

SLVC-DIDA: Signature-less Verifiable Credential-based Issuer-hiding and Multi-party Authentication for Decentralized Identity

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ABSTRACT

As an emerging paradigm in digital identity, Decentralized Identity (DID) appears advantages over traditional identity management methods in a variety of aspects, e.g., enhancing user-centric online services and ensuring complete user autonomy and control. Verifiable Credential (VC) techniques are used to facilitate decentralized DID-based access control across multiple entities. However, existing DID schemes generally rely on a distributed public key infrastructure that also causes challenges, such as context information deduction, key exposure, and issuer data leakage. To address the issues above, this paper proposes a Permanent Issuer-Hiding (PIH)-based DID multi-party authentication framework with a signature-less VC model, named SLVC-DIDA, for the first time.

Our proposed scheme avoids the dependence on signing keys by employing hashing and issuer membership proofs, which supports universal zero-knowledge multi-party DID authentications, eliminating additional technical integrations. We adopt a zero-knowledge RSA accumulator to maintain the anonymity of the issuer set, thereby enabling public verification while safeguarding the privacy of identity attributes via a Merkle tree-based VC list. By eliminating reliance on a Public Key Infrastructure (PKI), SLVC-DIDA enables fully decentralized issuance and verification of DIDs. Furthermore, our scheme ensures PIH through the implementation of the zero-knowledge Issuer set and VC list, so that the risks of key leakage and contextual inference attacks are effectively mitigated. Our experiments further evaluate the effectiveness and practicality of SLVC-DIDA.

CCS CONCEPTS

• **Security and privacy** → **Authentication; Privacy-preserving protocols; Digital rights management**; • **Theory of computation** → **Cryptographic protocols**.

KEYWORDS

Decentralized Identity, Signature-less Verifiable Credential, Zero-knowledge Proof, Cryptographic Accumulator

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1 INTRODUCTION

Digital identity is a fundamental concept of user-centric online services, which is used to uniquely identify an entity's subset of the entire attribute set (e.g., name, age, and post codes) in contemporary digital age. Authentication and authorization generally are key components for ensuring authenticity and legitimacy of user identities in digital identity, supported by the implementation of the Public Key Infrastructure (PKI) framework [3, 30, 36]. A typical PKI-based digital identity is issued and managed by a Centralized Identity Provider (IdP) and a Certificate Authority (CA). However, such centralized framework arises security and privacy concerns, since users lack controls over their own identities such that personal data governance and usage are restricted. When considering the complexity of modern network applications, the centralized setting also brings the restriction of scalability, single points of failure issue, and interoperability obstacle.

Decentralized identity is deemed to be a new paradigm for replacing traditional centralized identity governance, promoting a higher-level privacy-preserving and user-centric approach to authentication and authorization [5, 12, 31]. World Wide Web Consortium (W3C) has standardized and formalized Decentralized Identifier (DID) and Verifiable Credential (VC) for decentralized identity. Specifically, a DID uniquely identifies an entity's identity and supports proof of ownership of identity attribute data. As an alternative

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to digital certificates, a VC facilitates decentralized identity authentication by establishing an extensive digital identity trust across multiple network services.

Multi-party Authentication for DID. In the context of decentralization, completing a DID authentication and validating a VC's issuance require multiple trust sources, since identity attributes are dispersed among distinct issuers (e.g., official agency, enterprises, or institutions). Users need to configure subsets of VC collections from distinct issuers to facilitate multi-party authentication of DID [25, 29]. Existing solutions typically link issuers with digital certificates through public key cryptographic signatures, involving threshold signatures [4, 15] and aggregate signatures [41, 43]. Such techniques improve signature-based digital certificates to support secure and effective multi-party authentication from multiple issuers.

Privacy Protection for DID Authentication. Privacy concerns has always been one of the key challenges to DID authentication and authorization. On one hand, it requires that a user passes a third-party identity verification without disclosing any identity information in a user-centric privacy-preserving DID authentication. Thanks to selective disclosure credentials [14, 36] and anonymous credentials [5, 19], current DID and VC schemes achieve the unlinkability of identity information and enable users to selectively reveal identity attributes to the third party, thereby ensuring users to obtain network services while not being tracked. Therefore, each VC contains an issuer's signatures that can be verified by the third party by using the issuer's public key. However, that is to say, the third party is able to infer a user's identity attributes on the basis of the corresponding issuer in specific scenarios, since each VC is linked to a specific issuer and offers substantial contextual information [9, 29]. On the other hand, an issuer-hiding DID authentication requires the third party to only verify whether the VC is issued by a legitimate issuer, rather than directly obtaining the issuer's public key. We observe that some recent work on anonymous credentials [6, 7, 33, 35] also considers the hidden characteristics of the issuer. However, additional privacy challenges are caused since existing solutions generally rely on PKI and public key encryptions [10, 17]. To be specific, the confidentiality of the specific issuer linked to each VC should be maintained, even though the issuer's public key is compromised or encryption is cracked. We call this feature as a *Permanent Issuer-Hiding* (PIH) in this work.

1.1 Past Work and Practical Limitations

A few previous methods have been developed to address limitations of DID and VC concerning authentication and authorization, which primarily focus on enhancing distributed issuance across multiple issuers and improving privacy protections.

Signature-based credential for DID multi-party authentication. To decentralize the trust relying on a single issuer, prior work has explored cryptographic credential-based schemes for achieving distributed issuance of DIDs and VCs across multiple authorities, such as threshold signatures [24, 30, 34] and aggregate signatures [18, 23, 29]. A few schemes have been evidenced to strengthening multi-party authentication of DIDs while considering both privacy-preserving and issuer-hiding, e.g., anonymous credentials [29, 33].

Nevertheless, most existing signature-based certificates methods rely on PKI framework, where IdPs and CAs manage the issuance and signing keys, as well as govern digital identities and encryption protocols used for issuing credentials. The challenging issue is that issuers maybe not competent to being CAs, for instance, due to lack of qualified security infrastructure for governing and defending signing keys in practice. That is to say, adversaries can not only forge legitimate VCs with specific identity attributes but also hide the malicious activities, when issuers/signing keys are compromised. Incompetent issuers might implement a lower-level security protocol for encrypting credential issuance, which brings a potential risk of a failure to issuer-hiding. It implies that PIH issues widely exist in current signature-based credentials.

Moreover, while threshold and aggregate signatures facilitate the implementation of multiple issuers collaborating on the issuance of DIDs and VCs, these schemes inherently support only homogeneous digital signature algorithms. The restriction becomes apparent in cases where DID authentication involves multiple issuers to employ heterogeneous encryption protocols for signing VCs. In such cases, signature-based credentials may restrict the distributed issuance and multi-party authentication of DID.

Decentralized anonymous credential for DID distributed issuance. Recent work [16, 32, 33] has explored flexible decentralized anonymous credentials and tried signature-less methods for DID distributed issuance to eliminate reliance on PKI-based issuers while ensuring privacy protections. Typically, credentials are stored on decentralized bulletin boards while removing signing keys, e.g., transparent logs or Byzantine systems, to ensure the credentials are publicly maintained by the user community rather than a CA or a centralized IdP. The validity and authenticity of such anonymous credentials can be publicly audited and verified, i.e., guaranteeing legitimacy without compromising anonymity of users. However, PIH issues are not solved by decentralized anonymous credential methods, as certain issuers' information might be exposed. The issuance of decentralized anonymous credentials requires customized infrastructure, so that the adaptability is limited, such as OpenID [2].

Zero-knowledge proof for DID privacy-preserving authentication. Another technical idea is to employ Zero-Knowledge Proof (ZKP) techniques for achieving privacy-preserving PIH authentication. For example, [8, 29] applied succinct Non-Interactive Zero-Knowledge (NIZK) arguments of proofs, e.g., zk-SNARKs, to verify the given user identity attributes on VCs with the issuer's key while remaining anonymity. However, combining naive zk-SNARKs with multi-party authentication for DIDs brought extensive costs on certification and verification, since the process involved $O(M)$ -sized \mathbb{G}_1 multiple exponentiations and Fast Fourier Transform (FFT) operations, where M was the number of issuers. [7] explored the implementation of non-succinct Schnorr-type NIZK through Fiat-Shamir to reduce the cost of issuer-hiding proofs and verification, but resulting in a linear relationship between non-compact proof sizes and the number of issuers (M). Due to limitations of ZKP in NIZK, there is a potential risk of issuer identity exposure when adding/removing issuers within multi-party authentication [42].

The goal of this paper is to develop the first signature-less PIH VC for multi-party authentication model of DID, which covers

multiple technical merits, such as multi-party issuing, VC register on Byzantium system, and zero-knowledge of the issuer.

1.2 Our Techniques and Contribution

In this paper, we have proposed the first *Signature-less Verifiable Credential-based DID Authentication* (SLVC-DIDA) model to achieve PIH across multiple issuers. Our model offers privacy-preserving identity assertions and avoids the dependence of PKI-based signature keys for distributed VCs issuance. Key technologies and contributions made by SLVC-DIDA are outlined as follows.

