A Blockchain-Assisted Trust Access Authentication System for Solid

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ABSTRACT The Solid (Social Linked Data) project focuses on data sharing and privacy security and aims to build a decentralized ecosystem that radically changes the way web applications work today. Our goal is to introduce a “trust access authentication system” to achieve secure authentication and fine-grained access control, thereby promoting the implementation of Solid. Blockchain, equipped with multiple security properties and authentication functions, is a crucial technology. In this paper, we present a blockchain-assisted system for secure authentication in Solid and for implementation of fine-grained access control policies. Specifically, we explore to integrate threshold RSA signatures in a permissioned blockchain system to enable a fault-tolerant distributed signature scheme, thereby enhancing the resilience and robustness of authentication system. Moreover, we utilize smart contracts to control transaction flows and manage access control policies automatically. Experimental results show that our proposed trust access authentication system enhances security, scales well, and is efficient and economically feasible.

INDEX TERMS Solid, blockchain, authentication, access control, smart contract, threshold signatures.

I. INTRODUCTION

Solid (Social Linked Data) is a web re-decentralization project led by Tim Berners-Lee, the inventor of the World Wide Web [1]. This project aims to build a decentralized ecosystem for current social web applications, where the data are completely owned by users themselves who can allow external applications how to use it for certain purposes such as social media [2]. This may respond to our current pressing issues on social web applications, such as Twitter, Facebook, Wikipedia, Doodle, and many other online platforms that usually store user data in centralized repositories, consequently preventing users from controlling their data. For example, they cannot reuse their data across different storage services, or specify trusted authentication and personal access control mechanisms [3]. Thus, many centralization problems have attracted proposals for re-decentralizing the web; some examples are WebBox, Diaspora, and Musubi, but none of them has been widely adopted [4]. In this context, efforts to promote Solid as a high-potential project are of great significance.

The Solid ecosystem consists of four main layers, namely, Linked Data Resources, Decentralized Web, Pod Servers, and Solid Applications, as shown in Fig. 1. The Linked Data Resources are owned by users and can be stored in personal online datastores (pods) via the Decentralized Web. To access Linked Data Resources, the Solid Applications need to obtain an identity profile from the Pod Servers, and then access data in the user’s pod. The users control their data in pods through using a resource description framework (RDF) profile stored in the pod [5], [6].

Data sharing and privacy security is one of most important concerns associated with the implementation of Solid [7]. Blockchain, as a recent technology applied in academia and industry, has attracted increasing attention to provide secure authentication and privacy for distributed systems [8], [9]. To this end, we propose the introduction of blockchains to assist Solid in developing a trust access authentication system. In a blockchain-assisted Solid application scenario, for example,
when a Solid application requests linked data resources from the pod servers, the blockchain provides secure authentication for the requestor and grants access to the corresponding resource after validation. The blockchain brings the following advantages:

- **Trustworthy Transactions:** In the blockchain, a group of participants work cooperatively to validate and record transactions and thus maintain a public ledger [10]. This non-tampering property enables the Solid entity act in trusted environments.

- **Fine-grained Access Control:** Solid uses an RDF-based access control mechanism to achieve resource authorisation [2]. Whereas, blockchain can utilize smart contracts to gain a more fine-grained effect to manage access control policies in a secure and automatic manner.

- **Traceability and Auditability:** Activities such as the Solid application’s access history, instead of being stored in pod servers, are recorded in the blockchain where all access records are traceable and auditable.

Although applying the blockchain into a Solid ecosystem is a promising development, difficulties and challenges still remain. In this paper, we only focus on how to exploit the blockchain to ensure secure authentication with fine-grained access control that is suitable for a Solid system. Digital signatures, as a key component of a blockchain system, can be integrated to provide secure authentication [11], [12]. Different from mainstream signatures such as the elliptic curve digital signature algorithm (ECDSA) adopted in the Bitcoin and Ethereum blockchains, our proposal is to introduce a threshold signature scheme in blockchain systems. Threshold signatures can enhance the robustness and resilience of an applied system while maintaining the decentralized nature of blockchains, which is why a threshold signature scheme is necessary [13]. Furthermore, threshold signatures eliminate the high cost of transmission arise from an increasing number of signatures that occurs in a multi-signature scheme. Our goal is to integrate threshold signatures with the blockchain to enhance the security performance of Solid, i.e., provide distributed yet fault-tolerant signatures to authenticate Solid entities.

