Password-authenticated Decentralized Identities

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Abstract—Password-authenticated identities, where users establish username-password pairs with individual servers and use them later on for authentication, is the most widespread user authentication method over the Internet. Although they are simple, user-friendly, and broadly adopted, they offer insecure authentication and position server operators as trusted parties, giving them full control over users’ identities. To mitigate these limitations, many identity systems have embraced public-key cryptography and the concept of decentralization. All these systems; however, require users to create and manage public-private keypairs. Unfortunately, users usually do not have the required knowledge and resources to properly handle cryptographic secrets, which arguably contributed to the failures of many end-user public-key infrastructures (PKIs). In fact, as of today, no end-user PKI, able to authenticate users to web servers, has a significant adoption rate.

In this paper, we propose Password-authenticated Decentralized Identities (PDIDs), an identity and authentication framework where users can register their self-sovereign username-password pairs and use them as universal credentials. Our system provides a global namespace, human-meaningful usernames, and resilience against username collision attacks. A user’s identity can be used to authenticate the user to any server without revealing that server anything about the password, such that no offline dictionary attacks are possible against the password. We analyze PDIDs and implement it using existing infrastructures and tools. We report on our implementation and evaluation.

I. INTRODUCTION

Passwords have a particularly long history as a means of authenticating users to computer systems [1]. Despite their inherent limitations and drawbacks, they are surprisingly robust to any techniques that try to disrupt them [2]. User identities are usually expressed as user-selected usernames and are authenticated with passwords. Usernames and their corresponding password-related information are shared with a server upon registration. Then to authenticate, a user sends its username-password pair to the server which checks whether the pair matches the registered record. Such identities are local (to the server), but single sign-on systems, such as OpenID [3], extend them allowing a registered identity to be reused ‘globally’ for authenticating to other servers without a need of creating a new identity. Although convenient for users, such identities have significant limitations. Most importantly, they are controlled by their providers (i.e., the servers that have registered them). Thus, a user who should be an owner of its identity has to trust that the server operator manages (and will manage) the identity appropriately. Moreover, systems like OpenID, allow identity providers to undermine users’ privacy by learning which websites and when users are connecting to. Finally, the currently dominating password-based authentication method requires users to send their passwords in plaintext, making them prone to various attacks.

To provide better security guarantees and enable new applications (like signatures), public-key infrastructures (PKIs) were introduced, where trusted authorities verify identities and assert bindings between them and their public keys in digital certificates [4]. Identities in these systems are human-meaningful and global (usually based upon DNS), but their security relies on a set of globally trusted authorities and the security of the namespace they express identities in (i.e., DNS). In past, we have witnessed multiple attacks on authorities that resulted in impersonation attacks on high-profile websites [5], where a trusted authority could easily ‘collide’ an identity by simply creating a new certificate. To eliminate globally trusted authorities, the idea of distributed PKIs was presented [6]. In so called, web-of-trust PKIs [7] users create peer-to-peer trust assertions and make trust decisions basing on them. An important disadvantage of distributed PKIs is that they either still rely on DNS or express identities in local namespaces, thus cannot be used universally. Self-certifying identifiers [8] propose names that are cryptographically-derived from public keys. Such a namespace is global and secure, but generated names are pseudorandom, thus it is difficult to memorize and use them by human beings. The limitations of these systems led to an observation, referred to as Zooko’s trilemma [9], and a related informal conjecture that no naming system can simultaneously provide human-meaningful, global, and secure names. Although naming systems built upon blockchain platforms [10], [11] seem to refute this conjecture, they require to associate names with public keys. Thus, similar to other PKIs, they rather target servers that, unlike end-users, are capable to manage their cryptographic keys.

