

BioZero: An Efficient and Privacy-Preserving Decentralized Biometric Authentication Protocol on Open Blockchain

Junhao Lai, Taotao Wang, Shengli Zhang, Qing Yang, and Soung Chang Liew

Abstract—Digital identity plays a vital role in enabling secure access to resources and services in the digital world. Traditional identity authentication methods, such as password-based and biometric authentications, have limitations in terms of security, privacy, and scalability. Decentralized authentication approaches leveraging blockchain technology have emerged as a promising solution. However, existing decentralized authentication methods often rely on indirect identity verification (e.g. using passwords or digital signatures as authentication credentials) and face challenges such as Sybil attacks. In this paper, we propose BioZero, an efficient and privacy-preserving decentralized biometric authentication protocol that can be implemented on open blockchain. BioZero leverages Pedersen commitment and homomorphic computation to protect user biometric privacy while enabling efficient verification. We enhance the protocol with non-interactive homomorphic computation and employ zero-knowledge proofs for secure on-chain verification. The unique aspect of BioZero is that it is fully decentralized and can be executed by blockchain smart contracts in a very efficient way. We analyze the security of BioZero and validate its performance through a prototype implementation. The results demonstrate the effectiveness, efficiency, and security of BioZero in decentralized authentication scenarios. Our work contributes to the advancement of decentralized identity authentication using biometrics.

Index Terms—Biometric authentication, zero-knowledge proof, Pedersen commitment, homomorphic computation, blockchain.

I. INTRODUCTION

Digital identity is a collection of attribute information in digital form that uniquely identifies the subject. It not only represents a person's identity from the physical world in digital space, but also serves as a passport for navigating the digital world. In various Internet applications, it is crucial for users to authenticate their real identities with their digital identities to gain authorized access or perform specific operations on resources. This user identity authentication process plays a pivotal role in upholding information security and ensuring data integrity [1]. Moreover, in the realm of Web 3.0, which places a strong emphasis on users' individual data sovereignty and privacy protection, user identity authentication is increasingly crucial in safeguarding data ownership [2].

From the point of view of authentication credential, there are two categories of authentication methods: indirect authen-

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tication using secret information as authentication credentials and direct authentication using user's own biometric as authentication credentials. Among them, indirect authentication is the most traditional and most commonly used authentication method. Users indirectly authenticate their identities by providing the verifier with some secret information as credentials associated with the digital identities, such as passwords, mnemonics or digital certificates. Thanks to the recent booming development of sensor technology, image processing and deep-learning-based pattern recognition technology, high-precision biometric identification technology has become practical; users thus can use local devices to extract their own biometric data, such as faces, irises, fingerprints and other features, and directly authenticate their identities by comparing the similarity with the biometric data already stored in the system. Compared with indirect authentication that relies on additional secret information, the credential of direct authentication is biometric data that is the inherent physiological characteristics of user's human body, which is unique and relatively stable. For direct biometric authentication, there is no need to implement an additional management scheme of credentials on the user side and it can effectively prevent identity theft and fraud. Therefore, direct biometric authentication is becoming more and more popular and is widely used in practice [3].

From the point of view of authentication organizations, there are two categories of authentication approaches: centralized authentication and decentralized authentication. Among them, centralized authentication is the current mainstream, which relies heavily on centralized identity providers to store and manage users' identity information and provide identity authentication services. However, with the development and evolution of Internet applications, centralized authentication has exposed many disadvantages. The first disadvantage is the risk of single point failure. Once the centralized identity authentication server is attacked or down, the identity authentication service will be unavailable, thus affecting the normal operation of the entire system. The second disadvantage is the risk of privacy leakage. Centralized institutions hold a large amount of user identity information. Once the centralized institution is hacked or the user identity information is illegally used, it will lead to serious privacy leakage. The third drawback is the low scalability. With the continuous increase in the number of users, centralized authentication is difficult to meet the growing demand for identity authentication, and it is also difficult to meet the cross-platform and cross-

domain identity authentication needs. Recently, decentralized authentication has emerged as an innovative way of identity authentication [4]. The existing decentralized authentication approaches mainly apply blockchain technologies and cryptographic protocols to record and verify identity information in a decentralization manner. In decentralization authentication, users have complete control over their identity information without relying on any centralized third-party agency, which can effectively overcome the limitations of centralized authentication and is geared towards the next-generation of Internet characterized by decentralization.

However, the current mainstream decentralized authentication approaches are still indirect authentication using secret information as authentication as credential. In such decentralized authentication, users can use asymmetric encryption algorithms to generate public-private key pairs, convert public keys into unique identity identifiers, and verify the ownership of identity identifiers through private key signatures. The account systems of open and permissionless blockchain, such as Ethereum and Bitcoin, generally use this authentication approach. However, this authentication approach is designed to verify anonymous identities that are generated using asymmetric encryption by users at will, and thus the applications employing such authentication approaches usually face sever Sybil attack. Vitalik, the founder of Ethereum, advocated creating identity credentials that are bound to the user's soul, which will be of great significance to the construction of a trusted decentralized society [5]. As an inherent attribute of organisms, biometric are the natural link between user entities and decentralized digital identities. Therefore, many researchers have tried to implement decentralized identity authentication based on biometric.

Before we can realize decentralized authentication based on biometric, there are still many challenges to be solved. Implementing the user's biometric authentication directly on an open blockchain will lead to the theft of user identity and the leakage of biometric privacy. Therefore, when implementing secure biometric authentication on a completely open and permissionless blockchain, the privacy protection of users' biometric data must be guaranteed. Moreover, the computations of smart contracts on current mainstream open blockchain are slow and costly. However, the operation of biometric verifications often incurs a large number of computations, which are unaffordable for the current blockchain. Therefore, when developing a practical decentralized biometric authentication on an open blockchain, we must maintain privacy-preserving for users' biometric data and solve the involved computation burden of on-chain biometric verifications.

In this paper, we propose BioZero, a decentralized biometric authentication protocol on open blockchain, which can simultaneously satisfy the three properties of decentralization, privacy-preserving and efficient verification. The contributions of this paper can be summarized as the following three aspects.

- Firstly, we propose an efficient and privacy-preserving biometric authentication protocol based on Pedersen commitment. This protocol employs an extended Pedersen commitment [6] to protect the privacy of user biometric data and transforms the traditional plaintext-based bio-

metric similarity computation into a homomorphic computation process that using ciphertext of biometric data (i.e., Pedersen commitments of biometric data). Due to the low complexity of the Pedersen commitment protocol, the homomorphic computation of biometric similarity is very efficient.

- Meanwhile, in order to fit the decentralized application scenario, we adopt the Fiat-Shamir heuristic to improve the extended Pedersen commitment protocol for non-interactive homomorphic computation. The zero-knowledge proof algorithm of Groth16 [7] is used to generate a proof that the biometric difference given by the homomorphic computation is smaller than a specified threshold so that the user can be authenticated by a smart contract on an open blockchain that is treated as the verifier of Groth16. With these algorithm ingredients, a secure, decentralized on-chain biometric authentication protocol, BioZero, is thus realized.
- Finally, we use threat modeling to theoretically analyse the security of the proposed BioZero protocol and implement a prototype system using the smart contracts on Ethereum blockchain with controlled experiments to confirm its advantages. Our theoretical and experimental results show that BioZero is effective against common malicious attacks, and the authentication process consumes relatively short time and proof size, which confirms the efficient and secure application of BioZero in decentralized authentication scenarios.

The remainder of this paper is organized as follows. Section II provides backgrounds. Section III gives the overall framework for our approach. Section IV presents the design details about our approach. Section V delves into the system test. Section VI discusses related work and compares them with our scheme. Section VII concludes our paper.

II. PRELIMINARIES

A. Blockchain and Smart Contract

A blockchain is a decentralized ledger recording all transactions generated across a peer-to-peer network [8]. A valid transaction that transfers the ownership of a crypto asset must be appended with the asset owner's digital signature. The chain expands as new transactions are continually packaged into blocks appended to the blockchain by validating nodes governed by a distributed consensus protocol. Since each block must contain the hash of its parent block, the sequence of blocks in the blockchain is arranged in chronological order. Blockchain is made tamper-proof via cryptographic hash, distributed consensus protocol, and digital signature.

In the Bitcoin blockchain, transactions can only transfer bitcoin ownership and cannot trigger general logical computations. Ethereum adds smart contracts to blockchain to enable secure Turing-complete computations in a decentralized manner [9]. In the Ethereum blockchain, smart contracts are programs that contain executable codes and data; each validating node executes the logical computations encoded in smart contracts over the Ethereum Virtual Machine (EVM) after receiving transactions that trigger the execution of the smart

contract. The smart contract execution results are recorded into new blocks and validated by all validating nodes.

In our work, we will use the Ethereum blockchain as the infrastructure for our decentralized biometric authentication protocol, and the verification computations of the decentralized biometric authentication protocol are implemented using smart contracts on it. Unless otherwise specified, the blockchain in the remainder of this paper refers specifically to Ethereum.

B. Pedersen Commitment and its Homomorphic Encryption

Pederson commitment is a form of a cryptographic commitment scheme introduced by Torben Pryds Pedersen in [6]. For a Pedersen commitment defined on a multiplicative cyclic group \mathbb{G} that has a large prime order $p \in \mathbb{Z}$, the prover binds herself to the message $f \in \mathbb{Z}_p$ by computing the corresponding commitment c as

$$c = c_{g,h}(f, r) = g^f h^r \text{ mod } p \quad (1)$$

where g and h are a pair of generators belongs to \mathbb{G} , $r \in \mathbb{Z}_p$ is the randomly selected blinding factor of the commitment, $c_{g,h}(\cdot)$ represents the computation of Pedersen commitment with generators g, h .