Extending the previous conference version [14] that has already reported our preliminary works, we make advances and new contributions in this journal version, including: 1) adjust our centers around the “trust access authentication” to conduct more in-depth work; 2) a better representative system model is proposed, which is closer to a real Solid application scenario; 3) a new digital signature scheme is applied in blockchain systems; 4) two signature reconstruction algorithms are considered, thereby making our solutions available to many more potential applications in Solid; and 5) based on the theory and assessment in our previous version, this work implements the system designs such as developing and deploying smart contracts, integrating signature schemes in the transaction validation of permissioned blockchains, and implementing our solutions to evaluate them with benchmarks. Our main contributions are listed as follows:

- We propose a conceptual blockchain-assisted system that provides trust access authentication, suited for the web re-decentralization project Solid.
- We integrate threshold RSA signatures and the permissioned blockchain to enhance the resilience and robustness of the proposed authentication system, which can tolerate failed or corrupted peers.
- We leverage smart contracts to implement a fine-grained access control mechanism in which the access permissions on resources can be adaptively granted or revoked. We also evaluate the performance of our solutions in real-world scenarios.

The rest of this paper is organized as follows. In Section II, we present our system model. In Section III, we introduce the relevant building blocks used in our system. In Section IV, we describe how to design our proposed system in detail and provide the concrete implementation. In Section V, we present the security analysis of our system, measure the cost of smart contracts, and evaluate the performance on threshold RSA signatures. Finally, Section VI concludes the paper.

**II. SYSTEM MODEL**

In this section, we present the system model and the relevant functional descriptions. Fig. 2 shows the participants involved in our system, including Solid Applications, Blockchain Network, Pod Servers, Decentralized Web, and Linked Data Resources.

**A. SOLID APPLICATIONS**

Solid applications constitute a set of social web applications (e.g., Twitter, Facebook, and Wikipedia) that often request for access or process the linked data resources. When a Solid application is requesting an access, it needs to post a corresponding transaction to the blockchain network.

**B. BLOCKCHAIN NETWORK**

The blockchain in the proposed system adopts permissioned blockchains such as Hyperledger Fabric. Thus, the peers in a blockchain may have the following roles: submitting peers (submitter), who are responsible for submitting transactions by providing a client interface; endorsing peers (endorser), who is responsible for simulating and validating transactions with the execution of chaincodes (i.e., smart contract) [15], [16]. In general, any requests from the Solid applications...
can be recorded in the blockchain after reaching a consensus among peers.

**C. POD SERVERS**

Pod servers host a number of pods that store and process the linked data resources, and respond to the authorized access requests from Solid applications. A pod server is not controlled by any third party, and it can be from the free providers of commercial entity established by the Solid founding team or the users whose personal computers are installed and run as a node-solid server in the network.

**D. DECENTRALIZED WEB**

In a Solid ecosystem, the design of pods allow specific Solid applications to access the specific resource through a decentralized network, i.e., decentralized web. In our system, such a decentralized web monitors the blockchain, receives data operation requests, and helps transmit and store the linked data resources to corresponding pods.

**E. LINKED DATA RESOURCES**

Although differences exist between non-linked data (e.g., image, PDF file) and linked data (e.g., Turtle and JSON-LD formats) in a pod, all the data resources in Solid are grouped into data folders with public or private access rights [17]. Therefore, in our system, we do not consider their distinctions and uniformly represent them as the linked data resources.

**III. SYSTEM BUILDING BLOCKS**

In this section, we introduce the relevant building blocks used in our system, including the blockchain, distributed hash table for access control, threshold RSA signatures, and transactions.

**A. BLOCKCHAIN**

Blockchain is the core data structure that consists of key components such as the public ledger, consensus mechanism and smart contract, which enables multiple parties to participate in transactions without trusting each other [18]. Undoubtedly, the permissionless blockchains such as Bitcoin and Ethereum are the most popular blockchain systems where anyone can engage and validate transactions [4], [19]. However, our system adopts a permissioned blockchain (i.e., Hyperledger Fabric) to realize construction. The option is for two reasons: 1) transactions in a Solid ecosystem need to be scalable and fast, which in a permissioned blockchain such as Hyperledger Fabric can process thousands of transactions per second; and 2) a permissioned blockchain requires the transaction validators to be the approved selected participants, which is easy to satisfy in a Solid ecosystem.

Typical consensus mechanisms in blockchains are proof of work, proof of stake, delegated proof of stake, and practical byzantine fault tolerance (PBFT) [20]. The PBFT is used as a representative consensus algorithm for permissioned blockchains. In our design, every participating peer in the blockchain network uses an ordering service with the PBFT consensus protocol to maintain a synchronized ledger. The details on the PBFT consensus protocol are found in Castro’s scheme [21].

**B. DISTRIBUTED HASH TABLE FOR ACCESS CONTROL**

Distributed hash table (DHT), an implementation of storing access control policies that are similar to the off-chain
key-value store for blockchains, is adopted to offer privacy-aware fine-grained access control [22]. Let \( \mathcal{H} : \{0, 1\}^{256} \rightarrow \{0, 1\}^n \times \{0, 1\}^n \), where \( n \gg 256 \). That is, \( \text{hash}_\text{of\_predicate} : \text{predicate} \times \text{policy} \), where predicate maps to various permission policies corresponding to different access user \( ID \). For static access control rules, the policy keeps the same predicate for insert, update, delete, and query. In our system, the DHTs can be structured in the pod servers, which can only be updated with smart contract.