Universal Identity Authentication via Signature-less VC. Differing from existing DID authentication methods, we propose a scheme of signature-less VCs for PIH for the first time, which achieves universal user identity authentication in distributed issuance. To be specific, our scheme directly utilizes identifiers of both users and issuers to issue VCs and links VCs and issuers by configuring randomness, rather than using public key signatures. On one hand, inspired by decentralized anonymous credentials, the issued VC list is stored on a Byzantine system (e.g., blockchain) in a Merkle tree data structure, which is controlled/governed by derived predicates of identity attributes (i.e., the birth and death predicates). On the other hand, rather than directly obtaining the issuer’s public key, SLVC-DIDA uses an RSA accumulator to determine whether a VC is signed by a legitimate issuer. Our scheme supports universal multi-party identity authentication since it enables the VC issuance independently through identifiers, thereby facilitating seamless integrations into distributed/decentralized systems. By basing VC issuance solely on identifiers, our signature-less VC eliminates the needs for additional technical embedding in existing DID authentication infrastructure.

PIH qualification verification of legal issuers. A one-time randomness is generated when an issuer implements each DID authentication and provides one-way verification through the hash value of the randomness. Our scheme avoids signing keys so that it ensures PIH while maintaining the integrity of DID authentication process. We adopt a ZKP scheme that applies an RSA accumulator with batch membership proofs to certify each valid VC derives from a legitimate subset of issuers. Considering the case of dynamic changes/updates on issuers (e.g., adding/removing issuers), our scheme is designed to guarantee anonymity of issuers, thereby ensuring issuer-hiding and preventing the leakage of contextual information.

Privacy-preserving VC public verification. In our scheme, public verifiability is a critical feature that enables anyone to independently verify the authenticity and validity of DID and VC authentications. All VC sets are publicly auditable, since a Merkle tree-based VC list is maintained by the Byzantine system user community¹. Public verifiability allows for transparent verification, thereby enabling any key compromising events detectable and facilitating an effective revocation of illegitimate VCs. Our scheme avoids directly involving identity attributes to be elements of the Merkle tree, as a Merkle tree is composed of commitments to VCs, in order to achieve a higher-level privacy protection. Commitments

are derived by randomly hashing a prime number. Our proposed scheme ensures that the underlying attributes of VCs remain confidential while ensuring public verification of the authenticity, thus maintaining both privacy and transparency.

2 RELATED WORK

DID Framework. The development of DID framework has been addressed by a few recent studies that explored the technical capabilities, such as scalability and security [22, 38, 40]. For example, Deepak *et al.* [12] developed a DID framework, called CanDID, that used web authentication services to address the bootstrapping challenge through a decentralized node committee for seamless credential issuance, so that the capability of users’ control over identity data was improved. [1] tried to combine machine learning with blockchain to achieve scalability of identity management. Liu *et al.* [26] conducted a method of establishing trust via applying leader sharding and main chain, which used conventional sharding to manage DID related transactions. A multi-layer web3 DID architecture is proposed, by which utilized sharding blockchain to solve the issue of insufficient scalability of existing DID solutions. Some other efforts were made to reduce computation and storage costs, such as using a cryptographic accumulator-based solution to constructing a revocation mechanism for VCs in IoT networks [28]. ZKP-based methods [21, 33, 45] also were explored to enhance DID resolvers and VCs, such as aggregating signatures.

Multi-party Identity Authentication. Existing identity authentication schemes are primarily based on cryptographic techniques. For example, anonymous credentials have been probed to secure identity verification by prior studies [13, 18, 19, 29]. [19] used anonymous credentials to extend the aggregate signature mechanism within a Self-sovereign Identity (SSI) framework.; [18] applied attribute-based encryption for traceable certificates, supporting multi-party authentication.

Another type of methods was to utilize cryptographic primitives to achieve secure identity verification, such as the threshold signatures and aggregate signatures. Since threshold credentials typically enable users to obtain credentials in a decentralized manner while maintaining their privacy, Li *et al.* [24] proposed a dynamic method to support batch display of credentials and proof of the number of credentials, while keeping the user’s credential set private. Sonino *et al.* [36] proposed a selective disclosure credential scheme that supports distributed threshold issuance, public and private attributes, re-randomization, and multiple un-linkable selective attribute revelations. [18] introduced the use of aggregate signatures with randomized tags, allowing specific tracking authorities to perform tracking. [29] employed two signature primitives, aggregated signatures with randomized tags and public keys and aggregate Mercurial signatures, to propose an issuer-hidden multi-authorization anonymous credential scheme. Secure Multi-party Computation (SMPC) was a technical option for establishing distributed trust across multiple parties in DID authentication. For instance, Tan *et al.* [37] introduced an efficient protocol for establishing multi-factor authentication within SMPC. Despite the progress made in using cryptographic primitives, the existing solutions mostly focused on single-domain environments, so that the challenges of establishing a cross-domain DID authentication still exist.

¹We utilize only the distributed storage functionality of decentralized infrastructure. Theoretically, compared to the on-chain credential computation and issuance of zk-creds, the issuance and authentication efficiency of SLVC-DIDA is higher.

Privacy-preserving Identity. For DID authentication, user identity information must not be disclosed, thus requiring privacy protection for identity data. Prior studies [20, 27, 44, 46] have probed numerous methods to preserve privacy from various perspective. In the context of DID, existing methods are involved within two major categories, including attribute-based encryption and membership proof methods. For example, Campanelli *et al.* [8] tried using zk-SNARKs and RSA accumulators to prove batch membership and batch updates in zero-knowledge. This method supports effective privacy-preserving verification of identity attributes in DID and VC. [3] was an attempt to integrate Verifiable Random Functions (VRF) with blockchain technology, such that it balances auditability and privacy protections. This method hides users' identities and authentication information by relying on using VRFs and zk-SNARKs, while ensuring to maintain an auditable record of authentication events. Even though the progress was made as above, a critical issue still restricts these methods in DID framework, as the dynamic issuance and distributed management inherent had been rarely addressed.

3 BACKGROUND AND PRELIMINARIES

3.1 Decentralized Identity

As an emerging paradigm of digital identity, decentralized identity aims at achieving a complete user control over personal identity data, by which individuals are allowed to govern their own identity information without a centralized server. It is generally believed that the first DID standard specification was released by W3C, which mainly consisted of two fundamental components, namely, DID and VC. In details, a DID offers an identifier framework that provides digital identities with a global unique verifiable mechanism. The framework supports entities (e.g., individuals, organizations, or devices) to be uniquely identified online in a decentralized setting, covering a full control over identity data as well as verification methods. A few security components are also incorporated, such as DID documents, verifiable data registries, and blockchain.

VC is a digital document associated with DID, which contains the attributes' claims of entities (e.g., name, age, and address). In general, VCs can be used for transferring verifiable information on blockchain or other trustworthy systems, while the third party is able to verify certain attributes via verifying VCs. An across-sector/organization mutual identity verification can be achieved, as the issuance and verification of VCs can be configured to be a fine-grained setting, which is deemed to be an alternative for solving "data island" and privacy leakage issues in traditional identity verification systems. Figure 1 illustrates the workflow of W3C DID and VC scheme. To be specific, an **Issuer** is an entity that is authorized to issue certificates, such as an official agency. The legitimacy of the issuer is verified by a ZKP-RSA accumulator in our scheme. A **Holder** is a party that applies for VC from the issuer in order to acquire the requested network service once the VC is verified. In our proposed ZK-MultiAuth, all users have a complete control over their VCs, including operations of governing, sharing, and removing on VCs, due to the implementation of Byzantine fault-tolerant system.

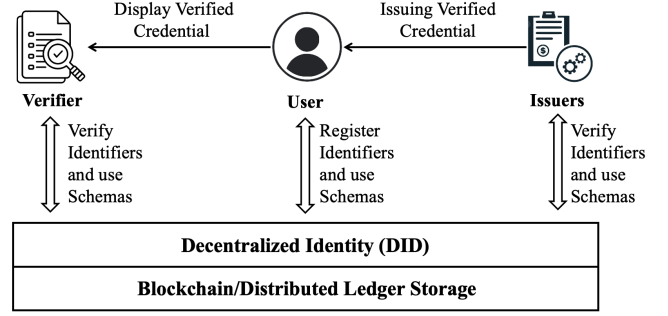


Figure 1: Verifiable credential data model.

3.2 Cryptographic Primitives

Collision-resistant Hash Function. The collision-resistant hash function CRH is an encryption algorithm that maps the message m of arbitrary length to a fixed-length hash digest. A typical hash function CRH involves two Probabilistic Polynomial-time (PPT) algorithms (CRH.Setup, CRH.Hash) as follows.

- $pp_{crh} \leftarrow \text{CRH.Setup}(1^\lambda)$: Inputs the security parameter λ and outputs the public parameters pp_{crh} for collision-resistant hash function.
- $h(m) \leftarrow \text{CRH.Hash}_{pp_{crh}}(m)$: Based on public parameters pp_{crh} , $\text{CRH.Hash}(\cdot)$ inputs message m and outputs a short hash value $h(m)$.

Collision-resistance and one-wayness are the key properties of hash functions. Collision-resistance ensures that for a given input message m , it is infeasible to find another distinct message m' such that $h(m) = h(m')$. One-wayness implies that it is computationally infeasible to reverse-engineer the original message m from its publicly known hash value $h(m)$.