Pederson commitment offers unconditionally hiding and computationally binding properties [6]. Its security is based on the discrete logarithmic problem, which ensures that even with unlimited computational resource, an attacker cannot fully determine the original committed message f from the commitment c unless the message is revealed. Additionally, the prover is unable to interpret the original committed message f as any other message $f' \neq f$ given the commitment c computed from the message f . These inherent properties have made Pedersen commitment widely utilized as a fundamental cryptographic building block in constructing more intricate cryptographic protocols.

At the same time, the cryptography of Pedersen commitment supports homomorphic encryption (HE), which allows arithmetic operations to be performed on committed messages without revealing the original committed messages. Suppose there are three Pedersen commitments generated by the same generators (g, h) of the multiplicative cyclic group \mathbb{G} on the three messages $f^{(0)}, f^{(1)}, f^{(0,1)} \in \mathbb{Z}_p$:

$$c^{(0)} = c_{g,h}(f^{(0)}, r^{(0)}) = g^{f^{(0)}} h^{r^{(0)}} \text{ mod } p \quad (2)$$

$$c^{(1)} = c_{g,h}(f^{(1)}, r^{(1)}) = g^{f^{(1)}} h^{r^{(1)}} \text{ mod } p \quad (3)$$

$$c^{(0,1)} = c_{g,h}(f^{(0)} f^{(1)}, r^{(0,1)}) = g^{f^{(0)} f^{(1)}} h^{r^{(0,1)}} \text{ mod } p \quad (4)$$

where $r^{(0)}, r^{(1)}$ and $r^{(0,1)}$ are three blinding factors belonging to \mathbb{Z}_p . Then, Pedersen commitment supports the following homomorphic arithmetic operations.

Addition: For two Pedersen commitments generated using the same generators g and h , the additive homomorphism property of Pedersen commitments allows anyone to compute the commitment of the sum of the committed messages

$f^{(0)} + f^{(1)}$ from the commitments $c^{(0)}, c^{(1)}$ without using the messages $f^{(0)}$ and $f^{(1)}$:

$$\begin{aligned} & c_{g,h}(f^{(0)}, r^{(0)}) \oplus c_{g,h}(f^{(1)}, r^{(1)}) \\ &= c_{g,h}(f^{(0)}, r^{(0)}) c_{g,h}(f^{(1)}, r^{(1)}) \\ &= g^{f^{(0)}} h^{r^{(0)}} g^{f^{(1)}} h^{r^{(1)}} \text{ mod } p \\ &= c_{g,h}(f^{(0)} + f^{(1)}, r^{(0)} + r^{(1)}) \end{aligned} \quad (5)$$

where \oplus is the homomorphic arithmetic operator of addition. With $c^{(0)}$ and $c^{(1)}$ given in (2) and (3), the verification of the Pedersen commitment homomorphic addition's result can be straightforwardly performed as expressed in (5).

Subtraction: Similar to the additive homomorphism, the subtractive homomorphism of Pedersen commitment allows anyone to compute the commitment of the difference of the original committed messages $f^{(0)} - f^{(1)}$ from the commitments $c^{(0)}, c^{(1)}$ without using the messages $f^{(0)}$ and $f^{(1)}$:

$$\begin{aligned} & c_{g,h}(f^{(0)}, r^{(0)}) \odot c_{g,h}(f^{(1)}, r^{(1)}) \\ &= c_{g,h}(f^{(0)}, r^{(0)}) c_{g,h}^{-1}(f^{(1)}, r^{(1)}) \\ &= g^{f^{(0)}} h^{r^{(0)}} (g^{f^{(1)}} h^{r^{(1)}})^{p-2} \text{ mod } p \\ &= c_{g,h}(f^{(0)} - f^{(1)}, r^{(0)} - r^{(1)}) \end{aligned} \quad (6)$$

where \odot is the homomorphic arithmetic operator of subtraction, c^{-1} is the inverse of the commitment c . It can be deduced from Fermat's Little Theorem [10] that, as Pedersen commitment is established on a group with a prime order, there is always an inverse for any element within this group. Consequently, the property of homomorphic subtraction holds for any Pedersen commitment. With $c^{(0)}$ and $c^{(1)}$ given in (2) and (3), the verification of the Pedersen commitment homomorphic addition's result can be straightforwardly performed as expressed in (6).

Multiplication: While Pedersen commitment cannot support the standard multiplicative homomorphism, it can achieve the homomorphic multiplication through a more complex interactive protocol to accomplish the following mapping [11]: $c^{(0)} \otimes c^{(0)} \rightarrow c^{(0,1)}$, where \otimes is the homomorphic arithmetic operator of multiplication, $c^{(0)}, c^{(1)}$ and $c^{(0,1)}$ are given in (2)-(4), respectively. To enable any a third party that acts as the verifier to check that this mapping relationship is valid for the given three Pedersen commitments $c^{(0)}, c^{(1)}$ and $c^{(0,1)}$, the prover first constructs the following Pedersen commitments as the auxiliary proof factors used in the verification process:

$$\alpha = c_{g,h}(b_1, b_2) = g^{b_1} h^{b_2} \text{ mod } p \quad (7)$$

$$\beta = c_{g,h}(b_3, b_4) = g^{b_3} h^{b_4} \text{ mod } p \quad (8)$$

$$\gamma = c_{g,h}(b_3, b_5) = (g^{f^{(1)}} h^{r^{(1)}})^{b_3} h^{b_5} \text{ mod } p \quad (9)$$

where b_1, b_2, \dots, b_5 are random numbers that belong to \mathbb{Z}_p . The prover then provides the verifier with the commitments α, β and γ . After that, the verifier needs to select a random integer e from the finite field \mathbb{Z}_p with uniform probability as the challenging value and returns the selected integer e to the prover. Furthermore, the prover continues to construct the following more auxiliary proof factors based on the challenging value returned by the verifier:

$$z^{(1)} = b_1 + e f^{(0)} \quad (10)$$

$$z^{(2)} = b_2 + er^{(0)} \quad (11)$$

$$z^{(3)} = b_3 + ef^{(1)} \quad (12)$$

$$z^{(4)} = b_4 + er^{(1)} \quad (13)$$

$$z^{(5)} = b_5 + e(r^{(0,1)} - r^{(0)}f^{(1)}) \quad (14)$$

The prover again sends these auxiliary variables $z^{(1)}, z^{(2)}, \dots, z^{(5)}$ back to the verifier. Finally, the verifier will verify whether the following equalities are valid:

$$\begin{aligned} c_{g,h}(z^{(1)}, z^{(2)}) &= g^{b_1}h^{b_2}(g^{f^{(0)}}h^{r^{(0)}})^e \bmod p \\ &= \alpha [c_{g,h}(f^{(0)}, r^{(0)})]^e = \alpha (c^{(0)})^e \end{aligned} \quad (15)$$

$$\begin{aligned} c_{g,h}(z^{(3)}, z^{(4)}) &= g^{b_3}h^{b_4}(g^{f^{(1)}}h^{r^{(1)}})^e \bmod p \\ &= \beta [c_{g,h}(f^{(1)}, r^{(1)})]^e = \beta (c^{(1)})^e \end{aligned} \quad (16)$$

$$\begin{aligned} c_{c^{(0)},h}(z^{(3)}, z^{(5)}) &= (g^{f^{(0)}}h^{r^{(0)}})^{b_3}h^{b_5}(g^{f^{(0)}}f^{(0)}h^{r^{(0,1)}})^e \bmod p \\ &= \gamma [c_{g,h}(f^{(0)}f^{(1)}, r^{(0,1)})]^e = \gamma (c^{(0,1)})^e \end{aligned} \quad (17)$$

After checking whether the above three equalities hold, the verifier can verify the result of the homomorphic multiplication without knowing the committed messages.

Although Pedersen commitment can support homomorphic arithmetic operations of addition, subtraction, multiplication, the verification of its homomorphic multiplication is an interactive process, for which open blockchain is not suitable to serve as a verifier. In BioZero, we exploit Fiat-Shamir heuristic [12] to transform the interactive process of homomorphic multiplication verification into a non-interactive process to enable the application of the Pedersen commitment homomorphic encryption over open blockchain.

C. Zero-Knowledge Proof

Zero-knowledge proofs are a cryptographic technique that proves the validity of a statement without revealing any private information about the statement [13]. In the zero-knowledge protocol, there are two players, the prover and the verifier. The prover wants to convince the verifier that a statement is true without revealing other information. There are several types of zero-knowledge proof algorithms [14]. Among them, the succinct non-interactive zero-knowledge argument of knowledge (zk-SNARK) is considered to be the most practical. We present a simplified model of zk-SNARK here. We refer the readers to [15] for the formal and complete model of zk-SNARK.

A zk-SNARK algorithm is usually represented by an arithmetic circuit that consists of the basic arithmetic operations of addition, subtraction, multiplication, and division. An \mathbb{F} -arithmetic circuit is a circuit in which all inputs and all outputs are elements in a field \mathbb{F} . Consider an \mathbb{F} -arithmetic circuit C that has an input $x \in \mathbb{F}^n$, an auxiliary input $w \in \mathbb{F}^h$ called a witness, and an output $C(x, w) \in \mathbb{F}^l$, where n, h, l are the dimensions of the input, auxiliary input, and output, respectively. The arithmetic circuit satisfiability problem of the \mathbb{F} -arithmetic circuit C is captured by the relation: $R_c = \{(x, w) \in \mathbb{F}^n \times \mathbb{F}^h : C(x, w) = 0^l\}$, and its expression is $L_c = \{x \in \mathbb{F}^n : \exists w \in \mathbb{F}^h \text{ s.t. } C(x, w) = 0^l\}$. A zk-SNARK algorithm consists of three algorithmic components [15]:

- $\text{GenKey}(1^\lambda, C) \rightarrow (pk_z, vk_z)$: GenKey is the key generation algorithm that generates the proving key pk_z and the verification key vk_z by using a predefined security parameter λ and an \mathbb{F} -arithmetic circuit C .
- $\text{GenProof}(pk_z, x, w) \rightarrow \pi$: GenProof is the proof generation algorithm that generates a proof π based on the proving key pk_z , the input x , and the witness w .
- $\text{VerProof}(vk_z, x, \pi) \rightarrow 1/0$: VerProof is the proof verification algorithm that outputs a decision to accept or reject π using vk_z, x and π as the input.