C. THRESHOLD RSA SIGNATURES

A blockchain-assisted system for Solid can ensure authenticity, integrity, pseudonymity, and non-repudiation with the help of cryptography, specifically, digital signatures [8, 23]. To achieve a single fault-tolerant signature from a group of participants, we integrate threshold signatures in the blockchain system. As the advantage of applications in Bitcoin discussed by Goldfeder et al., the threshold signatures can enhance our system’s robustness and resilience while maintaining the decentralized nature of blockchains [24].

However, applying the threshold signatures in blockchain systems has not been well exploited. In these limited studies, most threshold signatures are developed for Bitcoin based on a threshold ECDSA scheme [25]; thus, most of them focus on the improvement of security and performance for permissionless blockchains [26]. In our system, we implement an RSA threshold signature scheme based on Shoup’s work [27], in which security is proven in the random oracle model. To describe concrete construction, for example, a threshold signature with \((n, t)\), we assume a key generation center (KGC) \( D \notin P \), the actors are a group of \( n \) participants, and \( P = \{P_1, P_2, \ldots, P_n\} \), where \( t \) is the number of possible corrupted participants. In detail, we present the five general steps in threshold RSA signatures as follows.

1) GENERATE KEYS

The KGC selects two prime numbers \( P \) and \( Q \), where \( P = 2p + 1, Q = 2q + 1 \), \( p, q \) are prime numbers, and \( P, Q \) are both safe primes that are equal in length. Let \( N \) represents an RSA modulus, and \( N \) is equal to \( PQ \). Then, the KGC selects a prime number \( e \) as the public exponent for RSA, and \( e > n \); thus, the public key is established as \((N, e)\). Next, the KGC computes a secret key \( d \) that satisfies \( de \equiv 1 \mod m \). The KGC then sets \( a_0 = d \) and chooses the coefficients \( a_i(1 \leq i \leq tc) \) at random from \([0, \ldots, m - 1]\) to define a polynomial \( f(x) = \sum_{i=0}^{\Delta} a_iX^i \in \mathbb{Z}[X] \). For \( 1 \leq i \leq n \), the secret key shares \( s_j \) can be calculated as follows:

\[
s_i = f(i) \Delta^{-1} \mod m
\]

2) GENERATE SIGNATURE SHARES

Let \( M \) be a message, and \( u \in \mathbb{Z}_n^* \) be the random element where there is \((u/n) = -1 \) (i.e., Jacobi symbol). We have: 1) if \( (\hat{x} | N) = -1 \), then \( x = \mathcal{H}(M) = \hat{x}^u \), where \( \hat{x} = \mathcal{H}(M) \); and 2) if \( (\hat{x} | N) = 1 \), then \( x \) can be hashed as \( x = \mathcal{H}(M) = \hat{x} \). Every participant’s signature share can be generated as follows:

\[
s_i = x^{2^i} \in Q_n
\]

To verify the signature shares, a “proof of correctness” is provided along with the signature share \( s_i \). For this, we adopt an interactive protocol proposed by Chaum and Pedersen [28] in which a player randomly selects a \( r \in \mathbb{Z}_q \) and then sends \((a, b) = (g^r, x^r) \) to a verifier, where \( q \) represents the prime order of a group \( G_q \) generated by part of the public key, i.e., \( g \in G_q \). Then, verifiers randomly select and send a challenge \( c \) to the player; accordingly, the player returns a \( z = r + cs \) in which \( s \) is the secret key. Follow Shoup’s work in [27], a hash function \( H^\prime \) that produces a fixed-length output \( L_1 = 128 \) is adopted. Then, a participant \( P_i \) randomly selects a number \( r \in \mathbb{Z}_2^{L(N+2L_1)} \) to calculate \( v' = v^r \) and \( x' = \hat{x}^r \); thus, the following challenge is obtained:

\[
c = H^\prime(u, \hat{x}, v_i, x_i^2, v', x')
\]

For a signature share \( s_i \), the proof of correctness is tuple \((c, z)\) calculated as follows:

\[
z = s_i c + r
\]

3) VERIFY SIGNATURE SHARES

To verify the above generated proof of correctness, the log_{\(z^2\)} (\(x^2\)) = log_{\(v\)} (\(v_i\)) needs to be proved, that is:

\[
c = H^\prime(u, \hat{x}, v_i, x_i^2, v', x')
\]

We must point out that the exponentiation in \((5)\) is an expensive operation because \( z \) is the length of \( L(N + 2L_1) \).

