through the new proof $\pi''$.

Share. This algorithm is illustrated as follows:

(10) Patient $\tilde{j}$ wants to go to medical institution $\hat{D}$ for diagnosis. $\tilde{j}$ can access the corresponding transaction records he/she wants to share to $\hat{D}$, i.e. $\tilde{j}$ wants to share his/her medical records of medical institution $\hat{A}$ with $\hat{D}$ to get a better diagnosis. $\tilde{j}$ asks $\hat{A}$ to decrypt the cipher text with the key $K_{\hat{A}}$. Then $\tilde{j}$ decrypts the result with $K_{j}$ and obtain the $EMR$. Thus $\tilde{j}$ can obtain the entire history of diagnosis.

6. Evaluation and security analysis.

In this section, we first evaluate the performance of SPChain, then we discuss whether SPChain can fulfill the requirements and prevent attacks proposed in Section 4.

6.1. Evaluation

We evaluate the performance of SPChain in terms of throughput. We test our system on a computer with windows 10 system, an intel(R) core(TM) i5-6500 CPU, and 16 GB DDR 4 of RAM.
Throughput. In this part we analyze the maximum throughput of our system. We assume the consensus group controls 90% computing power. Since keyblocks in SPChain contain register transactions, so we analyze the throughput in terms of keyblocks and microblocks. From Figure 10 we can see that the keyblock throughput is similar to that of bitcoin systems since they are under the same mining strategy. And when fix the block size to 4MB, the system has higher throughput than that of 1MB and 2MB. As for microblocks, our results in Figure 11 show that when the block size is fixed, as the number of consensus nodes increases, throughput decreases gradually. For example, with the block size 1MB, the through decreases from 145 TPS to 116 TPS. Besides, from Figure 11 we can see that when fix the block size to 2MB, the system has higher throughput than that of 1MB and 4MB. In particular, when the consensus group consists of 4 nodes, the through can reach 218 TPS.

Reputation score and consensus time. We simulate the reputation cores of medical institutions by choosing the top 15 mining pools given in [20].
Figure 11: The throughput of SPChain (microblocks)

set the parameter $a = 5000$ and $\lambda = 20000$. Figure 12 describes the distribution of miners with different reputation scores over time. With the operation of SPChain, the reputation score of miners increase gradually, and the higher computing power the miner holds, the higher the reputation score it receives.

We now compare the performance of our system with other blockchain-based eHealth systems. From Table 2 we can see that BBDS, MeDshare and MedRec can not label wrong EMRs in the case of misdiagnosis. And these systems are vulnerable to blockchain underlying attacks such as flash attacks and selfish mining attacks. From the table we can conclude that SPChain can resist blockchain underlying attacks while achieving medical data sharing and privacy-preserving.

6.2. Security

In this section, we first discuss whether SPChain can fulfill the requirements proposed in Section 4.2. Then we describe in details how SPChain prevents attacks proposed in Section 4.3.
Figure 12: The throughput of SPChain (keyblocks)

| Scheme  | Share | Privacy | Label wrong records | Flash attacks | Selfish mining attacks |
|---------|-------|---------|---------------------|---------------|-----------------------|
| BBDS    | ✓     | ✓       | ×                   | ×             | ×                     |
| MeDshare| ✓     | ✓       | ×                   | ×             | ×                     |
| MedRec  | ✓     | ×       | ×                   | ×             | ×                     |
| SPChain | ✓     | ✓       | ✓                   | ✓             | ✓                     |

6.2.1. Property analysis

SPChain focuses primarily on four properties: confidentiality, privacy, modification, correctness and integrity.

Confidentiality and privacy. SPChain guarantees the confidentiality of patients’ EMRs. Note that the EMRs are encrypted sequentially by the patients and medical institutions with their symmetric keys. And the inputs of chameleon hash function are the ciphertext of EMRs. In this circumstance, the medical institution which generates the EMRs can not share the records with other medical institutions since they don’t have the symmetric keys of patients.
When verifying the accuracy of the chameleon hash value, the verifier receives the ciphertext of the EMRs, which won’t leak the privacy of patients either. So we claim that SPChain guarantees the confidentiality of the EMRs and preserves the privacy of patients.

Label and correctness. SPChain permits medical institutions to label wrong EMRs and allows patients to verify the correctness of the modified records. In the case of misdiagnosis, patients can ask authorized medical institutions to label the wrong EMRs with the label transaction and to generate the correct EMRs corresponding to the label transaction. With the proof $\pi$, patients can invoke $HVerify$ to check whether the modification is correct.