The proving key pk_z and the verification key vk_z generated by the GenKey algorithm is treated as the public parameters pre-generated by an authority. The GenProof algorithm is executed by the prover and the VerProof algorithm is executed by the verifier. Witness w is the secret owned by the prover that he/she does not want to reveal to others and yet wants to prove that he/she knows the secret.

zk-SNARK has the following technical advantages [14]. First, the generated proof has a size of just several bytes, the proof can be verified in a short running time, and the GenProof algorithm can be executed in polynomial time (the succinct property). Second, the prover and verifier do not need to communicate synchronously with each other to perform the challenge and response phases; the generated proof is sent to a verifier and can be verified offline (the non-interactive property). In this work, we use the Groth16 zk-SNARK algorithm [7] to implement our BioZero protocol.

III. BIOZERO PROTOCOL DESIGN

BioZero aims for an effective and privacy-preserving biometric authentication protocol on an open blockchain. To accomplish this objective, BioZero employs a rigorous combination of Pedersen commitment-based homomorphic encryption and the Groth16 zk-SNARK algorithm. We first give an overview of the BioZero biometric authentication protocol and then present the details on the generation and verification processes of authentication proof in the protocol.

A. Protocol Overview

Suppose there is a user, Alice, who already registered her biometric data to open a blockchain account and then she wants to gain access to her blockchain account via decentralized biometric authentication on the blockchain. We denote Alice's biometric data used to register her blockchain account by vector $\mathbf{f}^{(0)} = [f_1^{(0)}, f_2^{(0)}, \dots, f_i^{(0)}, \dots, f_N^{(0)}]$, and denote the newly extracted biometric data when Alice is authenticated by another vector $\mathbf{f}^{(1)} = [f_1^{(1)}, f_2^{(1)}, \dots, f_i^{(1)}, \dots, f_N^{(1)}]$, where $f_i^{(0)}(f_i^{(1)})$ is the i -th element of vector $\mathbf{f}^{(0)}(\mathbf{f}^{(1)})$, N is the length of the biometric data vectors. We can now formulate the biometric authentication as a biometric similarity matching problem:

$$d(\mathbf{f}^{(0)}, \mathbf{f}^{(1)}) = \sum_{i=1}^N (f_i^{(0)})^2 + (f_i^{(1)})^2 - 2f_i^{(0)}f_i^{(1)} < \epsilon \quad (18)$$

where $d(\mathbf{f}^{(0)}, \mathbf{f}^{(1)})$ is the distance between vectors $\mathbf{f}^{(0)}$ and $\mathbf{f}^{(1)}$, ϵ is the threshold for the biometric similarity matching.

Note that in (18) we employ the Euclidean distance as the metric to quantify the similarity of biometric data. However, it is worth mentioning that BioZero has the capability to accommodate various other biometric similarity metrics derived from the three fundamental arithmetic operations of addition, subtraction, and multiplication.

A centralized biometric authentication approach involves storing registered biometric data within a centralized server. During the authentication process, the newly acquired biometric data, ready for biometric similarity matching with the stored registered biometric data, must be transmitted to the server for computational processing, as expressed by (18). These biometric data are completely exposed to the server, and thus maybe abused by the server. To address this concern, BioZero is designed as a decentralized biometric authentication approach on an open blockchain. Due to the public nature of open blockchain, it is not feasible to store and process users' biometric data directly on an open blockchain. In order to safeguard users' biometric privacy, we adopt the Pedersen commitment-based homomorphic encryption to realize the decentralized biometric authentication on open blockchain. This cryptographic technique ensures the confidentiality of users' biometric information while enabling secure authentication within the decentralized blockchain environment.

Specifically, other than directly processing the biometric data of the user, $\mathbf{f}^{(0)}$, $\mathbf{f}^{(1)}$, BioZero performs biometric authentication using the Pedersen commitment vectors generated from the biometric data $\mathbf{f}^{(0)}, \mathbf{f}^{(1)}$, which are defied as:

$$\mathbf{c}^{(0)} = [c_{g,h}(f_1^{(0)}, r_1^{(0)}), \dots, c_{g,h}(f_N^{(0)}, r_N^{(0)})] \quad (19)$$

$$\mathbf{c}^{(1)} = [c_{g,h}(f_1^{(1)}, r_1^{(1)}), \dots, c_{g,h}(f_N^{(1)}, r_N^{(1)})] \quad (20)$$

where $c_{g,h}(\cdot)$ is the Pedersen commitment computation with generators g, h , and $r_i^{(0)}, r_i^{(1)}$ are the blinding factors used to compute the Pedersen commitments. The cryptograph of Pedersen commitment provides the support of homomorphic arithmetic operations, enabling computations to be performed while preserving the confidentiality of the original committed information. Therefore, with the Pedersen commitment vectors, $\mathbf{c}^{(0)}, \mathbf{c}^{(1)}$, we can employ the technique of Pedersen commitment-based homomorphic encryption to compute the Pedersen commitment of the Euclidean distance between the two biometric data vectors, $\mathbf{f}^{(0)}, \mathbf{f}^{(1)}$:

$$\begin{aligned} & c_{g,h}(d(\mathbf{f}^{(0)}, \mathbf{f}^{(1)}), r_d) \\ &= c_{g,h}\left(\sum_{i=1}^N (f_i^{(0)})^2 + (f_i^{(1)})^2 - 2f_i^{(0)}f_i^{(1)}, r_d\right) = \\ & \sum_{i=1}^N c_{g,h}((f_i^{(0)})^2, r_d) \oplus c_{g,h}((f_i^{(1)})^2, r_d) \odot 2c_{g,h}(f_i^{(0)}f_i^{(1)}, r_d) \end{aligned} \quad (21)$$

where r_d is the blinding factor used to compute this Pedersen commitment, \oplus, \odot and \otimes are the homomorphic arithmetic operators of addition, subtraction and multiplication supported by Pedersen commitment.

As expressed in (19)-(21), the user in BioZero now has no need to store and process plaintext of her biometric data, $\mathbf{f}^{(0)}, \mathbf{f}^{(1)}$, on blockchain, and she just needs to make

Pedersen commitments to her biometric data and all processing of the biometric authentication are executed based on these Pedersen commitments. According to the security property of Pedersen commitment, no information of biometric data will be revealed from their Pedersen commitments. Thus, this Pedersen commitment based homomorphic encryption for biometric authentication can protect users' biometric privacy.

However, while the Pedersen commitments can protect the users' biometric privacy, the Pedersen commitment of the biometric distance cannot be as a metric that can directly be compared with a threshold. To address this issue, BioZero utilizes the Groth16 zk-SNARK algorithm to generate a zero-knowledge proof, without revealing the biometric vectors, $\mathbf{f}^{(0)}$ and $\mathbf{f}^{(1)}$, to state:

- 1) The distance between $\mathbf{f}^{(0)}$ and $\mathbf{f}^{(1)}$ is smaller than a threshold, i.e., $d(\mathbf{f}^{(0)}, \mathbf{f}^{(1)}) < \epsilon$;
- 2) The Pedersen commitment vectors of $\mathbf{f}^{(0)}$ and $\mathbf{f}^{(1)}$ are $\mathbf{c}^{(0)}$ and $\mathbf{c}^{(1)}$ as defined in (19)-(20);
- 3) The Pedersen commitment of $d(\mathbf{f}^{(0)}, \mathbf{f}^{(1)})$ is $c_{g,h}(d(\mathbf{f}^{(0)}, \mathbf{f}^{(1)}), r_d)$ which can be computed using $\mathbf{c}^{(0)}$ and $\mathbf{c}^{(1)}$ as in (21).

All the computation results of Pedersen commitment homomorphic encryption and the proof generated by the zk-SNARK algorithm can be verified on the blockchain. Fig. 1 shows the diagram of the BioZero biometric authentication's functional building blocks and the work flow. The BioZero decentralized biometric authentication protocol is executed between two parties: a Prover and a Verifier.

- **Prover:** The prover is the party that prepares the Pedersen commitments of biometric data vectors, the auxiliary variables for homomorphic encryption and generates the zero-knowledge proof using the proving function of zk-SNARK. In BioZero, these functions of the prover are implemented on the user's local device.
- **Verifier:** The verifier is the party that conducts Pedersen commitment homomorphic encryption to compute the Pedersen commitment of the biometric distance and verifies the zero-knowledge proof using the verifying function of zk-SNARK. In general, anyone can be the verifier whose responsibility is to systematically verify the correctness of the biometric authentication result. In BioZero, the verifier is implemented on an open blockchain (Ethereum) using smart contracts.

All of the Pedersen commitments, auxiliary variables and zero-knowledge proof are stored onto the blockchain so that anyone can verify the correctness of the biometric authentication result anytime. In the following, we describe the details on the generation and verification processes of authentication proof in the BioZero decentralized biometric authentication protocol.