4) COMBINE SIGNATURE SHARES

According to an \((n, k, t)\) threshold signature scheme [33], a signature \( \sigma \) is required to be generated by some subset of at least \( k \) signers that work together. We assume that \( k \) is from a set of participants \( S \), and \( S = \{i_1, i_2, \ldots, i_k\} \subset \{1, 2, \ldots, n\} \). Let \( x = H(M) \in \mathbb{Z}_n^* \), we have

\[
w = \prod_{j \in S} a_j 2^i S_j^{-1}
\]

where \( a_j S_j = \Delta \prod_{i \in S \setminus \{j\}} (i - f) \prod_{i \in S \setminus \{j\}} (i - f) \in \mathbb{Z} \), which are always integers because \( \Delta \) is equal to \( n! \). According to the Lagrange’s interpolation formula, we can compute as follows:

\[
w^e = \left( \prod_{j \in S} 2^i S_j^{-1} \right)^e = x^{e \sum_{j \in S} \lambda_j S_j} = x^4 c
\]
The signature \( \sigma \) can be calculated as \( \sigma^e = x \). Furthermore, \( \text{gcd}(4, e) = 1 \), and \( a, b \) exist such that \( 4a + eb = 1 \); thus, \( \sigma = w^ax^b \) is the combined signature.

5) VERIFY SIGNATURE
The receiver can verify the signature \( \sigma \) simply as similar to verifying a standard RSA signature. That is, a message \( M \) that is hashed by a hash function \( H \) must be checked to satisfy \( \sigma^e = H(M) \).

To make the algorithm easy to describe, we generally denote the above steps as five main functions, i.e., \( \text{GenKeys()} \), \( \text{GenSigShares()} \), \( \text{VerSigShares()} \), \( \text{ComSigShares()} \), and \( \text{VerSig()} \).

To integrate such an RSA threshold signature scheme in our system, we implement a ThresholdSigner interface including the following two functions:

- \( \text{Sign()} \): Taking a massage \( M \), this method returns a signature share \( s_i \) based on the secret key share \( s_i \).
- \( \text{Verify()} \): Taking a massage \( M \) and a signature \( \sigma \), this method returns \( \text{true} \) if \( \sigma \) is valid.

D. TRANSACTION
We leverage the blockchain to validate and record transactions, thereby providing a trust access authentication system for Solid. Therefore, unlike a cryptocurrency in the blockchain systems such as Bitcoin and Ethereum, “transactions” in our system mainly refer to various instructions.

Specifically, the blockchain in our system accepts two types of transactions such as \( T_{\text{data}} \) and \( T_{\text{access}} \), as described in the following:

1) RESOURCE REQUEST TRANSACTION
A resource request transaction, denoted as \( T_{\text{data}} \), is a request for linked data resources such as a data retrieval from the Solid applications; or a storage request on the linked data resources. The following lists the possible items contained in a transaction \( T_{\text{data}} \). Therefore, we can formally define a \( T_{\text{data}} \) as follows: \( T_{\text{data}} = \text{Sign(from||to||type||timestamp||pk||res_info||chain_ID||tx_ID).} \)

- \( \text{from} \): a requestor’s address, perhaps a unique identity \( \text{requestor_ID} \) of the requestor, which is a necessary item;
- \( \text{to} \): a receiver’s address, e.g., the address of submitting peer in the blockchain network;
- \( \text{type} \): especially designs for data request transactions, which includes “storage” and “retrieval”;
- \( \text{timestamp} \): a sequence of characters that identifies when the transaction occurred;
- \( \text{pk} \): a requestor’s public key that can be used to encrypt messages when it communicates with the pod servers or decentralized web nodes;
- \( \text{res_info} \): the identity of the resource owner who controls the ownership of requested linked data;
- \( \text{chain_ID} \): the parameter or functions that are used to trigger the related smart contracts;
- \( \text{tx_ID} \): the unique identity of a transaction, which is generally a hash value of the transaction;
- \( \text{sig} \): the signature of a transaction signing with the requestor’s private key using the function \( \text{Sign()} \).

2) PERMISSION MANAGEMENT TRANSACTION
A transaction for permission management, denoted as \( T_{\text{access}} \), is used to manage access control over linked data resources. Specifically, we can grant or invoke permissions by updating the access policies related to different predicates. Based on the aforementioned items, we can define a \( T_{\text{access}} \) as \( T_{\text{access}} = \text{Sign(from||to||timestamp||pk||predicate||policy||chain_ID||tx_ID).} \)

IV. SYSTEM DESIGN AND IMPLEMENTATION
In this section, we explain how to integrate the threshold RSA signatures in a permissioned blockchain, i.e., HyperLedger Fabric. Furthermore, we use a Solid application scenario to describe our system design in detail.

A. IMPLEMENTING THRESHOLD RSA SIGNATURES IN THE BLOCKCHAIN
An RSA threshold signature scheme enables a group of participants to generate a single yet fault-tolerant signature in a cooperative distributed way [29], [30]. As a powerful tool, the threshold RSA signatures may have many potential applications for blockchain systems. For example, every peer in the Hyperledger Fabric is identified with a certificate signed by one certificate authority (CA), instead of which a group of CAs can be replaced using the threshold signature scheme [31]. In this paper, our goal is to integrate the threshold RSA signatures into Hyperledger Fabric and focus on the transaction flow working with the threshold signatures.