Cryptographic Accumulator. Cryptographic accumulators are used to generate a concise commitment that binds a set of elements together and provides succinct membership proofs for any element within the set. These proofs can be publicly verified using the commitment. Typical cryptographic accumulators include RSA accumulator and Merkle hash tree. Specifically, RSA accumulator consists of five PPT algorithms (RSA.Setup, RSA.KeyGen, RSA.ComAcc, RSA.ComMem, RSA.Verify):

- $pp_{rsa} \leftarrow \text{RSA.Setup}(1^\lambda)$: Inputs the security parameter λ and outputs the public parameters pp_{rsa} .
- $(sk_{rsa}, vk_{rsa}) \leftarrow \text{RSA.KeyGen}(pp_{rsa})$: Inputs the public parameters pp_{rsa} and outputs the key pair (sk_{rsa}, vk_{rsa}) . The secret key sk_{rsa} is used to compute the membership proofs, whereas the public verification key vk_{rsa} is employed to verify these proofs.
- $acc(X) \leftarrow \text{RSA.ComAcc}_{pp_{rsa}}(X; sk_{rsa})$: Based on pp_{rsa} , the algorithm $\text{RSA.ComAcc}(\cdot)$ inputs a set X and secret key sk_{rsa} , then outputs the accumulator value $acc(X)$ of set X .
- $\pi_{mem}(x) \leftarrow \text{RSA.ComMem}_{pp_{rsa}}(x, X, acc(X); sk_{rsa})$: On input an element x , the set X , the accumulator value $acc(X)$, and key sk_{rsa} , $\text{RSA.ComMem}(\cdot)$ computes the membership

proof $\pi_{mem}(x)$ which serves as a witness for the membership of the element x in the set X .

- $\{0, 1\} \leftarrow \text{RSA.Verify}_{pp_{rsa}}(\text{acc}(X), x, \pi_{mem}(x); vk_{rsa})$: This algorithm inputs the element x , the accumulator value $\text{acc}(X)$, the membership proof $\pi_{mem}(x)$ and the verification key vk_{rsa} . It outputs a bit value of 1 to denote ACCEPT. Otherwise, it outputs 0 to denote REJECT.

In addition, Merkle hash tree is a widely utilized cryptographic accumulator, structured as a binary tree. Specifically, each non-leaf node is derived from the concatenation and subsequent hashing of its two child nodes' hash values. This process culminates in a root hash value that encapsulates the integrity of the entire dataset represented by the tree. Any modification to the tree's data will lead to a detectable change in the root hash value.

Non-Interactive Zero-Knowledge (NIZK) Arguments of Knowledge. NIZK is a two-party cryptographic protocol that allows one party (the **prover**) to prove the correctness of an NP statement to another party (the **verifier**) without providing any additional information and without any interaction between the two parties. The cryptographic primitive of NIZK is a tuple of three PPT algorithms (NIZK.Setup, NIZK.Prove, NIZK.Verify) with the following syntax:

- $pp_{zk} \leftarrow \text{NIZK.Setup}(\mathcal{R}, 1^\lambda)$: On input the security parameter λ and the specification of an NP relationship \mathcal{R} , NIZK.Setup(\cdot) outputs the public parameters pp_{zk} as a relation-specific common reference string (crs).
- $(sk_{zk}, vk_{zk}) \leftarrow \text{NIZK.KeyGen}(pp_{zk})$: it inputs the public parameter pp_{zk} , and outputs a NIZK proving key sk_{zk} and a NIZK verifying key vk_{zk} .
- $\pi_{zk} \leftarrow \text{NIZK.Prove}_{pp_{zk}}(x, w; sk_{zk})$: Based on pp_{zk} , the algorithm NIZK.Prove(\cdot) inputs a statement x and a witness w such that the statement-witness pair $(x, w) \in \mathcal{R}$. It outputs the proof π_{zk} of the relationship.
- $\{0, 1\} \leftarrow \text{NIZK.Verify}_{pp_{zk}}(\pi_{zk}, x; vk_{zk})$: On input the statement x and the proof π_{zk} , NIZK.Verify(\cdot) outputs a bit value of 0 or 1.

4 SLVC-DIDA DESIGN

In this section, we present the architecture and threat model of the proposed SLVC-DIDA model. SLVC-DIDA is a DID multi-party authentication model that enables users to obtain signature-less VCs, achieving privacy presentation of issuer identities and public verification of credentials. Specifically, we illustrate the design of the signature-less VC, which serves as the key component within SLVC-DIDA.

4.1 Overview

Our model follows the W3C definitions for **Issuer**, **Holder**, and **Verifier**, with each entity uniquely identified by a DID. Upon receiving a DID authentication request from **Holder**, **Issuer** verifies the identity attributes and generates the corresponding VC without requiring a digital signature to protecting privacy. Typically, multiple issuers are required to endorse identity attributes in VC to enhance reliability.

The SLVC-DIDA model, as illustrated in Figure 2, presents a multi-party privacy-preserving DID authentication framework that

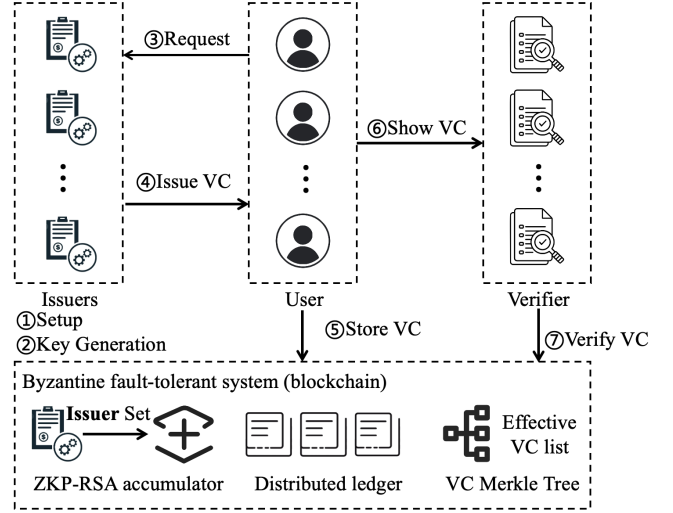


Figure 2: The architecture and workflow of our SLVC-DIDA model.

leverages ZKPs and a Byzantine fault-tolerant system (blockchain). SLVC-DIDA performs a **Setup** phase to generate public cryptographic parameters and key pairs for ZKP-RSA accumulator-based membership proof of legitimate **Issuer**. **Holders** store the issued VCs securely on blockchain and present them to **Verifiers** when needed. SLVC-DIDA model integrates the issued VC into a Merkle tree within a blockchain, allowing all parties to reach consensus on the list of issued VCs through a consensus mechanism. This setup supports efficient VC revocation, which requires only the removal of leaf nodes from the Merkle tree, with a logarithmic cost relative to the number of VCs. When the **Verifier** receives a VC from the **Holder** within the Byzantine fault-tolerant system, it verifies two key aspects, namely, (i) the legitimate qualifications of the issuer using the ZKP-RSA accumulator, and (ii) the integrity and validity of the privacy-preserving VC through the Merkle root. Upon successful verification, the **Holder** of the validated VC gains access to the associated network services.

4.2 Threat Model

In the DID authentication process, adversaries may disrupt VC verifications and DID authentication to infer **Holders'** private identity through speculative manipulation. Specifically, adversaries attempt to steal the identifier DID^I from a particular **Issuer** and use public encryption algorithms to brute-force the VCs issued by DID^I to compromise the PIH. By seizing control of DID^I , adversaries issue falsified/misleading VCs to deceive **Verifiers**, so that it potentially allows unauthorized entities to gain permissions within the network services. There is a possibility for adversaries to expose privacy from capturing VC issuance timestamps and tracking changes in issuer sets through some operations, such as the addition or removal of legitimate **Issuer** sets, thus issuance events to specific **Holder** and endangering PIH. Moreover, adversaries may exploit the public VC list to infer identity attributes of users.