B. Generation of Authentication Proof

In the user registration process, the user needs to upload her account identifier id with the Pedersen commitment vector $\mathbf{c}^{(0)}$ of her biometric data vector $\mathbf{f}^{(0)}$ to the blockchain. The vector $\mathbf{c}^{(0)}$ is computed from $\mathbf{f}^{(0)}$ according to (19). The vector $\mathbf{c}^{(0)}$ will be used in the Pedersen commitment homomorphic encryption for biometric authentication to identify each unique

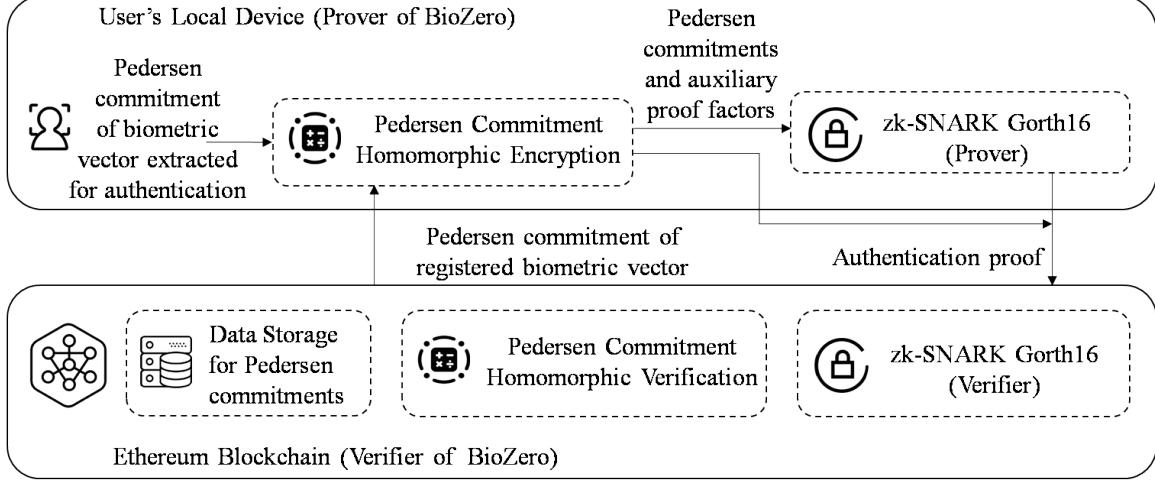


Fig. 1. The functional building blocks and the working flow of BioZero biometric authentication.

registered user, and it does not reveal any biometric information about the user. When the user needs to initiate a biometric authentication request, the following computational steps need to be performed.

① Pedersen Commitment Computation: The user obtains her latest biometric data vector $\mathbf{f}^{(1)}$ through the biometric extraction function employed by the local device and generates the corresponding Pedersen commitment vector $\mathbf{c}^{(1)}$ from $\mathbf{f}^{(1)}$ according to (20). The user is then required to generate a series of Pedersen commitment vectors that are used to compute the Euclidean distance between the biometric data vectors using homomorphic encryption, as expressed in (21). These specific Pedersen commitment vectors are given below:

$$\mathbf{c}^{(0,0)} = [c_{g,h}(f_1^{(0)}, r_1^{(0,0)}), \dots, c_{g,h}(f_N^{(0)}, r_N^{(0,0)})] \quad (22)$$

$$\mathbf{c}^{(1,1)} = [c_{g,h}(f_1^{(1)}, r_1^{(1,1)}), \dots, c_{g,h}(f_N^{(1)}, r_N^{(1,1)})] \quad (23)$$

$$\mathbf{c}^{(0,1)} = [c_{g,h}(f_1^{(0)}, f_1^{(1)}, r_1^{(0,1)}), \dots, c_{g,h}(f_N^{(0)}, f_N^{(1)}, r_N^{(0,1)})] \quad (24)$$

where $\mathbf{c}^{(0,0)}$ is the commitment vector of the squares of the elements in the user's registered biometric data vector, $\mathbf{c}^{(1,1)}$ is the commitment vector of the squares of the elements in the user's newly extracted biometric vector, $\mathbf{c}^{(0,1)}$ is the commitment vector of the cross product of the elements of the user's registered biometric data vector and the newly extracted biometric vector, $r_i^{(0,0)}, r_i^{(1,1)}, r_i^{(0,1)}$ are the blinding factors randomly generated by the user.

② Challenge Factor Generation: Then, the user, as the prover of the Pedersen commitment homomorphic encryption, needs to generate her own challenge factor that is given by

$$e = H(\mathbf{c}^{(0)} || \mathbf{c}^{(1)} || \mathbf{c}^{(0,0)} || \mathbf{c}^{(1,1)} || \mathbf{c}^{(0,1)} || id || nonce) \quad (25)$$

where $H(\cdot)$ is the used hash function $SHA256$, $nonce$ is the number used to keep track of the number of the user's initiated biometric authentication, and it is worth noting that $nonce$ starts at zero after registration and increases by one with each biometric authentication initiated. Here, with the help of Fiat-Shamir heuristic [12], the Pedersen homomorphic multiplication, which originally requires an interactive proving

process, is transformed into a non-interactive proving process. And the hash function $SHA256$ is used as an oracle to fulfill the security requirement.

③ Auxiliary Proof Factor Construction: With the self-generated challenge factor, the user can construct a series of auxiliary proof factors to demonstrate the correctness of the homomorphic encryption expressed in (21). These auxiliary proof factors are given below:

$$\alpha_1 = c_{g,h}(b_1, b_2) \quad (26)$$

$$\alpha_2 = c_{g,h}(b_3, b_4) \quad (27)$$

$$\beta^{(1)} = [c_{c_1^{(0)}, h}(b_1, b_5), \dots, c_{c_N^{(0)}, h}(b_1, b_5)] \quad (28)$$

$$\beta^{(2)} = [c_{c_1^{(1)}, h}(b_1, b_5), \dots, c_{c_N^{(1)}, h}(b_1, b_5)] \quad (29)$$

$$\beta^{(3)} = [c_{c_1^{(0)}, h}(b_3, b_7), \dots, c_{c_N^{(0)}, h}(b_3, b_7)] \quad (30)$$

$$\mathbf{z}^{(1)} = [b_1 + ef_1^{(0)}, b_1 + ef_2^{(0)}, \dots, b_1 + ef_N^{(0)}] \quad (31)$$

$$\mathbf{z}^{(2)} = [b_2 + er_1^{(0)}, b_2 + er_2^{(0)}, \dots, b_2 + er_N^{(0)}] \quad (32)$$

$$\mathbf{z}^{(3)} = [b_3 + ef_1^{(1)}, b_3 + ef_2^{(1)}, \dots, b_3 + ef_N^{(1)}] \quad (33)$$

$$\mathbf{z}^{(4)} = [b_4 + er_1^{(1)}, b_4 + er_2^{(1)}, \dots, b_4 + er_N^{(1)}] \quad (34)$$

$$\mathbf{z}^{(5)} = [b_5 + e(r_1^{(0,0)} - r_1^{(0)} f_1^{(0)}) \dots b_5 + e(r_N^{(0,0)} - r_N^{(0)} f_N^{(0)})] \quad (35)$$

$$\mathbf{z}^{(6)} = [b_6 + e(r_1^{(1,1)} - r_1^{(1)} f_1^{(1)}) \dots b_6 + e(r_N^{(1,1)} - r_N^{(1)} f_N^{(1)})] \quad (36)$$

$$\mathbf{z}^{(7)} = [b_7 + e(r_1^{(0,1)} - r_1^{(0)} f_1^{(1)}) \dots b_7 + e(r_N^{(0,1)} - r_N^{(0)} f_N^{(1)})] \quad (37)$$

where b_1, b_2, \dots, b_7 are some random numbers that belong to \mathbb{Z}_p , e is the self-generated challenge factor given in (25), the computation of Pedersen commitments, $c_{\bullet, \bullet}(\bullet, \bullet)$, is defined in (1).

④ Zero-Knowledge Proof Generation: Finally, the user computes the Euclidean distance between the two biometric data vectors as

$$d = d(\mathbf{f}^{(0)}, \mathbf{f}^{(1)}) = \sum_{i=1}^N (f_i^{(0)} - f_i^{(1)})^2 \quad (38)$$

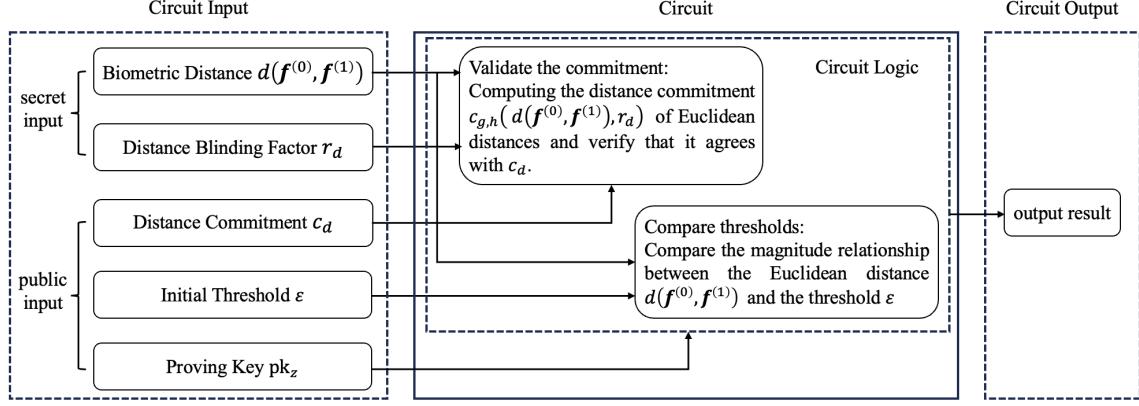


Fig. 2. The block diagram of the circuit used in the Groth16 zk-SNARK algorithm.

and also computes a new blinding factor as

$$r_d = \sum_{i=1}^N (r_i^{(0,0)} + r_i^{(1,1)} - 2r_i^{(0,1)}). \quad (39)$$

Based on d and r_d , the user can obtain the commitment of the Euclidean distance between the biometric data vectors, c_d , and generates a zero-knowledge proof, π using the Groth16 zk-SNARK to prove that the distance of the two biometric data vectors is less than a specific threshold:

$$\pi = \text{GenProof}(pk_z, d, r_d, c_d, \epsilon) \text{ for } d \in [0, \epsilon] \quad (40)$$

where pk_z is the Groth16 proving key, d , r_d are the Groth16 secret inputs, c_d , ϵ are the Groth16 public inputs. The block diagram of the circuit used in this Groth16 zk-SNARK algorithm is given in Fig. 2.