1) SIGNATURE SHARE COMBINATION ALGORITHM
Signature shares enable robustness in a threshold signature scheme; thus, how to combine such shares into a signature plays an important role in our system design [32]. Assuming this scenario, we find a \( (n, k, t) \) threshold signature scheme, where \( n \) represents the signing servers \( S_1, S_2, \ldots, S_n \). A client \( C \) wants to sign a message \( M \) with such a threshold signature [33]. To this end, client \( C \) needs to request at least \( k (t < k < n - t) \) valid signature shares from the singing servers and then reconstruct a signature \( \sigma_C \) using an equipped function \( \text{ComSigShares()} \). Assuming that a reliable and synchronized network transmits the signature shares to client \( C \), we present two solutions to achieve the aforementioned purpose.

Solution 1: \( C \) calls the function \( \text{ComSigShares()} \) after it receives \( k \) validated signature shares, and thereby reconstructs the final signature \( \sigma_C \) as shown in Algorithm 1.

Solution 2: Algorithm 2 takes the first received \( k \) signature shares as the arguments of function \( \text{ComSigShares()} \) to reconstruct an assumed signature \( \sigma_t \), and then validates if \( \sigma_t \)
Algorithm 1 Unoptimistic Signature Reconstruction

Input: \( s_1, s_2, \ldots, s_n \)

Output: \( \sigma_C \)

1: function UnCombineSignature(s)
2: \( \text{validShares} \leftarrow [ ] \)
3: \( \text{length} \leftarrow 0 \)
4: for \( s \in \text{signatureShares} \) do
5: if \( \text{VerSigShares}(s) \) then
6: \( \text{validShares}.\text{add}(s) \)
7: \( \text{length} \leftarrow \text{length} + 1 \)
8: end if
9: end for
10: if \( \text{length} > k \) then
11: \( \sigma_C \leftarrow \text{ComSigShares}(\text{validShares}) \)
12: return \( \sigma_C \)
13: end if
14: end function

is valid. If it is valid, then \( \sigma_t \) is the correct signature \( \sigma_C \). If it fails, then the algorithm continues to receive signature shares and tries other different combinations of subsets of \( k+i \) shares until a final signature is obtained.

Algorithm 2 Optimistic Signature Reconstruction

Input: \( s_1, s_2, \ldots, s_n \)

Output: \( \sigma_C \)

1: function OpCombineSignature(s)
2: \( \text{invalidCombinations} \leftarrow [ ] \)
3: for \( i \in 0, 1, \ldots, n-k \) do
4: \( \text{validCombinations} \leftarrow \{s_1, s_2, \ldots, s_{k+i}\} \)
5: for \( c \in \text{validCombinations} \) do
6: if \( c \notin \text{invalidCombinations} \) then
7: \( \sigma_C \leftarrow \text{ComSigShares}(c) \)
8: if \( \text{Verify}(\sigma_C) \) then
9: return \( \sigma_C \)
10: else
11: \( \text{invalidCombinations}.\text{add}(c) \)
12: end if
13: end if
14: end for
15: end for
16: end function

2) TRANSACTION FLOW WITH THRESHOLD SIGNATURES

In this subsection, we explain how to exploit the threshold signatures to validate transactions in the proposed system. Fig. 3 illustrates the transaction flow with adopted threshold signatures. In our design, we accelerate the transaction validation by integrating the threshold signatures in transaction endorsement, so that we do not need to verify every one of the endorsements. In detail, our solution consists of the following phases:

Phase 0: When a transaction is created and delivered to a submitting peer via a client, the submitter needs to verify the signature of the client. If the verification is successful, then the transaction is wrapped as a proposal message and the proposal is sent to a group of endorsers.

Phase 1: Once the endorsers receive the proposal, they start to simulate the transaction after successfully verifying the signature and then return the proposal response messages (i.e., endorsements) to the submitter together with their signatures. The submitter, upon receiving the required number of endorsements, utilizes these endorsers’ signature shares to reconstruct a signature, thereby adding only one endorsement message signed with the signature to the transaction, which is submitted to the ordering service.

Phase 2: After receiving the endorsed transaction, the ordering service orders the transaction, packages it in a block, and broadcasts it to all peers in the blockchain network.

Phase 3: The peers engage with the endorsement validation in which they only need to verify only one signature because of our threshold signature scheme in the endorsement procedure, as described in Phase 1. Thereafter, the peers chains the transaction in local ledger and modify the world state.