In this work, we make the following contributions. We propose Password-authenticated Decentralized Identities (PDID), a system that removes the above limitations. Up to our best knowledge, it is the first identity and authentication framework which allows users to establish human-meaningful and global password-authenticated identities that are also resilient to collision attacks. We instantiate PDIDs with a combination of a blockchain platform offering confidential smart contracts and a modified password-authenticate key exchange protocol allowing users to use their passwords for authentication. We present PDIDs in the client-server setting, where a user authenticates to the server with its username-password pair, but the scheme can be extended to other models and applications. We discuss the security of our framework and present its implementation and evaluation which indicate the feasibility of our protocol (the most common operation requires around 20 ms plus network latency).
Notation and Cryptography Throughout the paper we use the following notation
- \( G \) denotes a finite cyclic group of order \( q \) with a generator \( g \in G \);
- \( r \overset{\$}{\leftarrow} S \) denotes that \( r \) is an element randomly selected from the set \( S \);
- \( f_k(m) \) is a keyed-pseudorandom function that for key \( k \) and message \( m \) outputs a pseudorandom string from \( \{0,1\}^n \);
- \( H(m) \) and \( H^*(m) \) are cryptographic hash functions that for message \( m \) output values from \( \{0,1\}^n \) and \( G \), respectively;
- \( \text{AE}_{pk}(m) \) is an encryption algorithm of an authenticated encryption scheme, that for key \( k \) and message \( m \) outputs the corresponding ciphertext \( c \);
- \( \text{AD}_{sk}(c) \) is the corresponding decryption algorithm, decrypting the message \( m \) from the ciphertext \( c \) given the key \( k \), or failing with incorrect input;
- \( \text{Gen}(\cdot) \) is a public-key generation algorithm, returning a private-public keypair \((sk, pk)\);
- \( \text{PE}_{pk}(m) \) is a public-key encryption algorithm, that produces ciphertext \( c \) for the given public key \( pk \) and message \( m \);
- \( \text{PDec}_{sk}(c) \) is the corresponding public-key decryption algorithm, recovering the message \( m \) given the ciphertext \( c \) and the corresponding secret key \( sk \), or failing with incorrect input.

Password Authentication Password-based authentication on the Internet is dominated by the following method (or its slight modification):
- **Registration.** The user registers its identity by providing, via a secure channel, a username \( U \) and a password \( pwd \) to the server. The server selects a random salt \( s \overset{\$}{\leftarrow} \{0,1\}^n \) and stores the mapping \( U : (s,H(s,pwd)) \).
- **Authentication.** To authenticate the user sends its username-password pair \((U,pwd)\) to the server, which identifies the mapping, and checks if \( H(s,pwd') \overset{?}{=} H(s,pwd) \).

Despite its popularity and wide-spread adoption, this protocol has a major flaw since in every authentication the password is sent in plaintext. This limitation requires a secure channel between the parties for each authentication, but even then, it makes passwords vulnerable to multiple attack vectors (like server-side malware). To address this limitation, Bellovin and Merrit [12] proposed the first password-authenticated key exchange (PAKE) protocol, where two parties can securely establish a high-entropy secret key from the memorable password they share (with an already established secret key, the user can easily authenticate to the server). Since then, there have been proposed multiple PAKE protocols with various efficiency and security properties; however, most of them require either to send salt in plaintext (facilitating offline precomputation attacks) or to store effective passwords by servers (allowing adversaries to instantly compromise all passwords after the server’s compromise). Only recently, Jarecki et al. proposed OPAQUE [13], a PAKE protocol that removes these issues and introduces low transmission and computation overheads. OPAQUE bases on the oblivious pseudorandom function (OPRF) defined as \( F_k(m) = H(m, (H^*(m))^k) \).
platform that bases on the TEE assumption; however, with the continuing progress of platforms basing upon cryptographic assumptions, we do not see major obstacles in implementing PDIDs with such a platform. We assume that the platform exposes public keys (e.g., as described previously) which allow users to interact with platform contracts confidentially, by sending encrypted transactions. We do not assume a specific consensus protocol, but we require that the platform allows to generate inclusion proofs for appended transactions.

III. THE PDID FRAMEWORK

A. Problem Formulation

Our goal is to propose a user identity and authentication framework. Although we present our system in the client-server model where only users are authenticated, it can be adjusted to other models and authentication scenarios (e.g., mutual authentication). We introduce the following parties. 

User is a human being that wishes to use a service that requires authentication. The user inputs the service name $S$, as well as its username and password credentials $(U, pwd)$, used for his authentication. The user operates its client software to execute the actual authentication protocol. Server represents the service the user wants to use and which requires authentication. The server participates in the authentication protocol and aims to verify the user’s credentials (i.e., whether the user is an owner of the identity he claims). We assume that the protocol parties have access to a blockchain platform with confidential smart contracts (see [S.11]). For our framework, we seek the following properties.