After the user completes the aforementioned steps, she needs to construct the authentication proof as:

$$\Gamma = \{id, \text{nonce}, \mathbf{c}^{(1)}, \mathbf{c}^{(0,0)}, \mathbf{c}^{(1,1)}, \mathbf{c}^{(0,1)}, \alpha_1, \alpha_2, \beta^{(1)}, \dots, \mathbf{z}^{(7)}, \pi\} \quad (41)$$

The authentication proof is encapsulated in a transaction and is sent to the open blockchain to invoke the smart contract that serves as the verifier of the biometric authentication protocol. The pseudocode of the authentication proof generation is summarized as Algorithm 1.

C. Verification of Authentication Proof

The verifier (the smart contract deployed on the open blockchain) will systematically conduct the following checks upon receiving an authentication request.

① Pedersen Commitment Verification: When the verifier receives a validation request, it first checks the value of nonce to ensure that it is greater than the value recorded used in the user's last authentication. If the value of nonce is valid, using the information contained in the authentication proof sent by the user, the verifier independently re-generates the challenge factor e according to (25). Then using the auxiliary proof factors $\{\alpha_1, \alpha_2, \beta^{(1)}, \beta^{(2)}, \beta^{(3)}, \mathbf{z}^{(1)}, \dots, \mathbf{z}^{(7)}\}$ sent by

the user, the verifier checks if the following equations hold for $i = 1, 2, \dots, N$:

$$c_{g,h}(z_i^{(1)}, z_i^{(2)}) = \alpha_1 (c_i^{(0)})^e \quad (42)$$

$$c_{c_i^{(0)}, h}(z_i^{(1)}, z_i^{(5)}) = \beta_i^{(1)} (c_i^{(0,0)})^e \quad (43)$$

$$c_{g,h}(z_i^{(3)}, z_i^{(4)}) = \alpha_2 (c_i^{(1)})^e \quad (44)$$

$$c_{c_i^{(1)}, h}(z_i^{(3)}, z_i^{(6)}) = \beta_i^{(2)} (c_i^{(1,1)})^e \quad (45)$$

$$c_{c_i^{(0)}, h}(z_i^{(3)}, z_i^{(7)}) = \beta_i^{(3)} (c_i^{(0,1)})^e. \quad (46)$$

If (42) and (43) hold for $i = 1, 2, \dots, N$, $\mathbf{c}^{(0,0)}$ is indeed the vector of the commitments to the square of the user's registered biometric data; if (44) and (45) hold for $i = 1, 2, \dots, N$, then $\mathbf{c}^{(1,1)}$ is indeed the vector of the commitments to the square of the user's newly extracted biometric data when authentication; if (42), (44) and (46) hold for $i = 1, 2, \dots, N$, then $\mathbf{c}^{(0,1)}$ is indeed the vector of the commitments to the product of the user's two biometric data. Only if all the equations hold for $i = 1, 2, \dots, N$, it means that the Pedersen Commitments are correctly computed corresponding to the registered biometric data $f^{(0)}$; otherwise, it implies that the commitments are incorrect, and then prompting an authentication failure.

② Pedersen Commitment Construction: Using the Pedersen commitments $\mathbf{c}^{(0,0)}, \mathbf{c}^{(1,1)}$ and $\mathbf{c}^{(0,1)}$ sent by the user (and are verified in the last step), the verifier can construct the Pedersen commitment of the Euclidean distance between the two biometric vectors by itself. The Pedersen commitment of the Euclidean distance c'_d is constructed as

$$c'_d = \sum_{i=1}^N c_i^{(0,0)} \oplus c_i^{(1,1)} \odot 2c_i^{(0,1)} \quad (47)$$

which is actually constructed according to (21).

③ Zero-Knowledge Proof Verification: Utilizing the constructed c'_d and the zero-knowledge proof π sent by the user, the verifier verifies the result of biometric similarity matching through the Groth16 verification algorithm $\text{VerProof}(vk_z, c'_d, \epsilon, \pi) \rightarrow b$. If $b = 1$, it signifies that the Euclidean distance of the biometric vectors used to generate

Algorithm 1 Generation of Authentication Proof

Input: account identifier id ; biometric vectors $\mathbf{f}^{(0)}$; blinding factors $r^{(0)}$; commitment generating elements g, h ; Pedersen commitment vector $c^{(0)}$;

Output: authentication proof $\{id, nonce, \mathbf{f}^{(1)}, \mathbf{f}^{(0,0)}, \mathbf{f}^{(1,1)}, \mathbf{f}^{(0,1)}, \alpha_1, \alpha_2, \beta^{(1)}, \beta^{(2)}, \beta^{(3)}, z^{(1)}, \dots, z^{(7)}, \pi\}$.

- 1: Get the user's latest biometric data vector $\mathbf{f}^{(1)}$ by the local device.
- 2: **for** i in range(Length of the biometric code N) **do**
- 3: Select a random integer $r_i^{(1)} \in \mathbb{Z}_p$, and then compute $c_i^{(1)} = g f_i^{(1)} h^{r_i^{(1)}} \text{ mod } p$;
- 4: Select a random integer $r_i^{(0,0)} \in \mathbb{Z}_p$, and then compute $c_i^{(0,0)} = g f_i^{(0)} f_i^{(0)} h^{r_i^{(0,0)}} \text{ mod } p$;
- 5: Select a random integer $r_i^{(1,1)} \in \mathbb{Z}_p$, and then compute $c_i^{(1,1)} = g f_i^{(1)} f_i^{(1)} h^{r_i^{(1,1)}} \text{ mod } p$;
- 6: Select a random integer $r_i^{(0,1)} \in \mathbb{Z}_p$, and then compute $c_i^{(0,1)} = g f_i^{(0)} f_i^{(1)} h^{r_i^{(0,1)}} \text{ mod } p$;
- 7: **end for**
- 8: Get $nonce$ used for the last authentication and compute generate a bigger $nonce$.
- 9: $e \leftarrow SHA256(\mathbf{c}^{(0)} || \mathbf{c}^{(1)} || \mathbf{c}^{(0,0)} || \mathbf{c}^{(1,1)} || \mathbf{c}^{(0,1)} || id || nonce)$;
- 10: Select seven random integers b_1, b_2, \dots, b_7 , and compute $\alpha_1 = g^{b_1} h^{b_2} \text{ mod } p$ and $\alpha_2 = g^{b_3} h^{b_4} \text{ mod } p$;
- 11: **for** i in range(Length of the biometric code N) **do**
- 12: Compute $\beta_i^{(1)} = (c_i^{(0)})^{b_1} h^{b_5} \text{ mod } p$;
- 13: Compute $\beta_i^{(2)} = (c_i^{(1)})^{b_1} h^{b_5} \text{ mod } p$;
- 14: Compute $\beta_i^{(3)} = (c_i^{(0)})^{b_3} h^{b_7} \text{ mod } p$;
- 15: Compute $z_i^{(1)} = b_1 + e f_i^{(0)}$ and $z_i^{(2)} = b_2 + e r_i^{(0)}$;
- 16: Compute $z_i^{(3)} = b_3 + e f_i^{(1)}$ and $z_i^{(4)} = b_4 + e r_i^{(1)}$;
- 17: Compute $z_i^{(5)} = b_5 + e(r_i^{(0,0)} - r_i^{(0)} f_i^{(0)})$;
- 18: Compute $z_i^{(6)} = b_6 + e(r_i^{(1,1)} - r_i^{(1)} f_i^{(1)})$;
- 19: Compute $z_i^{(7)} = b_7 + e(r_i^{(0,1)} - r_i^{(0)} f_i^{(1)})$;
- 20: **end for**
- 21: Compute $d(\mathbf{f}^{(0)}, \mathbf{f}^{(1)}) = \sum_{i=1}^N (f_i^{(0)} - f_i^{(1)})^2$ and then $r_d = \sum_{i=1}^N (r_i^{(0,0)} + r_i^{(1,1)} - 2r_i^{(0,1)})$
- 22: Compute $c_d = g^{d(\mathbf{f}^{(0)}, \mathbf{f}^{(1)})} h^{r_d} \text{ mod } p$;
- 23: Get the proof key pk_z , the threshold ϵ and generate the proof $\pi \leftarrow GenProof(pk_z, d(\mathbf{f}^{(0)}, \mathbf{f}^{(1)}), r_d, c_d, \epsilon)$;
- 24: Send $\{id, nonce, \mathbf{f}^{(1)}, \mathbf{f}^{(0,0)}, \mathbf{f}^{(1,1)}, \mathbf{f}^{(0,1)}, \alpha_1, \alpha_2, \beta^{(1)}, \beta^{(2)}, \beta^{(3)}, z^{(1)}, \dots, z^{(7)}, \pi\}$ to verifier.

c'_d is indeed less than a specific threshold ϵ . Otherwise, it indicates that the two biometric vectors do not match, resulting in a biometric authentication failure. The open blockchain, as the verifier, verifies the biometric authentication result through the steps described above without using the plaintext of the user's biometric data. All authentication results together with the related authentication proof sent by the users are recorded on the blockchain so that anytime anyone who cares about the results can re-verify them.

The pseudocode of the authentication proof verification is summarized as Algorithm 2.