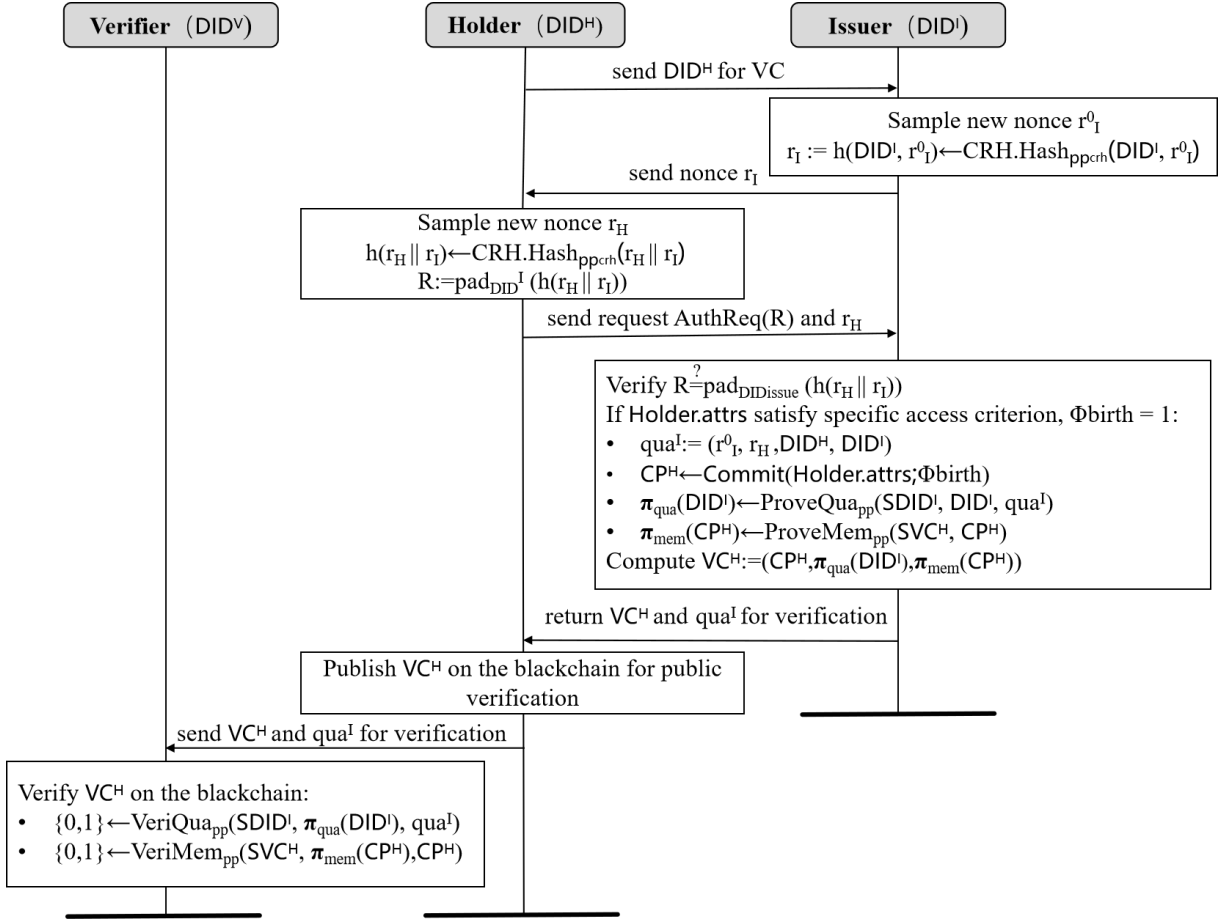


Figure 3: Unilateral issuance and verification process of signature-less VCs. The function $\text{pad}_{\text{DID}^H}(\cdot)$ applies padding based on the length of DID^H . The Issuer generates a valid qualification proof, defined as $\text{qua}^I := (r_1, r_H, \text{DID}^H, \text{DID}^I)$. The Verifier can confirm the validity of the qualification proof by executing $\text{VeriQua}(\text{SDID}^I, \pi_{\text{qua}}(\text{DID}^I), \text{qua}^I)$. Blockchain stores the issued VC^H of the Holder DID^H to support public verification.

To mitigate these threats, we assume the presence of a trusted third-party auditor with sufficient computational resources to manage the ZKP-RSA accumulator, including generations and updates of both accumulator value and witness. In this work, we set the trusted auditor as the Byzantine fault-tolerant system. In addition, we adhere to the minimal trust principles of decentralized anonymous credential, where only VCs issued by legitimate non-colluding **Issuers** are valid and conspiracy is not allowed. We assume that users act honestly since they have no incentive to compromise their own DID authentication processes.

4.3 Signature-less VC Design

When a **Holder** possessing the identifier DID^H initiates a request for DID authentication, the procedure for the issuance and verification of VCs is subsequently activated, as illustrated in Figure 3. It is important to note that Figure 3 depicts the unilateral issuance and verification process of VCs in the absence of signatures. Additionally, SLVC-DIDA supports multi-party VC verification.

For the purpose of unilateral issuance and verification within the SLVC-DIDA framework, the process commences with an **Initialization** phase. During this phase, SLVC-DIDA initializes public parameters, denoted as pp , based on a predefined security parameter λ . This initialization encompasses the establishment of collision-resistant hash parameters (pp_{crh}), RSA parameters (pp_{rsa}), and parameters for a NIZK proving system (pp_{zk}). Subsequently, these individual parameter sets are combined to form the complete public parameters, denoted as $\text{pp} := (\text{pp}_{\text{crh}}, \text{pp}_{\text{rsa}}, \text{pp}_{\text{zk}})$. The public parameters pp can be called by all other algorithms. For **Initialization**, the algorithm $\text{Setup}(1^\lambda)$ is used to generate public parameters pp and executes as follows:

- $\text{pp}_{\text{crh}} \leftarrow \text{CRH.Setup}(1^\lambda)$: Inputs the security parameter λ and outputs the public parameters pp_{crh} for collision-resistant hash.
- $\text{pp}_{\text{rsa}} \leftarrow \text{RSA.Setup}(1^\lambda)$: Outputs the public parameters pp_{rsa} for RSA accumulator.

- $pp_{zk} \leftarrow \text{NIZK.Setup}(1^\lambda)$: Outputs the public parameters pp_{zk} for NIZK.
- Return $pp := (pp_{crh}, pp_{rsa}, pp_{zk})$ for the issuance and verification of signature-less VC.

Proceeding to the **Key Generation** phase, our scheme utilizes the public parameters pp to generate a pair of keys, secret key sk and verification key vk . This process includes generating an RSA key pair (sk_{rsa}, vk_{rsa}) and a NIZK key pair (sk_{zk}, vk_{zk}) . The secret key is stored as $sk := (sk_{rsa}, sk_{zk})$ and the verification key as $vk := (vk_{rsa}, vk_{zk})$. We remark that the key pair generated by the $\text{KeyGen}(pp)$ algorithm is only utilized for computing the ZKP-RSA accumulator and the membership proof of the **Issuer** and VC, and is not involved in the issuance of VCs. For **Key Generation**, the algorithm $\text{KeyGen}(pp)$ is used to generate key pair (sk, vk) and executes as follows:

- $(sk_{rsa}, vk_{rsa}) \leftarrow \text{RSA.KeyGen}(pp_{rsa})$: Inputs the RSA parameter pp_{rsa} and outputs the key pair (sk_{rsa}, vk_{rsa}) to compute the membership proof and RSA accumulator.
- $(sk_{zk}, vk_{zk}) \leftarrow \text{NIZK.KeyGen}(pp_{zk})$: Inputs the NIZK parameter pp_{zk} and outputs the key pair (sk_{zk}, vk_{zk}) to compute the NIZK proof.
- Return $sk := (sk_{rsa}, sk_{zk})$ and $vk := (vk_{rsa}, vk_{zk})$ for the zero-knowledge signature-less VC.

In **Request and Nonce Sampling** phase, the **Issuer**, identified by DID^I , initiates authentication process by generating a new random value r_I . This value is computed as $r_I := h(\text{DID}^I, r_I^0)$, where r_I^0 represents freshly sampled nonce. Subsequently, the generated r_I is transmitted to the **Holder**. The **Holder** then samples another random value r_H , which is utilized to compute R , a padded and hashed value for the authentication request. Specifically, R is derived as $R := \text{pad}_{\text{DID}^H}(h(r_H \parallel r_I))$, where \parallel denotes logical concatenation. To satisfy size constraints and ensure the confidentiality of R on the blockchain, we employ a cryptographic hash function denoted as CRH and apply padding in terms of the length of DID^I . The **Holder** then submits an authentication request, denoted as $\text{AuthReq}(R)$, along with r_H to the **Issuer**. Upon receipt, the **Issuer** verifies R by comparing it with the computed padded hash of $h(r_H \parallel r_I)$. When the **Holder's** attributes satisfy the predefined access criteria (e.g., $\Phi_{\text{birth}} = 1$), the **Issuer** proceeds with the following steps.

- A legitimate qualification tuple is constructed, denoted as $\text{qua}^I := (r_I, r_H, \text{DID}^H, \text{DID}^I)$.
- When the **Holder's** attributes satisfy the specific access criterion, the birth predicate $\Phi_{\text{birth}} = 1$, then the **Issuer** makes a commitment to the **Holder's** attributes, denoted as $\text{CP}^H \leftarrow \text{Commit}(\text{Holder.attrs}; \Phi_{\text{birth}})$.
- The qualification proof of legitimate **Issuer** DID^I is generated, expressed by $\pi_{\text{qua}}(\text{DID}^I) \leftarrow \text{ProveQua}(\text{SDID}^I, \text{DID}^I, \text{qua}^I)$, where SDID^I denotes the set of legitimate issuers.
- The membership proof of the commitment for a VC is generated, denoted as $\pi_{\text{mem}}(\text{CP}^H) \leftarrow \text{ProveMem}(\text{SVC}^H, \text{CP}^H)$, where SVC^H denotes the issued VC list.
- A VC is computed, denoted as $\text{VC}^H := (\text{CP}^H, \pi_{\text{qua}}(\text{DID}^I), \pi_{\text{mem}}(\text{CP}^H))$.

The **Issuer** publishes the VC (VC^H) onto the blockchain, accompanied by the qualification information qua^I .