Integrity. SPChain provides integrity guarantee of patients’ EMRs. The medical institutions that hold the trapdoor $x$ can tamper the contents of the EMRs without changing the corresponding chameleon hash value. But with the proof $\pi$, the patients can verify the correctness and integrity of the EMRs. Thus any modifications on the EMRs can be detected by the patients, so we conclude that SPChain guarantees the integrity of the EMRs.

6.2.2. Defense against attacks

This section discusses defences of the attacks mentioned in Section 4.3.

51% attacks and flash attacks. SPChain is resilient to flash attacks. Although an attacker can gain temporary majority of computing power, the attack also need a very long period of time to gain reputation to harm the system. According to RepuCoin, an attacker that joins after 1.5 years of system operation would need to have more than 90% of the system’s computing power for 6 months to successfully attack the system. And even the attacker successfully attacks the system, he/she will lose all reputation he/she has gained since he/she joined the system.

Selfish mining attacks (block withholding attacks). SPChain pins each keyblock, and the pinned keyblocks can not be roll back. Every new created keyblock is chained behind the pinned keyblocks. So if an attacker publishes a keyblock which is conflict with the pinned keyblock, he/she can not
get advantage of gaining rewards over the honest miners because the keyblock he/she publishes would not be admitted by the system. When mining a new keyblock, the miners need to take the hash value of the previous keyblock and the last microblock of the penultimate keyblock as inputs. Since there is no conflict when generating microblocks, we do not need to consider the microblock withholding attacks. In summary, SPChain can resist selfish mining attacks.

**Reputation fraud attacks.** A malicious medical institution controls a group of "zombie" patients to generate fake transactions to cheat the system. In this way, the malicious medical institutions can gain extra reputation. In SPChain, we stipulate that every transaction contains a fixed service fee and transaction fee. The stipulation can crease the cost of reputation fraud attacks. If necessary, we advice that patients can register with their ID card.

**Inhibition attacks.** A medical institution in consensus group may intentionally ignore the transactions of other medical institutions. In this case, the consensus group always verify their own transactions first, which can increase their reputation in an unfair way. We stipulate that the transactions of medical institutions are verified proportionally according to the reputation. We illustrate the notations of reputation calculating in Table 3 and detail the transaction processing algorithm to resist inhibition attacks in Algorithm 2.

| Symbol | Description |
|--------|-------------|
| $m_i$  | the i-th medical institution; |
| $T_i$  | the transaction set of $m_i$; |
| $G$    | the consensus group; |
| $n$    | the total number of the medical institutions; |
| $R_i$  | the reputation score of $m_i$; |
| $\Delta$ | the time interval; |
| $k$    | a nonce; |
| $T_m$  | the maximum number of transactions processed by consensus group at a time; |
**Algorithm 2**: Transaction processing algorithm

**Input**: \( m_i, R_i, T_i, k, p = \sum_{i=1}^{k} |T_i|, P = \sum_{i=1}^{k} T_i, \Delta \) and \( G \).

**Output**: The pinned transaction set \( T \).

1: \( m_i \) sends \( T_i \) within \( \Delta \) to \( G \)

2: \( G \) collects \( T_i \) and forms a table \( B = [T_1, \ldots, T_n] \)

3: \( G \) selects \( t_i \in T_i \) according to reputation ranking, where \( t_i = 10 \lfloor R_i \rfloor \)

4: **Case 1**: \( k \leq N \)
   - \( G \) picks \( T_i \) from \( B \) until \( p = \sum_{i=1}^{k} |T_i| \)

5: **Case 2**: \( k > N \)
   - \( G \) picks transactions from the beginning medical institution until \( p = \sum_{i=1}^{k} |T_i| \)

6: \( P \) is the final verified set \( T \)

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7. **Conclusion and future work**

In this paper, we consider misdiagnosis and data sharing in medical scenarios. Based on RepuCoin and SNARKs-based chameleon hash function, we have proposed a medical data sharing and privacy-preserving system. In our system, patients can share their EMRs among different medical institutions in privacy-preserving way. Besides, in the case of misdiagnosis, patients can ask the authorized medical institutions to amend the wrong records. We design reputation-based consensus mechanism and reward system to guarantee that SPChain can resist the blockchain underlying attacks. We have conducted a comprehensive performance and security analysis of our system, which proves that SPChain is practical and efficient in terms of throughput.

For the future work, we intend to reduce the patients’ communication overhead and to future improve the throughput of our system.
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