FIGURE 3. Transaction flow with the proposed threshold RSA signatures.
Algorithm 3 Smart Contract for Access Control

1: procedure AcContract
2:  linked_data_requestor ← apolicy, apre
3:  policyCheck ← false
4:  procedure Create( )
5:    dataOwner_ID ← sender.pk
6:  t ← [ ]
7:  length ← 0
8:  end procedure
9:  procedure UpdateDHT(pk, predicate, policy)
10:     if sender.pk is dataOwner then
11:        if t [i].hash = H (predicate) is exist then
12:           if policy = NULL then
13:              Delete( t [i])
14:             length ← length − 1
15:          else
16:             policy ← t [i].policy
17:          end if
18:        else
19:           if policy! = NULL then
20:              length ← length + 1
21:             t [length].hash ← H (predicate)
22:             t [length].policy ← policy
23:          end if
24:      end if
25:  end procedure
26:  procedure CheckPolicy(apre, apolicy)
27:     if (t [i].hash = H (apre) is exist) and (apolicy ∈ t [i].policy) then
28:        policyCheck ← true
29:     else
30:        policyCheck ← false
31:     end if
32:  end procedure
33:  end procedure
34: end procedure

B. SYSTEM DESIGN

1) INITIALIZATION

The proposed system needs to initialize related system parameters, which mainly comprises the following two phases:

- **Signature Initialization:** Select the required arguments such as the RSA modulus size $N$, number of signing nodes $n$, and number of secret shares $t$ based on the Solid application scenario. The proposed system generates the public key pair $(N, e)$, the secret key shares $s_i$, and the group of verification keys $v_i$ by invoking the method GenKeys(). When a Solid application first registers through a client, a signing key $sk_A$ combined by $n$ signature shares can be generated using the method ComSigShare().

- **Contract Deployment:** Code the designed smart contracts such as Algorithm 3 and Algorithm 4, compile and deploy them on the blockchain. Smart contracts deployed on blockchains are successful transactions, which means they have passed the validation process and been recorded into blocks. Each smart contract on the blockchain has one unique address, for example, we use $A$ to stand for $AcContract$ and $T$ for $TxContract$.

2) REQUEST ISSUANCE

We assume that $A$ is a Solid application that wants to publish a request on linked data resource. It needs to execute the following steps:

- **Create Transaction:** Prepare all components required in a request transaction as defined in Section III(D) to construct a transaction $T_{data}$. Specifically, $T_{data} = \text{Sign}_{sk_A}(A|ID||sp||timestamp||pk_A||TID, UploadTx (pk_sp, H (nonce)), 0 ||H (nonce))$, where $from$ is the unique identity $A$ of $A$; $to$ refers to the target receiver, a submitting peer $sp_i$ in the blockchain network; $chain_ID$ instantiates as the function $UploadTx()$ with parameters $pk = pk_{sp_i}$, $tx = H(nonce)$, and $s = 0$, which means that transaction $T_{data}$ will trigger
the smart contract as shown in Algorithm 4 and thereby be added to invalid transactions \( uvTx[i] \); and \( Tx_{ID} \) is the unique identity \( \mathcal{H}(nonce) \) of transaction \( T_{access} \). In addition, the public and private key pair \((pk_A, sk_A)\) used in \( T_{data} \) are generated by the CA when registered for initialization.

- **Simulate Transaction**: After the transaction invocation, the transaction \( T_{data} \) is sent to the endorsing peers in the blockchain network to simulate the transaction. Notably, the simulation of \( T_{data} \) is executed by the transaction chaincodes (i.e., smart contracts \( TxContract \) and \( AcContract \)), and then the result of a simulation \( proposal \_response \) returns to the submitting peer \( sp_i \) together with the signature \( \sigma_i \) of each endorsing peer. As illustrated in Fig. 3, the submitting peer \( sp_i \) waits to collect required \( t \) signature shares of \( \sigma_i \) \((1 \leq i \leq n)\) to reconstruct the signature \( \sigma \) (see algorithms in Section IV(A)), and adds only one endorsement result appended with the signature \( \sigma \) to the transaction \( T_{data} \).

3) **CHAIN TRANSACTION**
This phase needs to validate transactions, record and chain the verified transactions on blockchains, and modify the world state in the blockchain network.

- **Ordering Transactions**: The endorsed transaction \( T_{data} \) is signed by the submitting peer \( sp_i \) and is submitted to the ordering service. In the ordering service, the transaction \( T_{data} \) is ordered into a block with other endorsed transactions in \( uvTx[i] \) using a consensus procedure (i.e., PBFT). Thereafter, all peers in the blockchain network receive the broadcasted transaction \( T_{data} \) from the ordering service.

- **Validate and Record Transaction**: To validate the transaction \( T_{data} \), the peers must check if the predicate of \( T_{data} \) is the permission granted by the resource owner by invoking the \( CheckPolicy() \) in \( AcContract \), and if the signature \( \sigma \) is valid using the function \( Verify() \). Here, the peers utilize the PBFT consensus mechanism to make an agreement. After validation, the transaction \( T_{data} \) is recorded in the blockchain ledger. Notably, a validated \( T_{data} \) can first be obtained from invalid transactions \( uvTx[i] \) by invoking a \( getTx(0) \) and then set as a valid transaction in \( vTx[i] \) by invoking the function \( UploadTx(pk_A, uvTx[i], 1) \), as illustrated in Algorithm 4.