Finally, in a **Verification** phase, the **Verifier** performs two checks to verify VC^H on the blockchain: (i) validates the qualification proof by verifying $\text{VeriQua}(\text{SDID}^I, \pi_{\text{qua}}(\text{DID}^I), \text{qua}^I)$, ensuring that the **Issuer's** qualification conditions are satisfied; (ii) confirms the membership proof by verifying $\text{VeriMem}(\text{SVC}^H, \pi_{\text{mem}}(\text{CP}^H), \text{CP}^H)$, establishing that the **Holder's** attributes meet the required conditions.

Once both proofs are validated, the VC is considered to be verified, and the **Holder** can access the associated network services based on the issued credential. This signature-less design uses ZKPs (see Section 5.1) and blockchain-based public verification to maintain privacy and integrity without requiring a digital signature. The issuance process for VCs involving multiple issuers is similar to the unilateral issuance process. In the case of multi-party DID authentication, the value of R is computed by $R := \text{pad}_{\text{DID}^H}(h(r_H \parallel r_{I_1} \parallel r_{I_2} \parallel \dots \parallel r_{I_N}))$, where $r_{I_1}, r_{I_2}, \dots, r_{I_N}$ are nonces generated by multiple **Issuers**, identified as $\text{DID}^{I_1}, \text{DID}^{I_2}, \dots, \text{DID}^{I_N}$.

5 METHOD CONSTRUCTION

In this section, we present three key method constructions involved in SLVC-DIDA. To achieve PIH in SLVC-DIDA, we formalize the statement for zero-knowledge, signature-less VC issuance and verification and provide the ZKP circuit for this statement. We instantiate the membership proof for legitimate **Issuers** using RSA accumulators and instantiate the list of issued VCs using a Merkle tree.

5.1 Zero-knowledge Issuer Qualification Verification

To protect sensitive information from **Issuer** and achieve PIH, we propose a zero-knowledge scheme to protect legitimate **Issuer** qualification verification. **Issuers** do not publish VCs in plaintext in this scheme; instead, SLVC-DIDA computes a ZKP for the set of legitimate **Issuers' identities**.

SLVC-DIDA involves the **Issuer's** identity token $\text{DIDTok} := (\text{DID}^I, R) = (\text{DID}^I, h(r_I \parallel r_H))$, which is used to link VCs and **Issuers**. To preserve privacy, we publicly disclose a derived version of the token $\text{pubDIDTok} = (r_I, h(\text{DIDTok}))$. Importantly, the hash $h(\text{DIDTok})$ is available as public input, while DID^I and r_H remain private.

We generate the ZKP $\pi_{\text{qua}}(\text{DID}^I) := \text{NIZK}_S.\text{Prove}_{\text{pp}}(\text{priZKDID}, \text{pubZKDID})$, where priZKDID represents the witness and pubZKDID is the instance. Specifically, we define $\text{priZKDID} := (r_H, \text{DID}^I)$ as the witness, and $\text{pubZKDID} := (\text{SDID}^I, \text{pubDIDTok})$ as the public instance. Such ZKP construction ensures that the statement \mathcal{S} holds, where $\text{NIZK}_S.\text{Prove}_{\text{pp}}(\cdot)$ allows the prover to demonstrate knowledge of the witness priZKDID without revealing any information beyond the validity of the statement \mathcal{S} . This proof guarantees that the **Verifier** can check the validity of certain properties of priZKDID against the public information pubZKDID in a secure and privacy-preserving manner. The details of statement \mathcal{S} are shown as follows:

Statement \mathcal{S} :

I know private DID^I and r_H such that:

- 1: $DID^I \in SDID^I$.
- 2: $h(DIDTok) = CRH.Hash_{pp}(DID^I, h(r_I \parallel r_H))$

For the statement \mathcal{S} , as described in Section 4.3, the algorithm $ProveQua_{pp}(\cdot)$ is used to compute the zero-knowledge qualification proof $\pi_{qua}(DID^I)$ for an **Issuer** identified by DID^I , based on public parameters pp . Specifically, the ZKP-RSA accumulator is used to prove the membership of the **Issuer** DID^I in the set of legitimate **Issuers**, denoted as $SDID^I$. The **Verifier** executes the algorithm $VeriQua_{pp}(\cdot)$ to determine the legitimate qualification of the **Issuer** DID^I . This process accepts DID^I as a valid **Issuer** when it belongs to the legitimate set or rejects it when it is illegal. Details of algorithms $ProveQua_{pp}(\cdot)$ and $VeriQua_{pp}(\cdot)$ are shown as follows:

Compute qualification proof of the Issuer:

$(DID^H, pubDIDTok, r_I^0, \pi_{qua}(DID^I)) \leftarrow ProveQua_{pp}(SDID^I, DID^H, (r_I^0, r_H, DIDTok); sk)$:

- 1: Compute $R := pad_{DIPH}(h(r_H \parallel r_I))$ and $r_I := h(DID^H, r_I^0) \leftarrow CRH.Hash_{pp}(DID^H, r_I^0)$
- 2: $h(DIDTok) \leftarrow CRH.Hash_{pp}(DID^I, h(r^I \parallel r^H))$
- 3: Compute $pubDIDTok := (r_I, h(DIDTok))$
- 4: $acc(SDID^I) \leftarrow RSA.ComAcc_{pp}(SDID^I; sk)$
- 5: $\pi_{qua}(DID^I) \leftarrow NIZK_S.Prove_{pp}(priZKDID, pubZKDID) := NIZK_S.Prove_{pp}((r_H, DID^I), (SDID^I, r_I, h(DIDTok)); sk)$: $(SDID^I, r_I, h(DIDTok))$ are used as statement and (r_H, DID^I) are used as witness to compute ZKP proof of DID^I qualification.
- 6: Return $(DID^H, pubDIDTok, r_I^0, \pi_{qua}(DID^I))$.

Verify qualification proof $\pi_{qua}(DID^I)$ by Verifier:

$\{0, 1\} \leftarrow VeriQua_{pp}(DID^H, pubDIDTok, r_I^0, acc(SDID^I), \pi_{qua}(DID^I); vk)$:

- 1: Verify $r_I \stackrel{?}{=} h(DID^H, r_I^0)$
- 2: $\{0, 1\} \leftarrow NIZK_S.Verify_{pp}(\pi_{qua}(DID^I), (pubDIDTok, SDID^I, acc(SDID^I)))$
- 3: **Verifier** accepts the legitimate **Issuer** DID^I if both functions in line 1 and line 2 yield a result of 1. If either function in line 1 or line 2 produces a result other than 1, the then **Verifier** rejects the VC issued by **Issuer**.

The algorithm above ensures the verifiability of the **Issuer's** qualifications. The ZKP membership proof of statement \mathcal{S} safeguards the **Issuer's** identity, so that it effectively conceals potentially sensitive information, including any links between signature-less VCs and specific **Issuer** identities. Our scheme guarantees **Issuer** anonymity when both **Holder** and **Issuer** act honestly. Moreover, our scheme ensures that the **Issuer's** identity remains protected throughout the verification process since PIH is achieved by employing ZKP.

Our signature-less VC issuance and verification process neither modify the underlying DID protocol (e.g., DID documents, DID resolvers, etc.) nor require specialized infrastructure, such that the proposed scheme is suitable for practical DID systems. Under the

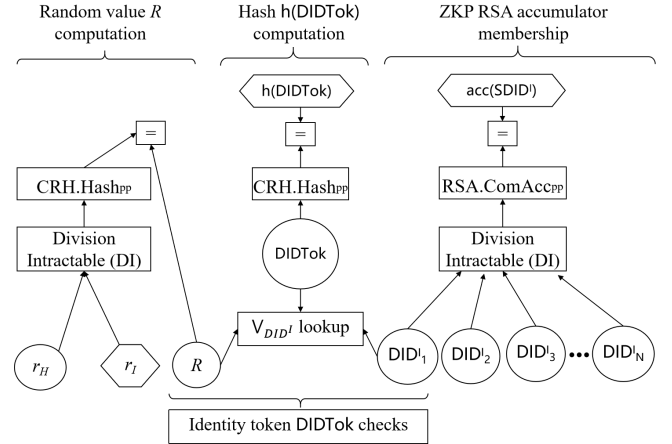


Figure 4: ZKP circuit of statement \mathcal{S} . Circular nodes represent private inputs, while hexagonal nodes represent public inputs. Our $CRH.Hash_{pp}(\cdot)$ and $RSA.ComAcc_{pp}(\cdot)$ algorithms uses the **Division Intractable (DI)** hash function, which is realized by **Poseidon hash** in our **RLVC-DIDA**. Each arrow represents a group of wires.

condition of underlying DID protocol preserves privacy of both users and VCs, the signature-less VC of SLVC-DIDA can preserve privacy, since our scheme does not interact with or expose any privacy components of the DID protocol. Similarly, verifiable properties (e.g., self-verifiability, regulatory compliance, etc.) of the underlying DID protocol remain stored, since our scheme does not interfere with verifiable checks of the DID protocol when SLVC-DIDA is employed.