- **Human-meaningful Names**: identifiers are memorable by human beings, such that users do not need special infrastructures or devices to remember them. Ideally, they are user-selected usernames.

- **Global Namespace**: identifiers resolve to the same identity no matter when and where they are being resolved. It guarantees that identities can be used universally.

- **Collision-secure Names**: identities cannot be impersonated by forging identifiers (e.g., by hijacking or creating a new identity with the same identifier). In practice, this property requires that there is no trusted authority(ies) privileged to manage identities. For instance, in authority-based PKIs, an authority can simply impersonate an identity by creating a malicious certificate claiming the same identifier, while in OpenID the identity provider can freely modify or use stored user records.

- **Memorable Secrets**: users can use memorable secrets (i.e., passwords) for authenticating their identities. This property is desired due to the popularity and advantages of passwords in user authentication. It also enables to design an identity system which is seamless to end-users.

- **Secure Authentication**: the user authentication process does not reveal, even to the verifying server, the user’s password or any information allowing to run offline dictionary attacks against the password.

The first three properties constitute Zooko’s trilemma. Although some PKI systems refute the trilemma, they operate on public-private keypairs. This may be acceptable for servers able to manage their keys and certificates, but it may be too demanding for users who prefer to authenticate using username-password pairs. Therefore, we introduce the fourth requirement on memorable secrets which also allows to avoid user-side changes. In addition to secure authentication, we also require that the system is efficient (i.e., does not introduce prohibitive overheads), and keeps the users’ privacy on the same (or a similar) level as in today’s authentication.

We assume an adversary whose goal is to authenticate on behalf of the user or to learn the user’s password. We assume that the adversary cannot compromise users’ passwords, the used cryptographic primitives and protocols, and the deployed blockchain platform. The adversary can compromise a server to which the user authenticates, and in this case, the adversary aims to attack the user’s password. We require that the system not only protects from revealing users’ passwords but in particular, should not reveal to the adversary any information which would enable her to run offline attacks on passwords. We require that the smart contract execution and the consensus protocol are secure, although we assume that the adversary can compromise up to a tolerable number of blockchain nodes (e.g., up to 1/3 of all nodes in Byzantine consensus). We assume that the adversary operating such a compromised node may be interested in attacking the system properties (e.g., attempting to run offline attacks). Side channel attacks, like timing, power, or cache attacks, are out of the scope of our adversary model.

B. Intuitions and Design Rationale

To illustrate our design process better, in this section, we first consider a naive approach to the problem. In this protocol, we introduce a trusted and highly available entity called the **Global Password Manager** (GPM). The GPM is responsible for handling identity registrations, keeping all username and password pairs, and for assisting servers with user authentication requests. To participate in the protocol, the user selects its username and password and registers this pair with the GPM, which ensures that the username is unique and saves the credentials in its database. After the identity is established, the user can use it for authentication, using the two-step protocol: a) To authenticate, the user sends its credentials to a targeted server. b) The server, to verify whether the credentials are valid, contacts the GPM which checks and notifies the server whether the username-password pair is recorded in its database and notifies. Depending on the outcome, the server either successfully authenticates the user or terminates the protocol.

With our assumption about the GPM, the protocol satisfies some of our challenging requirements. With a single trusted GPM who manages its local credentials database, the protocol guarantees that identities are global and unique, and kept private. Moreover, the credentials are universal, since a user registering once with the GPM, can use its username and password to authenticate with any server supporting the protocol. Unfortunately, such a simple approach has two following fundamental issues.

Firstly, realizing such a trustworthy centralized GPM would be difficult in practice. Centralized systems are single points
of failure (in terms of security, privacy, and availability), introduce higher censorship risks, and can be manipulated easier. These limitations make a centralized GPM an unacceptable design, especially in the context of universal and global identities. GPM could be implemented using a highly-available infrastructure, like cloud computing, but then the system would be prone to censorship by the infrastructure’s operator. Therefore, one of our design decision is to implement the GPM’s functionality as a confidential smart contract (see §II) executed over a decentralized blockchain platform. In such a setting, the GPM is replaced by a smart contract, keeping and managing credentials according to the rules specified by the code. The system would also benefit from the blockchain properties, providing verifiability and distributed control (mitigating censorship), while keeping the state and the execution of the GPM smart contract confidential.