4) **RESPONSE REQUEST**
Pod servers and decentralized web gateways continue communicating with the blockchain to make instant request response. A new valid request that is validated and recorded by blockchains can be processed by the corresponding entity, as explained in the following:

- **Pod Servers**: The pod servers are responsible for responding to validated transactions such as \( T_{data} \) which requests for data storage or retrieval. For instance, the type in \( T_{data} \) is retrieval, and then the final response is \( (En_{pk_A}(data), SHA256(En_{pk_A}(data), pk_{pod})) \), where \( En_{pk_A}(data) \) is the encrypted request resources with the public key of requestor \( A, pk_{pod} \) represents the responding pod server, and \( SHA256() \) ensures the confidentiality and authentication of messages.

- **Decentralized Web**: A validated transaction for permission management such as \( T_{access} \) is handled by the decentralized web. For example, we assume that \( T_{access} \) is a validated request to change the permissions on some data resources granted to a Solid application. The new set of permissions specified by the data owner can be functioned by revoking the function \( UpdateDHT() \) in smart contract \( AcContract \) via the decentralized web.

V. EVALUATION
A. SECURITY ANALYSIS
The application of blockchains establishes a secure access environment for multiple entities in Solid without mutual trust. We integrate threshold RSA signatures into the transaction validation process and utilize smart contracts to achieve the following security performances:

1) **All Solid entity behaviors in the system are trustworthy**: Each valid operation on the data resource is formalized as one transaction, which is verified and then recorded on chains. This immutable records on the blockchain enables a trustworthy data sharing ecosystem for Solid.

2) **Fault tolerant**: Due to the threshold RSA signatures, our system allows a group of peers in the blockchain network to engage in the signature reconstruction. All peers create signature shares, which are combined into a single fault-tolerant signature.

3) **Security authentication**: Different from blockchain systems such as Bitcoin and Ethereum, our system is built on a permissioned blockchain (i.e., HyperLedger Fabric). In this manner, other than digital signatures, a Fabric CA is used to help issue and validate certificates.

4) **Fine-grained access control**: In a smart contract, the resource owner can predefine the mappings of predicate and policy. Furthermore, during the transaction, the permission of predicates can also be modified by revoking the function \( UpdateDHT() \).

5) **Privacy protection**: In our proposed system, the linked data resource can be sent for storage in the pods in encrypted form so that eavesdroppers in a network cannot obtain it.

B. PERFORMANCE OF SMART CONTRACT
We consider the performance of our proposed smart contracts because the cost affects the system overhead. To this end, we exploited the Remix IDE\(^1\) to develop, deploy, and test the smart contracts such as \( AcContract \) and \( TxContract \). In Table 1, we list the gas cost of all functions included in the two smart contracts with 100 resource requestors. Gas, a

\(^1\)http://remix.ethereum.org/
TABLE 1. Cost of functions in smart contracts

| Type       | Function         | Execution Cost in Gas | Other Cost in Gas | Total Cost in Gas | Total Cost in $  |
|------------|------------------|-----------------------|-------------------|-------------------|------------------|
| AcContract | Create           | 1768831               | 586008            | 2354839           | 0.463905283      |
|            | AddDHT           | 8789                  | 21878             | 30667             | 0.006041399      |
|            | DeleteDHT        | 10246                 | 23442             | 33688             | 0.00636536       |
|            | CheckPolicy      | 6208                  | 17809             | 24098             | 0.004747306      |
|            | Resource Owner Total | 19035             | 45320             | 64355             | 0.012677935      |
| TxContract | Create           | 1542208               | 435974            | 1978182           | 0.389701854      |
|            | UploadTx         | 27832                 | 21622             | 49454             | 0.009742438      |
|            | GetTx            | 20466                 | 22704             | 43170             | 0.008504490      |
|            | Resource Requestor Total | 91127            | 103716            | 196843            | 0.038778071      |

A special unit in the Ethereum blockchain, is used as a meter to measure the resource consumption of the smart contract. The execution cost shows the gas costs of executing the contract instructions, whereas the other cost indicates the consumed gas on transactions calling the function. As shown in Table 1, the total gas for AcContract is 64355 gas, which enables a permission management transaction that includes AddDHT and DeleteDHT. According to the current exchange rate, i.e., 1 Ether ≈ 197$ and 1 Wei = 10^{-18} Ether; thus, only 0.012677935$ is required for a resource owner to manage the DHT. As shown in TxContract, the total cost for a resource requestor is 0.038778071$, which includes calling the functions AddDHT, CheckPolicy, and GetTx once, and running the UploadTx function twice. The total cost for function Create seems somewhat a little high, but it only runs once at the first time when the smart contract is created. From the results, we can conclude that the cost of smart contracts could be economically feasible for our system.