Figure 4 illustrates a complete ZKP circuit of statement \mathcal{S} , which is used to prove the knowledge of a legitimate identity token $DIDTok$. The ZKP circuit can fulfill statement \mathcal{S} while ensuring PIH, since the token is able to privately link the identity of the **Issuer's** to the VC(s) that the token is issued by; thus, the **Issuer's** anonymity within the DID authentication process is preserved. We instantiate the algorithm $CRH.Hash_{pp}(\cdot)$ by using the Poseidon hash function and compute the random value R through the public input r_I and the private input r_H . Obtained from the random sampling, once r_I and r_H are used to enhance the unpredictability of cryptographic operations. When verifying the identity token ($DIDTok$), the function $lookup(\cdot)$ is used to verify whether the lengths of the padding R , $DIDTok$, and DID^I are consistent. Additionally, $DIDTok$ is used to compute the public input $h(DIDTok)$, which ensures the privacy and integrity of ZKP. The final part of the statement \mathcal{S} is the membership proof of DID^I in $SDID^I$. The identifiers ($DID_1^I, DID_2^I, \dots, DID_N^I$) of all legitimate **Issuers** are added to the circuit through hash computations and a **Division Intractable (DI)** hash-instantiated ZKP-RSA accumulator. By only showing the valid proof of the public input $acc(SDID^I)$, $DID^I \in SDID^I$ is verified.

5.2 ZKP-RSA Accumulator-based Permanent Issuer-hiding Membership Proof

A zero-knowledge accumulator is a cryptographic construct that allows a prover to demonstrate the membership of a specific element within a set, without revealing any information about other elements in the set. Specifically, in an RSA accumulator, the accumulated value is computed using modular exponentiation over a product of primes, providing a succinct representation of the set. The zero-knowledge property is achieved by generating a NIZK proof that allows the verifier to be convinced of the element's membership with hiding and binding properties.

Zero-knowledge RSA Accumulator. Refer to [39], we ensure binding and concealment by employing a blinding factor t , denoted as $g^{ut} \bmod N$, where g is a generator and u represents the product of all elements. We utilize a DI hash for ZKPoKE construction [8] and generate non-membership proofs through the Zero-knowledge Argument of Positivity (ZKAoP) [11]. The details of ZKP-RSA accumulator are shown as follows:

RSA.Setup(1^λ):

- 1: Sample two random primes p, q of length λ , and then compute the related primes $p' = 2p + 1$ and $q' = 2q + 1$, ensuring both p' and q' are also prime.
- 2: Compute the RSA modulus $N = p'q'$ and ensure that \mathbb{G} is the Quadratic Residue (QR) group QR_N , excluding $\{-1, 1\}$, i.e., $\mathbb{G} = QR_N \setminus \{-1, 1\}$. The QR group is typically used to ensure security properties in cryptographic applications.
- 3: Generate random elements g, h as generators from the group \mathbb{G} .

RSA.KeyGen(pp_{rsa}):

- 1: Return the sk_{rsa} and the vk_{rsa} , i.e., $sk_{rsa} = vk_{rsa} = (N, g, h)$.

RSA.ComAcc $_{pp_{rsa}}(t, X; sk_{rsa})$:

- 1: Compute the product u of the hashed values of all elements in the set X , denoted as $u = \prod_{i=1}^m h_{DI}(x_i)$, for all elements $x_i \in X$.
- 2: Compute the accumulated value $acc(X)$ using $acc(X) = g^{ut} \bmod N$.
- 3: Return $acc(X)$ as the accumulator value.

RSA.ComMem $_{pp_{rsa}}(x, X, acc(X); sk_{rsa})$:

For $x \in X$:

- 1: Compute α as the product of all elements in the set X except x , i.e., $\alpha = \prod_{y \in X \setminus \{x\}} h_{DI}(y)$.
- 2: Compute the membership proof $\pi_{mem}(x) = g^{\alpha t} \bmod N$.
- 3: Return $v = 1$ for $x \in X$ and the membership proof $\pi_{mem}(x)$.

For $x \notin X$:

- 1: Compute $\alpha = h_{DI}(x)$.
- 2: Use the Extended Euclidean Algorithm (EEA) to compute coefficients a, b such that $a, b \leftarrow \text{EEA}(ut, \alpha)$.
- 3: Sample a random value $\gamma \in [1, K]$.
- 4: Compute A, B and C as follows:

$$\begin{aligned} A &= g^{(a+\gamma\alpha)ut} \bmod N \\ B &= g^{-b\gamma ut} \bmod N \\ C &= (A \times B^\alpha)^{-1} \times g^\alpha = g^{\alpha-z} \bmod N \end{aligned}$$

- 5: Compute non-interactive zero-knowledge proofs (π_1, π_2, π_3) using the ZKPoKE and ZKAoP protocols as follows:

$$\begin{aligned} \pi_1 &\leftarrow \text{ZKPoKE.Prove}(A, acc(X); a - \gamma\alpha) \\ \pi_2 &\leftarrow \text{ZKPoKE.Prove}(C, g; \alpha - z) \\ \pi_3 &\leftarrow \text{ZKAoP.Prove}(A \times B^\alpha, g; z) \end{aligned}$$

- 6: Return $v = 0$ for $x \notin X$ and non-membership proof $\pi_{mem}(x) = (A, B, \pi_1, \pi_2, \pi_3)$.

$$\text{RSA.Verify}_{pp_{rsa}}(acc(X), x, \pi_{mem}(x), v; vk_{rsa}):$$

For $v = 1$:

- 1: Accept the proof if $(\pi_{mem}(x))^{h_{DI}(x)} = acc(X) \bmod N$. This ensures that the element x contributes correctly to the accumulated value.

For $v = 0$:

- 1: Parse $\pi_{mem}(x)$ as $(A, B, \pi_1, \pi_2, \pi_3)$.
- 2: Parse $C = (A \times B^\alpha)^{-1} \times g^\alpha \bmod N$.
- 3: Verify the correctness of the proofs using the ZKPoKE and ZKAoP protocols as follows:
Accept if $1 \leftarrow \text{ZKPoKE.Verify}(A, acc(X), \pi_1)$,
Accept if $1 \leftarrow \text{ZKAoP.Verify}(C, g, \pi_2)$,
Accept if $1 \leftarrow \text{ZKAoP.Verify}(A \times B^\alpha, g, \pi_3)$.
- 4: If any of the verifications fail, return 0. If all verifications succeed, return 1.

Zero-knowledge Multiswap. To maintain zero-knowledge when adding or removing members from the set of legitimate **Issuers**, we introduce ZK-Multiswap [39] for the ZKP-RSA accumulator of our SLVC-DIDA. ZK-MultiSwap demonstrates that removing a subset W and inserting a new subset Y from the zero-knowledge RSA accumulator $acc(X)$ will result in a new zero-knowledge RSA accumulator $acc(X)'$. The tentative relationship between (W, Y) can be verified by a NIZK proof. The details of ZK-Multiswap are shown as follows:

ZK-MultiSwap:

- 1: $pp_{zk} \leftarrow \text{NIZK.Setup}(1^\lambda, \mathcal{R}^{tent})$: \mathcal{R}^{tent} is the tentative relation for (W, Y) where W denotes the removal subset and Y denotes the added subset such that $acc(X)$ changes to $acc(X)'$. It outputs the public parameter pp_{zk} as the common reference string.
- 2: $\pi \leftarrow \text{NIZK.Prove}_{pp_{zk}}(acc(X), acc(X)', acc(X)_{mid}, d_0, d_1; \beta_0, \beta_1, W, Y)$: $acc(X)_{mid}$ are zero-knowledge RSA accumulator. Hash values of set W and β_0 are committed in d_0 and hash values of set Y and β_1 are committed in d_1 . Hash of β_0 and β_1 are used as randomizers.
- 3: $\{0, 1\} \leftarrow \text{NIZK.Verify}_{pp_{zk}}(acc(X), acc(X)', acc(X)_{mid}, d_0, d_1, \pi)$

By utilizing ZKP-RSA accumulators and ZK-Multiswap, SLVC-DIDA ensures both binding and hiding properties remain intact during **Issuer** qualification verification and changes in the legitimate **Issuer** set, thereby guaranteeing PIH.

5.3 Merkle Tree-based Membership Proofs for VC

In SLVC-DIDA, to demonstrate signature-less VCs, provers leverage the knowledge revealed by their credentials and the position of their credentials in the VC list to craft a membership proof based on a Merkle tree. To enhance privacy, the leaf nodes of the Merkle tree consist of commitment values of the VCs instead of their specific attribute data. **Verifiers** only require knowledge of the root value of the Merkle tree representing the issued VC list.

The construction of valid transactions on the blockchain ledger L involves aggregating VC commitment proofs into a ledger digest, which is then added to the blockchain ledger L . As shown in Figure 5, each transaction tx on the blockchain includes a set of new VC commitment proofs CP_1^H, \dots, CP_n^H , representing the cryptographic commitments of individual VCs issued within the transaction. These commitment proofs are then structured in a Merkle tree, where each leaf node $h(CP^H)$ corresponds to the hash of an individual commitment proof. The Merkle tree structure is utilized to efficiently aggregate and verify multiple VCs, allowing the generation of a single root hash that represents all VC commitments included in the transaction. This root hash is stored as part of the Ledger Digest (LD), which serves as a compact summary of the current state of all committed VCs.