Another major drawback of the naive protocol is that the server learns the user’s credentials. This limitation is quite standard in centralized identity systems (where a user and server share the user’s effective password). However, with universal decentralized identities it is unacceptable since otherwise, only one malicious server could compromise universal credentials which could be used for authentication to any other servers. Therefore, our goal is to realize the authentication process, such that the user can authenticate to any server, but without revealing to the server any information allowing to learn the password. To realize it, we extend the OPAQUE protocol to the three-party setting, where the protocol is run between the user, the server, and the GPM.

C. Details

In Fig. 1, we show a high-level overview of our framework instantiated with a TEE-based blockchain platform offering confidential smart contracts. The GPM is implemented as a smart contract with the encrypted state which can be accessed and modified only by trusted enclaves. A GPM instance is created before the protocol’s deployment, and on its creation, it is assigned with a unique blockchain’s public-private keypair (see §II), denoted as $\langle pk_b, sk_b \rangle$. GPM can be created by anyone, as long as its address and code (to potentially audit it) are publicly known and agreed upon. When created, GPM does not have to be maintained. Interactions with the GPM are conducted via transactions that are sent to (untrusted) blockchain nodes running (trusted) enclaves that execute the GPM’s code. The confidentiality of these transactions is protected by public-key encryption using the public key of the GPM instance (i.e., $pk_b$), and users and servers are preloaded with this key. The GPM consists of two main methods, for PDID registration and authentication, and the users[] dictionary which maps usernames to their password metadata (the dictionary is empty upon the contract creation).

In the following, we describe the registration and authentication procedures. For a simple description, in our protocols and pseudocodes, we omit some basic sanity checks like parsing, checking whether received elements belong to the group $G$, or decryption failures. We emphasize; however, that if an error occurs at one of those, the party should terminate the protocol in the failure mode.

1) Registration: The registration process is depicted in Fig. 2. To register its identity (i.e., PDID), the user first prepares the password metadata which is computed using his password $pwd$. In OPAQUE, the metadata is computed as shown in Fig. 2 using OPRF (see Eq. 1), modular exponents of secret values, and authenticated encryption. The password metadata $m$ is:

$$m = \{k_s, p_s, P_{u_c}, c\}. \quad (3)$$

Originally, in OPAQUE, this phase is run by an entity storing the password metadata (the GPM in our case). In the PDID framework, it is generated on the user’s side since a) the process requires a good source of entropy which smart contracts, being fully deterministic, cannot themself provide, b) similarly, TEEs able to provide randomness, like Intel SGX, have been demonstrated to do it unreliably [18], and c) in this setting, only the user knows the password $pwd$, thus, even in the case of a catastrophic attack (like compromised $sk_b$), the adversary learns the only one-way transformation of the password and not $pwd$ itself, d) the complexity of the GPM’s code is minimized.

After the metadata $m$ is created, it is accompanied with the username $U$, encrypted under the blockchain public key $pk_b$ as the ciphertext $\bar{c}$, and sent to the blockchain platform as a transaction triggering the registration method of the GPM. After the transaction is appended to the ledger, a blockchain node, noticing the request, restores the GPM’s code and state, and calls its $\text{NewPDID()}$ method. As presented in Fig. 2, the code first ensures that the username $U$ is not registered yet and then assigns the password metadata to the username in the users[] dictionary. At this point, the user’s PDID is established and ready for being used in the authentication process. (We note that even though the GPM’s state is encrypted, storing
the password metadata instead of plain passwords, gives an additional level of security, since even with a catastrophic event, like compromised $sk_u$ or the GPM, the adversary still needs to run dictionary attacks again every single password.)

2) Authentication: After a PDID is registered, the user should be able to use its credentials. We require that a) the user is able to use its credentials ($U$, $pwd$) to authenticate to any server (supporting the scheme), b) the server is able to verify that the user knows the password corresponding to its claimed identity $U$, c) the server does not learn $pwd$ or any information enabling to recover it (e.g., via offline dictionary attacks).

The last two requirements may seem contradictory since the server needs to verify the identity without possessing its corresponding password metadata. In the PDID framework, servers indeed do not store password metadata, which instead is stored only as part of the GPM’s confidential state. Then, to satisfy these requirements, we extend the OPAQUE authentication protocol to the three-party setting, where the GPM’s trusted code assists the server in verifying the user’s credentials.