C. PERFORMANCE EVALUATION OF THRESHOLD RSA SIGNATURES

This section provides a group of experiments to evaluate the proposed threshold signature schemes for a blockchain-assisted Solid system. We conducted the simulations using a laptop on which installed a Linux virtual machine (VMware Workstation Pro 15.5) with Ubuntu OS. The hardware parameters of the laptop were as follows: Intel(R) Core(TM) i7-8550U CPU @ 2.80 GHz, 16 GB RAM, Windows 10 Professional 64 bit. The technical characteristics of the virtual machine are listed: Ubuntu 18.04.3 LTS (64-bit), 12 GB RAM.

To evaluate the performance of our proposals, we measured execution time of a signature reconstruction operation. Specifically, we compared the performance of our proposed two algorithms in Section V(A), i.e., the unoptimistic and optimistic solutions. To simulate the signature reconstruction, we considered a network of n signing peers among which p signature peers might be faulty. Let n = 5p + 1 and k = p + 1, and we adopted the (3p+1, p+1, p) threshold signatures [24]. We conducted comparison experiments under two different presumed scenarios: 1) all received signature shares from the signing peers are valid; and 2) p corrupted signature shares are randomly distributed in n signing peers. For an RSA modulus, we selected the size of 2048 bits and 3072 bits because at least a 2048-bit modulus size in a RSA scheme is considered safe up to now. Fig. 4 and Fig. 5 show the time required for a signature reconstruction operation in the RSA threshold signature scheme with the increasing number of participants under the 2048-bit and 3072-bit RSA modulus, respectively. Fig. 6 compares the proposed two signature reconstruction algorithms in different RSA modulus sizes.

On the other hand, we compared our proposed threshold RSA signatures with RSA multisignatures, an efficient distributed signature scheme. In contrast to the threshold signatures, a multi-signature scheme only has one solution to reconstruct a signature, that is, the reconstruction occurs when a sufficient number of valid signatures are received.
from signers, which means that each signature needs to be verified until \( k \) valid signatures are collected. Such procedures of the RSA multi-signature scheme are equal to the unoptimistic solutions to the RSA threshold signature scheme. In this part, we first compared the time cost for a signature reconstruction operation in two RSA signature schemes, and then tested the verification time of their reconstructed signatures. The experiments also considered an all-valid share scenario and a part-invalid share scenario where the experimental settings were \( n = 3p + 1 \) and \( k = p + 1 \), and a 3075-bit RSA modulus was adopted. Fig. 7 and Fig. 8 show the comparison of time costs in signature reconstruction operations under two scenarios such as all-invalid signature shares and part-invalid signature shares. Fig. 9 shows the comparison of time costs in signature verification operation of the two RSA signature schemes.

Fig. 4 and Fig. 5 show that the time costs in the signature reconstruction operation are different with an RSA modulus, i.e., the threshold signatures with a 3072-bit RSA modulus are more expensive but have higher security. Fig. 6 also illustrates this trend that the optimistic algorithm performs better than the unoptimistic algorithm with an increasing RSA modulus size, even in cases where signature shares are partly corrupt or invalid. Therefore, we suggest that the choice between the unoptimistic and optimistic algorithms depends on the real application. The optimistic algorithm is more efficient and suitable for a small and reliable network that does not have too many corrupted signature shares. Besides, the combination of such two algorithms in a signature reconstruction operation can also be a good choice.

In Fig. 7 and Fig. 8, the RSA multisignature scheme is more efficient than the RSA threshold signatures for a signature reconstruction operation. We must point out that the operation costs for the RSA multisignatures are less than 22 ms. The high costs in the RSA threshold signatures are due to the expensive verification of signature shares. Moreover, compared with the multisignatures, the threshold signatures have extra operation costs of the polynomial interpolation. In Fig. 9, we can observe that the verification time of the RSA threshold signatures keeps an average value of 0.025 ms/op because only one signature is to be verified in a threshold signature scheme. However, the overhead costs for RSA multisignatures increase linearly as the number of verification operations grows. To summarize, for a signature reconstruction operation, the RSA threshold signature scheme is more
expensive than that of the RSA multisignatures. By contrast, in a signature verification operation, the threshold RSA signatures require a fixed cost of time and can scale better in a large network with numerous participants. Furthermore, the signature size of the threshold RSA signatures is 384 bytes, whereas that of the RSA multisignatures is $384 \times k$ bytes, thereby validating the proof that the RSA threshold signature scheme has better scalability.

VI. CONCLUSION

Solid is not a concept just out of reach, but an ongoing project that promises a new working approach for the existing web. To promote the implementation of such a web decentralized project, this paper focused on how to exploit the permissioned blockchain to implement secure authentication with fine-grained access control system suited for a Solid ecosystem. Specifically, the proposed system applies threshold RSA signatures in the blockchain to authenticate Solid applications, and uses smart contract to manage access control policies. We analyzed the security of the system and evaluated the performance of our solutions.

How to leverage blockchain technologies to empower the Solid project is still an open issue. In a future research, we will explore how to use threshold signatures to implement a group of CAs in a permissioned blockchain. Furthermore, a Solid ecosystem requires fast and efficient transactions, so we are motivated to improve the blockchain performance.

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