Algorithm 2 Verification of Authentication Proof

Input: authentication proof $\{id, nonce, \mathbf{f}^{(1)}, \mathbf{f}^{(0,0)}, \mathbf{f}^{(1,1)}, \mathbf{f}^{(0,1)}, \alpha_1, \alpha_2, \beta^{(1)}, \beta^{(2)}, \beta^{(3)}, z^{(1)}, \dots, z^{(7)}, \pi\}$.

Output: Authentication result $pass/fail$.

- 1: **if** $nonce$ is not greater than the number user's used **then**
- 2: Return $fail$.
- 3: **else**
- 4: Get $c^{(0)}$ from the blockchain based on id .
- 5: **end if**
- 6: $e \leftarrow SHA256(c^{(0)} || \mathbf{c}^{(1)} || \mathbf{c}^{(0,0)} || \mathbf{c}^{(1,1)} || \mathbf{c}^{(0,1)} || id || nonce)$;
- 7: **for** i in range(Length of the biometric code N) **do**
- 8: Check if $z_i^{(1)}, z_i^{(2)}, \alpha_1$ and $c_i^{(0)}$ satisfy the equation $g^{z_i^{(1)}} h^{z_i^{(2)}} \text{ mod } p = \alpha_1 (c_i^{(0)})^e$;
- 9: Check if $z_i^{(1)}, z_i^{(5)}, \beta_i^{(1)}$ and $c_i^{(0)}, c_i^{(0,0)}$ satisfy the equation $(c_i^{(0)})^{z_i^{(1)}} h^{z_i^{(5)}} \text{ mod } p = \beta_i^{(1)} (c_i^{(0,0)})^e$;
- 10: Check if $z_i^{(3)}, z_i^{(4)}, \alpha_2$ and $c_i^{(1)}$ satisfy the equation $g^{z_i^{(3)}} h^{z_i^{(4)}} \text{ mod } p = \alpha_2 (c_i^{(1)})^e$;
- 11: Check if $z_i^{(3)}, z_i^{(6)}, \beta_i^{(2)}$ and $c_i^{(1)}, c_i^{(1,1)}$ satisfy the equation $(c_i^{(1)})^{z_i^{(3)}} h^{z_i^{(6)}} \text{ mod } p = \beta_i^{(2)} (c_i^{(1,1)})^e$;
- 12: Check if $z_i^{(3)}, z_i^{(7)}, \beta_i^{(3)}$ and $c_i^{(0)}, c_i^{(0,1)}$ satisfy the equation $(c_i^{(0)})^{z_i^{(3)}} h^{z_i^{(7)}} \text{ mod } p = \beta_i^{(3)} (c_i^{(0,1)})^e$;
- 13: **end for**
- 14: **if** the checks didn't all go through **then**
- 15: Return $fail$.
- 16: **else**
- 17: Compute $c_d = \sum_{i=1}^n c_i^{(0,0)} \oplus c_i^{(1,1)} \odot 2c_i^{(0,1)}$.
- 18: **end if**
- 19: Get the verify key vk_z , the threshold ϵ and verify the proof π by $VerProof(vk_z, c_d, \epsilon, \pi) \rightarrow b$.
- 20: **if** $b == 1$ **then**
- 21: Return $pass$.
- 22: **else**
- 23: Return $fail$.
- 24: **end if**

IV. SYSTEM PERFORMANCE

In this section, we first conduct a security analysis on the BioZero protocol and then build an experimental prototype to evaluate its performance.

A. Security Analysis

The BioZero protocol has been meticulously designed to achieve a safe and efficient biometric authentication on the blockchain while mitigating concerns about sensitive biometric data leakage. The protocol aims to satisfy the following security properties:

- **Unforgeability:** The protocol prevents malicious attackers from forging the authentication proof of an honest user or impersonating it through other means.
- **Privacy:** Within the protocol, attackers are limited to accessing only the information explicitly provided by the user; and they are unable to gain insights into user attributes through observations, thereby guaranteeing the confidentiality of sensitive user information.

- **Non-Malleability:** The protocol prevents any malicious attacker from generating new authentication proofs from old authentication proofs. The integrity of the identity proof is maintained, and attackers cannot manipulate or modify the data to create fraudulent proofs.

Malicious attackers may attack the BioZero protocol from different dimensions. To provide a further understanding of BioZero's security, we have devised a hypothetical malicious attacker based on the following security preconditions. These preconditions establish the framework for assessing the protocol's resilience against potential attacks:

- **Precondition 1:** The malicious attacker is a computational adversary with polynomial time constraints.
- **Precondition 2:** Users will properly keep the original biometric data vectors used during the user registration and will not disclose it.
- **Precondition 3:** Verifiers are honest and will not collude with malicious attackers to accept false verification requests as validate ones.

The setups of preconditions 1 and 2 are commonly acceptable. Since BioZero exploits smart contracts on open blockchain to conduct the verification of authentication proofs, we assume that the security of smart contracts is supported by the underlying blockchain and thus the establishment of precondition 3 is reasonable. Meanwhile, the security of the zero-knowledge proof algorithm Groth16 and that of Pedersen commitment have been established in their papers [6], [7]. Therefore, we will assume the Groth16 and Pedersen commitment are secure. By considering these preconditions and already established securities of the cryptographic building blocks, we can holistically evaluate the security of the BioZero protocol and assess its ability to withstand potential attacks. We identify the following important attack vectors and analyse how BioZero can avoid them to maintain its security.

Replay Attack: The data of all the historical biometric authentication proofs, which have been used by a user, is recorded on the blockchain. Malicious attackers may take advantage of the openness and immutability features of the blockchain to replicate the data of a valid historical authentication proof (i.e., the biometric commitments $\mathbf{c}^{(1)}, \mathbf{c}^{(0,0)}, \mathbf{c}^{(1,1)}$ and $\mathbf{c}^{(0,1)}$, auxiliary proof factors $\{\alpha_1, \alpha_2, \beta^{(1)}, \beta^{(2)}, \beta^{(3)}, \mathbf{z}^{(1)}, \dots, \mathbf{z}^{(7)}\}$, and zero-knowledge proofs π from the blockchain, and construct a new biometric authentication proof using these old authentication data to pretend to be a real user. This type of attack is referred to as a replay attack.

Analysis: BioZero prevents such replay attacks by adding the serial number, *nonce*. The verifier will first check the validity of *nonce* when receiving a new authentication proof, detecting whether the *nonce* is larger than the serial number used in the user's previous authentication proof. If this check on *nonce* fails, the verifier will refuse to execute the following verification steps on the authentication proof avoid replay attacks. At this point, even if the malicious attacker changes the new *nonce*, it is not possible to pass the authentication because according to Equation (25), the new *nonce* will be used to compute a new challenge factor, which makes the

challenge factor in the historical authentication proof is no longer consistent with the changed *nonce* and thus all other relevant data in the historical authentication proof cannot be used again.

Timing Attack: Timing attacks are a common means of side-channel attacks that infer sensitive information by measuring and analyzing the time it takes for a system or algorithm to perform a particular operation [16]. For example, for the computation process of Pedersen commitment given in Equation (1), it can be seen that the generation time of Pedersen commitment is linearly related to the size of the commitment value. Thus, a malicious attacker can infer the plaintext of a user's biometric data by observing the small differences in the time it takes for the system to generate Pedersen commitment when processing different inputs.

Analysis: BioZero prevents timing attacks by means of a constant time algorithm. In BioZero, the Pedersen commitment module can be implemented using the Exponentiation by Squaring algorithm [17], which ensures that the execution time of the Pedersen commitment generation always remains constant under different inputs, and a malicious attacker cannot obtain any additional information by observing the generation time of Pedersen commitments. It is also demonstrated in the Groth16 module that the generation time also depends only on the size of the circuit and is independent of the specific input data, which ensures that a malicious attacker cannot infer the exact input data by only observing the execution time of the Groth16 algorithm.

Brute Force Attack: Malicious attackers may try to run the Pedersen commitment algorithm with all possible biometric data plaintexts as inputs until they find a correct biometric data plaintext that matches the Pedersen commitment recorded on the blockchain. This attack mainly damages the privacy of users' biometric data.

Analysis: The security of the Pedersen commitment is rooted in the computational difficulty of solving the discrete logarithmic problem. As a result, computing the Pedersen commitments of all possible biometric data plaintext within a finite amount of time is infeasible for any malicious attacking adversary, rendering this brute force attacks impractical. Furthermore, the probability that the adversary correctly guesses the committed value, (f_i, r_i) , corresponding to one commitment, $c_{g,h}(f_i, r_i)$, is given by [18]:

$$Pr((f_i, r_i) : c_{g,h}(f_i, r_i)) = 1/|\mathbb{G}|^2 \rightarrow 0 \quad (48)$$

where $|\mathbb{G}|$ is the size of the cyclic group \mathbb{G} . Therefore, for a commitment vector that consists of N commitments of N biometric data, the probability that a malicious attacker succeeds in finding the corresponding N correct biometric data is

$$Pr((\mathbf{f}, \mathbf{r}) : c_{g,h}(\mathbf{f}, \mathbf{r})) = N/|\mathbb{G}|^2 \rightarrow 0 \quad (49)$$

Therefore, the probability of a malicious attacker succeeding in deciphering users' biometric data from their commitments recorded on the blockchain approaches infinitesimally. This allows that BioZero can effectively protect the users' biometric privacy.