When abstracting the server and the GPM as a single entity, the protocol to the three-party setting, where the GPM’s trusted code assists the server in verifying the user’s credentials. In the PDID framework, servers indeed do not store password metadata, which instead is stored only as part of the GPM’s confidential state. Then, to satisfy these requirements, we extend the OPAQUE authentication protocol to the three-party setting, where the GPM’s trusted code assists the server in verifying the user’s credentials. When abstracting the server and the GPM as a single entity, they essentially execute the server’s side of the OPAQUE authentication; however, since the server alone does not have any password-related information it has to communicate with the GPM. The details of the PDID authentication process are presented in [Fig. 3] and described below.

1) The user, as in OPAQUE, computes his contributions $\alpha$ and $X_u$ to the authenticated key exchange protocol and sends the username $U$ together with $\alpha$ and $X_u$ to the server.

2) The server first generates its contribution $X_s = g^s$ to the key exchange. For similar reasons as in the registration, this step is conducted by the server and not by the GPM. Next, the server computes the session-unique values $e_u$ and $e_s$, which will be used in HMQV. Then the server generates a keypair $(pk_u, sk_u)$ that binds the server-GPM communication to the current session (without revealing the server’s identity). Then, the server encrypts (with $pk_u$) its transaction containing the user’s input ($U$, $\alpha$, and $X_u$), the server’s key exchange contributions ($X_s$, $e_u$, and $e_s$), as well as its name $S$ and the ephemeral public key $pk_s$. The encrypted transaction $\hat{c}$ is submitted to the blockchain platform.

3) The transaction, after being appended to the ledger, triggers the GPM’s AuthPDID() method, which is executed by a blockchain node within its secure enclave as follows.

(a) First, it calls the TxIncluded(\hat{c}) method to ensure that the transaction $\hat{c}$ is already appended in the blockchain (this check is blockchain- and consensus-specific – see [§ II]). The purpose of this check is to eliminate offline attacks conducted by a malicious blockchain node (see [Lemma 4] in [§ IV] for more details).

(b) Next, the code decrypts the ciphertext $\hat{c}$, identifies the user, and restores his password metadata.

(c) Then, the OPAQUE protocol is continued, computing $\beta$ from user-provided $\alpha$ and restored $k_s$. (The $\beta$ values will allow the user to restore the key $k$ which was used for encrypting the metadata’s ciphertext $\hat{c}$.)

(d) OPAQUE’s final phase is to derive a key that will be shared between the server and the user. To accomplish it, we combine OPAQUE with the method it uses by default, i.e., the HMQV protocol. Therefore, the GPM computes $(X_sP_u)^{\alpha + e_u}P_s$ and hashes it into a key $K$. (e) The AuthPDID() ends its execution by deriving (from $K$) the shared session key $SK$, which together with the values $\beta$ and $e$ is encrypted under $pk_s$ as the ciphertext $\hat{c}$ and sent back to the server.

4) The server decrypts $\hat{c}$, saves $SK$, and passes $\beta, e, c$ to the user, to enable him to obtain the same key $SK$.

5) After receiving these values, the user continues the protocol by computing $\beta^{1/r}$ (which equals $(H(pwd)^{k_s})$, which hashed with the user’s password $pwd$ generates the key $k$ under which the metadata’s ciphertext $c$ is encrypted (see [Fig. 2]). After decrypting $c$, the user finishes the protocol by computing $(X_sP_u)^{\alpha + e_u}P_s$ and $SK$.

The protocol finishes with the parties obtaining the same shared key $SK$, which, in addition to authentication, can be used for protecting their subsequent communication. To authenticate, the user can simply use $SK$ to (encrypt and) authenticate the exchanged messages together with the first application-layer data.

IV. Security Analysis

A. Global and Collision-secure Names

We require that the identity system provides global and collision secure names. In this section, we show that PDIDs provide those properties, assuming a secure blockchain platform.