To further ensure the integrity and validity of the aggregated VC commitments, the transaction includes a zkSNARK proof π of legitimate **Issuer** qualification. This proof allows for zero-knowledge verification of legitimate **Issuers** without revealing sensitive information. The use of a Merkle tree allows for logarithmic verification of individual VCs within the larger set, enabling efficient auditing and proof generation. The LD is updated with each new transaction and reflects the most recent state of the Merkle tree. By organizing the VC commitment proofs in this hierarchical manner, the blockchain ensures that any modifications to individual VCs are verifiable and traceable while maintaining privacy.

In a blockchain that uses a Merkle tree structure to manage VCs, deleting a specific VC can be accomplished efficiently by leveraging the properties of the tree. When a VC needs to be revoked or removed, its corresponding commitment proof, represented as a leaf node in the Merkle tree, is marked for deletion. Instead of directly removing the node, which would require restructuring the entire tree, the system updates the Merkle tree by replacing the hash of the deleted leaf node with a predefined null or “empty” hash. This nullification process preserves the overall structure and maintains the integrity of the tree while allowing the Merkle root to be re-computed with minimal changes. By updating only the affected paths up to the root, SLVC-DIDA achieves an efficient $O(\log n)$ complexity for deletion, where n is the number of leaf nodes in the tree. This approach allows for fast verification and re-computation of the Merkle root, ensuring that the state of blockchain ledger L remains consistent and publicly verifiable even after deletions.

6 IMPLEMENTATION AND EVALUATION

In this section, we implement the proposed SIVC-DIDA model and evaluate the performance of its three key components: signature-less VC, ZKP-RSA accumulator-based **Issuer** set, and the Merkle tree-based VC list.

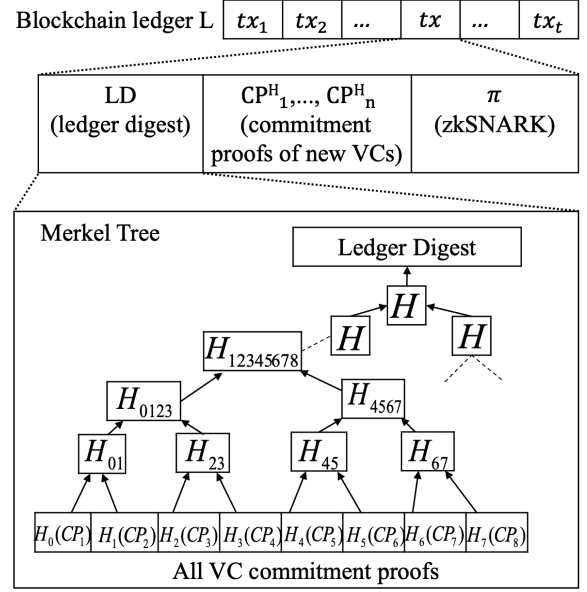


Figure 5: The construction of valid transactions on blockchain.

6.1 Experiment Configuration

The implementation of SIVC-DIDA is written in Golang and utilizes the following technology stack: the gnark cryptographic library² is employed to construct the Groth16-type SNARK circuits, with BN254 as the elliptic curve, and a Poseidon-based SNARK-friendly DI hash function is used for both the CRH. $\text{Hash}_{pp}(\cdot)$ and $\text{RSA.ComAcc}_{pp}(\cdot)$ algorithms. Additionally, we realize a ZKP-RSA accumulator with ZK-Multiswap refers to Notus code³. The experimental environments are running an Intel(R) Xeon(R) Platinum 8352V CPU @ 2.10GHz with 32 cores and 256GB of memory. We run 10 times for each experiment and record their average.

For the issuance and verification of signature-less VC across multiple **Issuers**, we implement the ZKP circuit illustrated in Figure 4 for the statement S , which facilitates zero-knowledge verification of **Issuer** qualification while preserving PIH. We consider a series of different numbers of legitimate **Issuers**, denoted as $NI \in \{4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048\}$, and evaluate the computational time costs for all phases involved in the signature-less VC issuance process under multiple numbers of **Issuers**. For the ZKP-RSA accumulator-based **Issuer** set, we evaluate the computational time costs of all algorithms in the ZKP-RSA accumulator for different sizes of the updated **Issuer** set, with updated set sizes denoted as $UIS \in \{5, 10, 15, 20, 25, 30\}$. For the Merkle tree-based VC list, we implement a Poseidon-hash-based, SNARK-friendly Merkle accumulator using the state-of-the-art bellman-bignat cryptographic library⁴. To simulate the Merkle SNARK-based VC list, we fix the height of the Merkle tree to 28 and evaluate the computational time

²The code is available at <https://github.com/Consensys/gnark.git>.

³The code is available at https://github.com/notus-project/rsa_accumulator

⁴The code is available at <https://github.com/alex-ozdemir/bellman-bignat>.

Table 1: Single-threaded experiment evaluation of Issuer qualification verification for signature-less VC. *Gen.*, *Num.*, *Cir.* and *Ver.* denotes the *Generation*, *Number*, *Circuit* and *Verification*, respectively. *sk* for \mathbb{G}_1 and *sk* for \mathbb{G}_2 are the secret keys to compute the polynomial commitment on \mathbb{G}_1 and \mathbb{G}_2 , respectively. *Cir.* and *Key Load* is the total time costs to load the complete SNARK circuit and the secret keys.

Performance of Zero-knowledge Issuer Qualification Verification		The number of Issuers NI									
		4	8	16	32	64	128	256	512	1024	2048
Initialization and Key Generation	<i>Num. of Constraints</i>	2956	5912	11824	23678	47296	94592	189184	378368	756736	1513742
	<i>sk</i> for \mathbb{G}_1 (bytes)	6402	12322	24162	47842	95202	189922	379362	758242	1516002	3031522
	<i>sk</i> for \mathbb{G}_2 (bytes)	250500	500868	1001604	2003076	4006020	8011908	16023684	32047236	64094340	128188548
Proof Generation	<i>Ver. Key vk</i> (bytes)	900	1156	1668	2692	4740	8836	17028	33412	66180	131716
	<i>ZKP Cir. Gen.</i> (s)	1.403	2.161	3.523	6.520	10.845	18.199	33.055	61.112	114.346	217.918
	<i>Cir. and Key Load</i> (s)	0.089	0.094	0.269	0.225	0.263	0.392	0.526	0.727	0.749	1.369
Proof Verification	<i>acc(NI) Gen.</i> (s)	0.035	0.048	0.076	0.149	0.252	0.456	0.909	1.761	3.218	5.093
	$\pi_{qua}(\text{DID}^I)$ <i>Gen.</i> (s)	0.495	0.619	0.575	0.751	0.485	0.987	1.531	2.499	2.675	4.481
	$\pi_{qua}(\text{DID}^I)$ <i>Ver.</i> (s)	0.004	0.002	0.004	0.003	0.003	0.003	0.005	0.004	0.004	0.004

Table 2: Experiment evaluation of Issuer set updates. *Gen.*, *Num.* and *Cons.* denotes the *Generation*, *Number*, and *Constraints*, respectively.

Performance of Zero-knowledge Issuer Set Updates		Size of the updated set UIS					
		5	10	15	20	25	30
Num. of Cons.		17665	26255	34845	43435	52025	60615
Proof Gen. (s)		0.734	1.042	0.766	0.888	0.935	0.957
Proof Ver. (s)		0.002	0.002	0.002	0.002	0.002	0.002

Table 3: Experiment evaluation of zero-knowledge issued VC list. *Gen.*, *Num.* and *Cons.* denotes the *Generation*, *Number*, and *Constraints*, respectively.

Performance of Merkle SNARK-based VC list		Size of the inserted VC set IV				
		4	8	16	32	64
Num. of Cons.		28540	57080	114160	228320	456640
Proof Gen. (s)		0.728	1.130	1.046	2.146	2.784
Proof Ver. (s)		0.003	0.003	0.003	0.004	0.004

costs of the Merkle SNARK algorithms under multiple sizes of the inserted VC set, denoted as $IV \in \{4, 8, 16, 32, 64\}$.

6.2 Experiment Results for SLVC-DIDA

Issuer qualification verification for signature-less VC. Our implementation of zero-knowledge verification for **Issuer** qualification operates in a single-threaded manner, and we evaluate the costs associated with the three main phases: **Initialization and Key Generation**, **Proof Generation** and **Proof Verification**. In particular, we specifically focus on the time costs incurred during the execution of these phases, as they directly impact the usability and practicality of signature-less VC.