Oracle Attack: Malicious Attacker may construct a special set of commitments $\mathbf{c}^{(0,0)}, \mathbf{c}^{(1,1)}$ and $\mathbf{c}^{(0,1)}$ such that the corresponding committed values satisfy $\sum_{i=1}^N (f_i^{(0,0)} + f_i^{(1,1)} - 2f_i^{(0,1)}) < \varepsilon$. Furthermore, if the attacker can predict the challenge factor e to be used in the verification process in advance, then the malicious attacker will have enough time to construct a specific set of auxiliary proof factors $\{\alpha_1, \alpha_2, \beta^{(1)}, \beta^{(2)}, \beta^{(3)}, \mathbf{z}^{(1)}, \dots, \mathbf{z}^{(7)}\}$, which will ensure the validity of Equations (42)-(46). This causes the verifier to incorrectly believe that $\mathbf{c}^{(0,0)}$ is the commitment vector of the square of the user's registered biometric data, $\mathbf{c}^{(1,1)}$ is the commitment vector of the square of the user's newly extracted biometric data, and $\mathbf{c}^{(0,1)}$ is the commitment vector of the product of the user's two biometric data, and this enables the subsequent authentication process to proceed smoothly without any disruptions or issues.

Analysis: BioZero uses the Fiat-Shamir heuristic to avoid this type of attack. In particular, users must use *SHA256* as a random number oracle to generate a challenge factor e during the generation process of authentication proofs. Since $\mathbf{c}^{(0,0)}, \mathbf{c}^{(1,1)}$ and $\mathbf{c}^{(0,1)}$ are the inputs of the random number oracle, this means that before the attacker inputs the data into the oracle, they cannot obtain the corresponding challenge factor in advance. Furthermore, due to the irreversibility of the hash function, attackers cannot reverse-engineer the input of the function based on specific challenge factors. This ensures that only users with genuine original data can successfully and accurately generate the authentication proof.

Forgery Attack: A malicious attacker may try to piece together a special set of $\{\mathbf{c}^{(1)}, \mathbf{c}^{(0,0)}, \mathbf{c}^{(1,1)}, \mathbf{c}^{(0,1)}, \alpha_1, \alpha_2, \beta^{(1)}, \beta^{(2)}, \beta^{(3)}, \mathbf{z}^{(1)}, \dots, \mathbf{z}^{(7)}\}$ from historical verification information so that the previous verification process can succeed, and then calculate $c'_d = \sum_{i=1}^N c_i^{(0,0)} \oplus c_i^{(1,1)} \odot 2c_i^{(0,1)}$. The next step is to generate a zero-knowledge proof π to convince the verifier that the Euclidean distance of the biometric encoding is less than a certain threshold. Since the malicious attacker does not know the plaintext of c_d , the malicious attacker needs to forge a false proof to make the verifier pass the verification by mistake. This type of attack is referred to as a replay attack.

Analysis: BioZero uses the security properties of zero-knowledge proofs to resist this attack. Since the security parameters utilized to initialize the arithmetic circuit of ZKP are rendered inaccessible once initialized, the attacker can only construct a fake proof employing the publicly available parameters. The probability of the fake proof being verified successfully can be given by [19]:

$$\begin{aligned} \Pr(\text{VerProof}(vk_z, c_d, \pi) \rightarrow 1 : \text{keyGen}(C) \rightarrow (pk_z, vk_z) \\ E(pk_z, vk_z) \rightarrow (c_d, \pi)) \leq \text{negl}(\lambda) \end{aligned} \quad (50)$$

where E represents a witness extractor that operates probabilistically within polynomial time and is applicable to any adversary within the same computational bounds. The term $\text{negl}(\lambda)$ is commonly used in cryptography to denote a probability that is considered negligible. The probability in (50) is inversely related to the computational domain of elliptic

curves used in zero-knowledge proofs (denoted as \mathbb{F}), and it is directly proportional to the number of terms (k) within the Quadratic Arithmetic Program (QAP) polynomials of the zero-knowledge circuits. As the size of \mathbb{F} is significantly larger than k , the probability $\text{negl}(\lambda)$ is deemed to be practically negligible. In summary, the used cryptographic primitives (Groth16 zk-SNARK, Pedersen commitment) and the protocol design of BioZero, make it computationally infeasible for an attacker to perform biometric forgery attack within polynomial time.

B. Experimental Evaluations

We constructed a test platform using the Ethereum private blockchain. On this test platform, we implemented our BioZero protocol. We also implemented the decentralized biometric authentication protocol that only employs the Groth16 zk-SNARK algorithm to generate proof of biometric similarity matching off-chain, and then verify it on-chain. For this purely Groth16-based biometric authentication protocol, the public inputs of Groth16 are the encrypted biometric vector used to register the user $\mathbf{c}^{(0)}$, the encrypted biometric vectors for identity authentication $\mathbf{c}^{(1)}$, the decision threshold ϵ and the proving key pk_z ; while the private inputs (witness) are the biometric data used to register the user $(\mathbf{f}^{(0)}, \mathbf{r}^{(0)})$ and the newly extracted biometric data when the user is authenticated $(\mathbf{f}^{(1)}, \mathbf{r}^{(1)})$, where $\mathbf{r}^{(0)}, \mathbf{r}^{(1)}$ are the vectors of blinding factors used in the computations of Perdersen Commitments. The prover of Groth16 zk-SNARK is executed to produce the proof that $\mathbf{f}^{(0)}$ and $\mathbf{f}^{(1)}$, whose commitment is $\mathbf{c}^{(0)}$ and $\mathbf{c}^{(1)}$, is matched. The proof is sent to the verifying contract on the blockchain for verification. We call this decentralized biometric authentication protocol the Vanilla ZKBio Protocol. We evaluate the performances of BioZero and Vanilla ZKBio. The performance of Vanilla ZKBio is treated as the benchmark of that of BioZero. We evaluate their performances using the following four five metrics:

- **Proof Generation Time:** the time consumed to generate an authentication proof;
- **Proof Verification Time:** the time consumed to verify an authentication proof;
- **Total Authentication Time:** the time consumed to finish the whole authentication process, which is the sum of proof generation time and proof verification time;
- **Proof Size:** the number of bytes used to construct an authentication proof;
- **Verification Costs:** The amount of gas required to execute the verifying smart contract on the blockchain to verify a Groth16 proof.
- **Circuit Size:** The number of R1CS constraints contained in the arithmetic circuits used by Groth16.

We used the cloud server provided by the matpool platform as the experimental environment. The server is equipped with Ubuntu 20.04 system, ten Intel Xeon Gold 5320@2.2G processors, an NVIDIA A30 24G graphics card, and 86G Random Access Memory.

We evaluate the proof generation time, the verification time and the total authentication time of BioZero and Vanilla

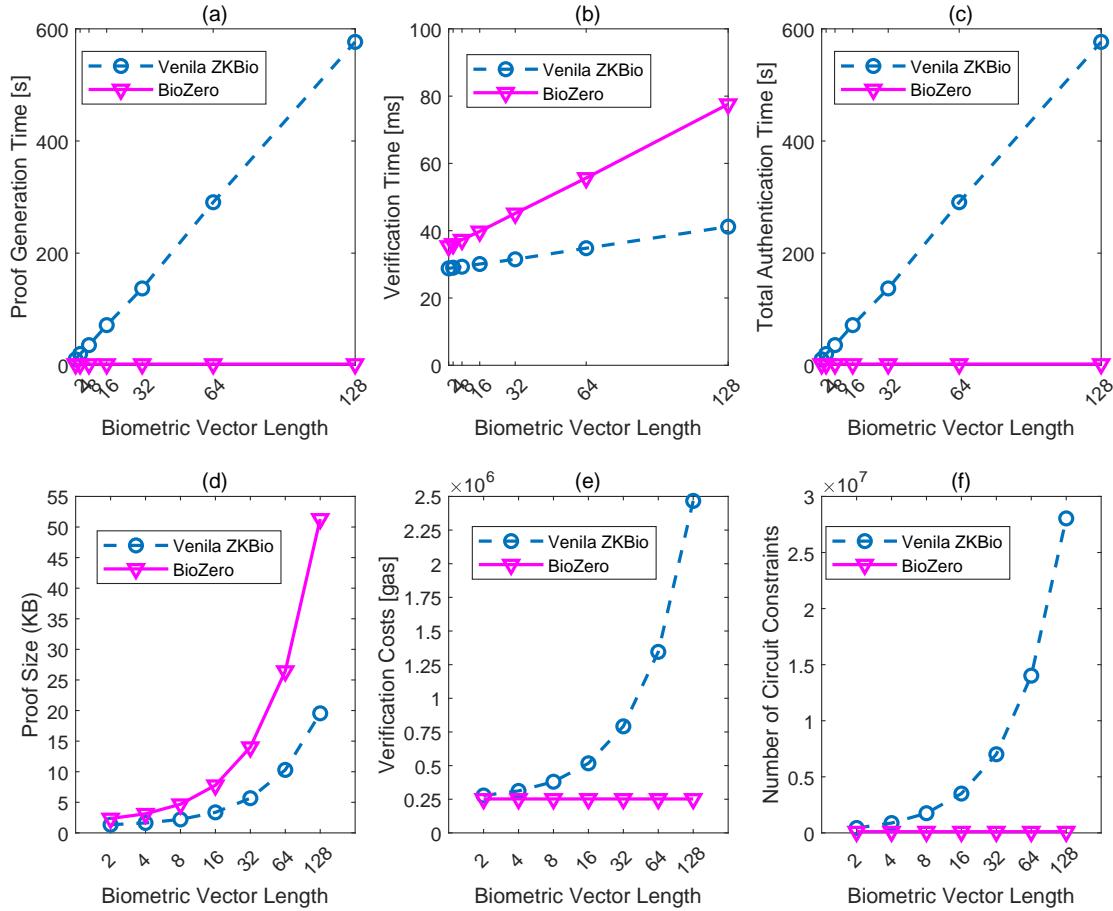


Fig. 3. Experimental evaluation results of BioZero and Vanilla ZKBio: (a) the proof generation time; (b) the verification time; (c) the total authentication time; (d) the proof size; (e) the verification cost; (f) the number of circuit constraints. All are given with respect to different biometric vector lengths.

ZKBio. Fig. 3 (a) shows the time consumed to generate an authentication proof by BioZero and Vanilla ZKBio with respect to different biometric vector lengths. It can be observed that the proof generation time of Vanilla ZKBio increases linearly with the biometric vector length; and the proof generation time of BioZero tends to be a constant. The reason is explained as follows. The time consumed by the Groth16 zk-SNARK algorithm of Vanilla ZKBio to generate an authentication proof is long due to the large size of the circuit used to implement the computation of biometric matching; however, for our BioZero protocol, the time consumed by the Pedersen commitment homomorphic encryption is short; and the circuit of Groth16 zk-SNARK is used to prove the reconstructed Pedersen commitments are valid because the reconstructed Pedersen commitment of the biometric distance is less than a threshold, which requiring much less inputs and constraints on the circuit.

Fig. 3 (b) shows the time consumed to verify an authentication proof by BioZero and Vanilla ZKBio with respect to different biometric vector lengths. We can see that the verification time of the authentication proof increases with the length of biometric vectors for both of BioZero and Vanilla ZKBio.

At the same time, the proof verification time of BioZero is longer than that of Vanilla ZKBio. This is because in addition to verifying the Groth16's ZK-proof, BioZero also requires additional computations to verify the Pedersen commitment homomorphic encryption. However, it is worth noting that BioZero still maintains a millisecond-level verification time, which makes its total authentication time short (as can be seen in the following).

Fig. 3 (c) shows the total time consumed to finish the whole authentication process by BioZero and Vanilla ZKBio with respect to different biometric vector lengths. We can see that the total authentication time of Vanilla ZKBio increases with the lengths of biometric vectors. Compared with Vanilla ZKBio, the total authentication time of BioZero tends to be a constant. This is because during the whole authentication process, the proof generation time is much longer than the proof verification time, and thus the total time is dominated by the generation time.

We then evaluate authentication proof size. Fig. 3 (d) shows the size of authentication proofs constructed by the prover with respect to different biometric vector lengths. As can be seen from Fig. 3 (d), the size of the proof increases with

the length of the biometric vectors for both of BioZero and Vanilla ZKBio. Moreover, the size of authentication proof generated by BioZero is larger than that of Vanilla ZKBio. This is because BioZero needs to generate more auxiliary proof factors during the Pedersen commitment homomorphic encryption process, and these auxiliary proof factors also constitute the authentication proof, besides the ZK-proof. Note that the increased proof size is within an acceptable range.

We evaluate the verification cost of the Groth16 verifying smart contract. Fig. 3 (e) shows the amount of gas required to complete the verification on one Groth16 ZK-proof in the verifying contracts of BioZero and Vanilla ZKBio with respect to different biometric vector lengths. We can see that the verification gas amount of Vanilla ZKBio increases with the biometric vector length. Compared with Vanilla ZKBio, the verification gas amount of BioZero is a constant. This reason is given as follows. The BioZero verifying contract only needs to verify that the recontraction of the homomorphically computed biometric distance is right and it is less than the threshold with the c_d, ϵ, π as the public inputs. The size of the public inputs to the BioZero verifying contract keeps constant and it is irrelevant to the lengths of biometric vectors. The Vanilla ZKBio verifying contract needs to verify the distance between two biometric vectors with $\mathbf{c}^{(0)}, \mathbf{c}^{(1)}, \epsilon, \pi$ as the public inputs. Thus, the size of the public inputs to the BioZero verifying contract increases with the length of biometric vectors, increasing the cost of the verifying contract.

Finally, we measure the number of constraints for the ZKP circuits in BioZero and Vanilla ZKBio. Fig. 3 (f) illustrates the number of constraints of the ZKP circuits in BioZero and Vanilla ZKBio when processing biometric vectors of different lengths. It is evident that the number of circuit constraints for Vanilla ZKBio increases with the length of the biometric vector, whereas the number of circuit constraints for BioZero remains constant. This difference arises because, in the biometric authentication process, the ZKP circuit in BioZero is designed to prove that the commitment c_d of the distance between biometric vectors is generated by $d(\mathbf{f}^{(0)}, \mathbf{f}^{(1)})$ and the commitment c_d is smaller than a specific threshold (i.e., scalars such as c_d are taken as the input to the circuit). In contrast, the ZKP circuit in Vanilla ZKBio is intended to prove that the commitment of the Euclidean distance between $\mathbf{f}^{(0)}$ and $\mathbf{f}^{(1)}$ is less than a specific threshold (i.e., vectors such as $\mathbf{f}^{(1)}$ are used as circuit inputs). Consequently, as the length of the biometric vectors increases, Vanilla ZKBio requires more gates for logic operations to process the vectors, thus increasing the number of circuit constraints.

Through the above experimental evaluations, we can see that the proof generation time of the BioZero protocol is short, and the verification time and proof size are controlled within an acceptable range. Importantly, the whole authentication time of BioZero is very short (around 2 seconds) and is reduced by 200X compared to a native design using only zk-SNARK. The short authentication time of BioZero is also reflected from its small verification cost, and less ZKP circuit constraints. The results provide evidence that BioZero can provide very efficient decentralized biometric authentication services.

V. RELATED WORK

To achieve decentralized biometric authentication on blockchain, many researches have made significant efforts. Nandakumar *et al.* [20] proposed a decentralized authentication scheme based on biometric tokens, which involves storing a token containing a hash of the user's biometric information on the blockchain. During identity authentication, the user only needs to provide the biometric information they registered with to the verifier. The verifier then hashes the user's biometric information and checks for consistency with the hash value stored in the token, further verifying the user's identity through a biometric algorithm. However, this scheme has security vulnerabilities. During the verification process, the verifier temporarily possesses the user's biometric encoding, which a malicious verifier could steal, leading to the leakage of the user's privacy.

Gao *et al.* propose an identity authentication scheme called BlockID [21], which leverages a trusted execution environment. In this scheme, users generate their own public-private key pairs within TrustZone, a trusted execution environment, and store the mapping relationship between the user's identity identifier and the public key on the blockchain. The biometric information and the private key are stored in the encrypted storage of TrustZone. For authentication, the user's current biometric traits are extracted and similarity detection is performed within TrustZone to confirm the user's identity. Both the user registration and authentication processes occur off-chain, without the involvement of other nodes, necessitating further assessment of the scheme's security.

Hamer *et al.* proposed a private digital identity scheme called USI [22], based on fully homomorphic encryption. In this scheme, the user provides Fourier-transformed fingerprint feature information to a trusted registrar. The registrar then adds a homomorphic signature of the user's fingerprint feature information to the blockchain. For authentication, the user's new fingerprint feature information is verified against the homomorphic signature stored on the blockchain. However, the verification efficiency of this scheme is low, restricting its use to the enrolment and revocation processes of the user's identity identifier rather than real-time authentication.

Worldcoin [23] proposes a biometric authentication scheme based on distance-sensitive hash. It employs a specialized biometric capture device called Ori to capture and map the user's iris information into a string of fixed-length hash values, verifying the user's identity based on the Hamming distance. However, this solution is inherently centralized, allowing Worldcoin to collect users' iris information and posing a risk of privacy leakage.

Lee *et al.* designed a distributed biometric authentication system named BDAS [24], which operates on blockchain technology. This scheme utilizes multi-party secure computation to partition a user's biometric information into multiple segments and stores them separately, aggregating the data only when authentication is required. The security of BDAS hinges on the integrity and trustworthiness of the participating parties; if collusion occurs among different participants, it could compromise the confidentiality of the user's biometric

information.

Sarier *et al.* [25] and Zhou *et al.* [26] employ fuzzy extraction techniques to transform user biometric information into a reproduction code and an extraction code. The reproduction code allows reconstruction of the biometric information, openly stored on the blockchain, while the extraction code, held privately by the user, facilitates reconstruction when used in conjunction with the reproduction code. During authentication, the user provides the extraction code and a new reproduction code, enabling the authenticator to verify against the reproduction code stored on the blockchain and the user-provided data. However, the algorithm's complexity and inefficiency pose challenges in computation.

In addition, there are a number of decentralized identity system designs. Yin *et al.* proposed SmartDID [27], which introduced a dual-credential model based on plaintext and Pedersen commitment to protect user identity information, and constructed a logic tree verification system based on a zero-knowledge proof system to verify user identity attributes on low-computing edge devices. However, SmartDID is essentially still an identity system based on traditional asymmetric keys, and has not overcome the limitations of key-based identity authentication methods. Maram *et al.* proposed CanDID [28], which uses zero-knowledge oracles and multi-party secure computing to transplant and verify identities from traditional social media accounts, and uses zero-knowledge proof algorithms to verify user identity attributes to provide a user-friendly identity management system. However, CanDID still faces the problem of scalability. The multi-party secure computing it uses is resource-intensive, which may affect the performance of large-scale deployments. In addition, CanDID is heavily dependent on the availability and accuracy of existing centralized identity services.

VI. CONCLUSION

This paper presents BioZero, a decentralized biometric authentication protocol on blockchain. By utilizing Pedersen commitment homomorphic encryption and the zk-SNARK algorithm, BioZero overcomes decentralization, privacy, and verification challenges in biometric authentication. Instead of traditional computations, BioZero employs homomorphic processes and zero-knowledge proofs to ensure data confidentiality and computational efficiency. The transformation to a non-interactive protocol using the Fiat-Shamir heuristic makes it suitable for blockchain applications. Through a detailed security analysis and experiments, BioZero proves its effectiveness, efficiency, and resilience against attacks, achieving a remarkable 200X reduction in authentication time. This development paves the way for decentralized authentication in finance, healthcare, e-commerce, and identity management. By uniting biometrics with blockchain, BioZero provides a secure, private solution for identity verification, enabling seamless interactions between users and decentralized systems.

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