Table 1 shows the specific time costs and key sizes under different number of **Issuers** (NI). **Initialization and Key Generation** involve the generation of public parameters and keys. In particular, we note that keys are specifically used for ZKP circuit computation and do not play a role for the issuance of VC. The experimental results are assessed based on several key metrics: the number of constraints in the ZKP circuit, the size of the secret key and verification key, and the time taken for SNARK-based ZKP circuit generation and verification. Each additional issuer introduces new constraints into the circuit, resulting in an exponential increase in the number of constraints, key sizes, and circuit generation time. In **Proof Generation** phase, the ZKP-RSA accumulator value for the **Issuer** set are computed by the $\text{RSA.ComAcc}(\cdot)$ algorithm. Therefore, the time to generate $\text{acc}(NI)$ corresponds to the execution time cost of

the $\text{RSA.ComAccpp}(\cdot)$ algorithm. Similarly, the time for generating $\pi_{qua}(\text{DID}^I)$ represents the execution time of the $\text{NIZK}_S.\text{Provepp}(\cdot)$ algorithm. When there are 2048 **Issuers** ($NI = 2048$) for a VC, the generation times for $\text{acc}(NI)$ and $\pi_{qua}(\text{DID}^I)$ reach their maximum, at 5.093 seconds and 4.481 seconds, respectively. In practical DID authentication scenarios, RLVC-DIDA demonstrates strong scalability, maintaining low proof generation times even with 2000 issuers, indicating both its usability and effectiveness. For **Proof Verification**, the verification time for $\pi_{qua}(\text{DID}^I)$ corresponds to the execution time cost of the $\text{NIZK}_S.\text{Verify}_{pp}(\cdot)$ algorithm. As shown in Table 1, the verification time for the ZKP proof of **Issuer** qualification does not exceed 0.005 seconds. The computational overhead of the verification phase is limited, with the verification time primarily affected by the size and optimization of the ZKP circuit rather than the increase in the number of issuers (NI).

ZKP-RSA accumulator-based PIH Issuer set updates. In addition to supporting legitimate **Issuer** qualification verification and VC issuance under PIH, SLVC-DIDA ensures that no **Issuer** information is disclosed during dynamic **Issuer** additions or removals. We conduct an evaluation of the time costs associated with zero-knowledge proof generation and verification for **Issuer** updates across various updated set sizes (UIS), with the experiment results showed in Table 2. While the number of constraints increases exponentially with the size of UIS , it is noteworthy that the proof generation time for $UIS = 15, 20, 25, 30$ is lower than that for $UIS = 10$. This anomalous behavior is attributed to the

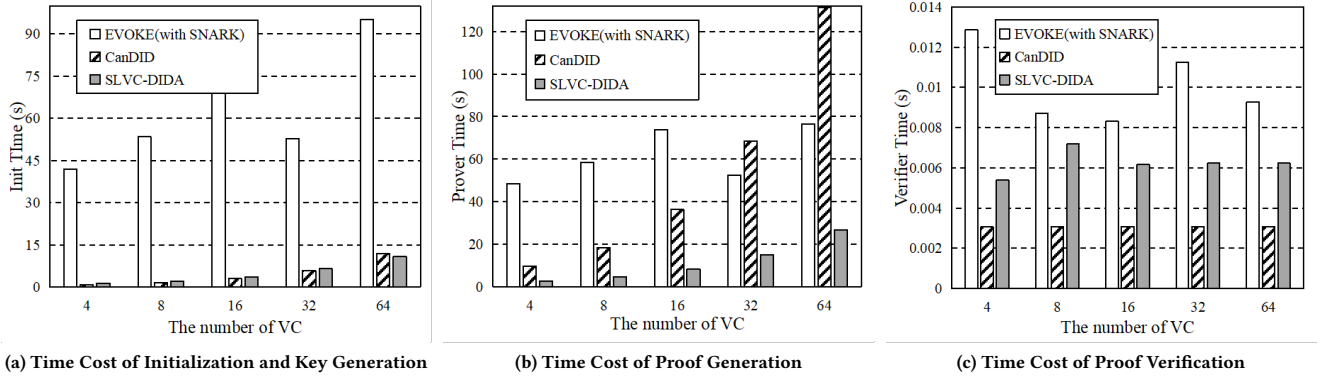


Figure 6: EVOKE(with SNARK), CanDID versus SLVC-DIDA for the computational overhead of Initialization and Key Generation, Proof Generation and Proof Verification.

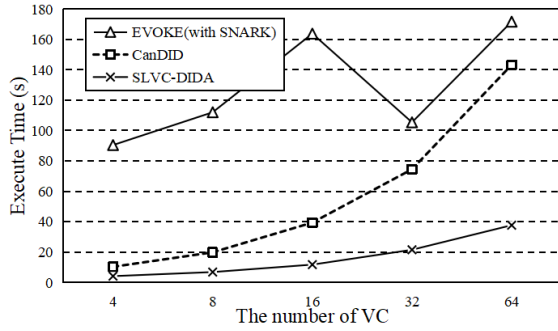


Figure 7: EVOKE(with SNARK), CanDID versus SLVC-DIDA for the execution time overhead. The execution time involves the computational overhead of Initialization and Key Generation, Proof Generation and Proof Verification.

parallelization of element interactions facilitated by MultiSwap, as well as the influence of system-level caching mechanisms. More specifically, although proof generation time generally exhibits an exponential growth pattern with respect to UIS , the time overhead of proof generation does not vary strictly linearly when UIS is small or when the variation between successive UIS values is relatively minor. Additionally, our proof verification time continues to maintain a low level, at just 0.002 seconds.

Merkle SNARK-based zero-knowledge VC list. RLVC-DIDA integrates a blockchain-based Merkle tree to store an effective VC list, which enables public verification of VCs. To ensure privacy, the VC list stores commitments CPs to VCs rather than their contents. Additionally, we use the Poisedon hash to implement a SNARK-friendly Merkle tree, supporting zero-knowledge proofs for the VC list. Newly issued valid VCs are inserted as leaf nodes in the Merkle tree. We evaluate the number of constraints, proof generation time, and proof verification time for zero-knowledge proofs under different sizes of the inserted VC set (IV), with the results presented in Table 3. The verification time for zero-knowledge proof remains limited, ranging from 0.003 to 0.004 seconds across all evaluated

IV s, demonstrating that RLVC-DIDA efficiently supports effective VC verification while maintaining privacy preservation.

6.3 SLVC-DIDA Performance

To further evaluate the performance of RLVC-DIDA, we implement two other DID approaches, namely EVOKE [28] and CanDID [12], in Rust and compare them with RLVC-DIDA. Specifically, EVOKE is designed for large-scale IoT environments and uses an RSA accumulator to manage VC issuance and revocation, while CanDID adopts a privacy-preserving approach for VC management, leveraging Pedersen commitments and ZKPs. We employ the bellman-bignat cryptographic library as the underlying stack to implement RSA accumulator-based VC registration in EVOKE, as well as SNARK-based DID membership proofs with Pedersen commitments in CanDID. It is important to note that EVOKE does not natively support ZKPs; therefore, we augment EVOKE's RSA accumulator with SNARK technology to incorporate zero-knowledge properties for VC issuance. Furthermore, both EVOKE and CanDID do not support multi-party VC issuance, so in our experimental settings, each VC is issued by a single **Issuer**.

We set a series of the number of VCs, denoted as $NV \in \{4, 8, 16, 32, 64\}$, and evaluate the performance of SLVC-DIDA, EVOKE (with SNARK), and CanDID under different numbers of VCs. Specifically, we assess the time costs in the three main phases: **Initialization and Key Generation**, **Proof Generation**, and **Proof Verification**. The results of the experiments are presented in Figure 6. Figure 6(a) shows the time costs for generating public parameters and keys for three DID management approaches when $NV \in \{4, 8, 16, 32, 64\}$. The initialization time overhead of SLVC-DIDA is on average 90% lower than that of EVOKE and on par with CanDID. As shown in Figure 6(b), SLVC-DIDA exhibits superiority in the **Proof Generation** phase compared to EVOKE and CanDID. Our prover time overhead is on average 81% lower than EVOKE and 78% lower than CanDID. Additionally, in the **Proof Verification** phase shown in Figure 6(c), due to SLVC-DIDA involving two ZKP verification algorithms, namely the legitimate **Issuer** qualification verification ($\text{VeriQua}_{pp}(\cdot)$) and the valid VC membership verification

(VeriMem_{pp}(·)), the verifier time overhead is on average 0.003 seconds higher than the smallest one, CanDID. However, as shown in Figure 7, due to the low computational overhead of SLVC-DIDA in **Initialization and Key Generation** and **Proof Generation**, the total execution time overhead of SLVC-DIDA remains significantly lower than that of (average 87% lower than) EVOKE and (average 72% lower than) CanDID.

7 CONCLUSION

In this paper we have proposed SLVC-DIDA, the first DID multi-party authentication scheme that implements signature-less VC-based PIH. SLVC-DIDA uses the hash value of nonce to establish a link between VCs and the issuers, and substitutes the signature key in PKI with a ZKP of the issuer's legitimate qualifications. Our scheme facilitates the issuance of universal signature-less VCs, independent of infrastructure such as bulletin boards. Furthermore, SLVC-DIDA ensures PIH by maintaining zero-knowledge and correctness during dynamic updates to the issuer set through the integration of ZKP-RSA accumulator and ZK-MultiSwap. A Merkle SNARK-based VC list is stored on the blockchain, so that VCs' privacy is protected while enabling the public verifiability of DIDs and VCs. In comparisons to other DID methods, experiment results have demonstrated that the proposed SLVC-DIDA performs more practical and effective in multi-party authentication of DID.

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