Theorem 1. PDIDs provide a collision-secure global namespace.

sketch. Since we assumed that the blockchain platform deployed is secure, the GPM’s state, at any point in time, has one canonical view which is consistent with all previous views. This guarantees, that the namespace consisting of identifiers recorded in the GPM’s users[] dictionary represents a global view of all usernames. The blockchain-platform assumption also implies that the transactions are processed by nodes correctly, i.e., the GPM’s state can only be changed by secure enclaves processing transactions whose order is agreed on with the underlying consensus algorithm. Given that, it is easy to show that the namespace is collision-secure since if there are two conflicting transactions, trying to register the same name $U$, the latter (according to their execution order in the ledger) will inevitably fail, as the enclave code processing it will not continue the NewPDID() method (see [Fig. 2]), after executing the following assertion: assert users[\(U\)] == \(\perp\).

B. Authentication

Another stated requirement is the security of the authentication process. This section argues that our framework provides secure authentication for PDIDs.

Lemma 1. No adversary can authenticate on behalf of the user $U$ without knowing the corresponding password $pwd$.

sketch. An adversary, without knowing the user’s password, can authenticate as the user only if one of the following occurs 1) the adversary can impersonate the user’s identity $U$, registering and authenticating with a new $⟨U, pwd⟩$ pair,
to the registration and authentication protocols, the knowledge of $k_5$ is necessary to run offline attacks against $pwd$. With $k_5$, the adversary could try to keep generating different symmetric keys $k'$ from potential passwords $pwd'$: $k' \leftarrow P_{\text{f1}}(pwd')$, and keep testing them against the known ciphertext $c$, which is computed as $\text{AEnc}_k(p_u, P_u, P)$. However, $k_5$ is a high-entropy secret which is not revealed to the adversary. The adversary can interact with the GPM, passing different $\alpha'$ values and obtaining $\beta' \leftarrow \alpha' k_1$, but if this interaction would allow the adversary to learn $k_5$, or even to compute $\alpha' k_5$ for any non-queried $\alpha'$, that would be equivalent with breaking the One-More Diffie-Hellman problem (assumed to be hard by the OPAQUE protocol), contradicting our assumptions.

Similarly, it is easy to show that such an adversary cannot learn any value of the password metadata ($p_u, P_u, P$), and subsequently, cannot learn a session key $SK$ for any authentication that she does not participate in.

Although we assume that the blockchain platform is secure, a tolerable number of individual nodes (usually, up to 1/3 of all nodes) can be compromised. Then, a particularly interesting case is when a malicious node operator interacts with the secure enclave it runs. Such an operator, cannot read the...
enclave’s memory or influence its execution steps but can interact with it offline. In particular, the node can emulate the authentication process (see Fig. 3) by trying multiple passwords, calling the GPM’s AuthPDID() method locally, and checking if the user’s session key and the key outputted by the enclave match. We show that the PDID framework eliminates such attacks.

**Lemma 4.** An adversary able to compromise a tolerable number of blockchain nodes cannot launch a successful offline dictionary attack against the user’s password pwd.

**sketch.** To prove this property, we show from the GPM’s construction, that its AuthPDID() method computes a shared secret key only for a transaction that was already added to the blockchain. In our construction, we use a technique similar to the one presented by Kaptchuk et al. [19], where upon receiving a transaction \(\tilde{r}\), its processing method AuthPDID() first calls assert TxIncluded(\(\tilde{r}\)), which guarantees that the transaction is already part of the ledger. Since the adversary, even compromising a tolerable number of nodes, is not able to compromise the properties of the blockchain platform, she is not able to overcome this assertion with any transaction that is not appended to the blockchain. With this check, the adversary controlling a compromised node and interacting with its trusted enclave offline, cannot emulate the user-server authentication, and to get any GPM’s output she needs to register the transactions on the blockchain, making her attack attempts visible to the network (i.e., online).

### D. Online Attacks

Online password guessing attacks, where an adversary interacts with the authentication system trying to guess correct username-password pairs, is a generic attack against any password system. The PDID framework is not an exception to such attacks, and an adversary can just try different passwords interacting with supporting servers or with the GPM directly. A popular way of mitigating such attacks is rate limiting. Usually, it introduces a trade-off between the security and availability, and such mitigation would be implementable at the network-level or within the GPM (e.g., via small state representing the number of recent authentication attempts). Moreover, blockchain platforms enable an interesting extension of this technique. Instead of limiting authentication attempts, after a threshold number of attempts in a time window, the platform could require a small payment that could disincentivize adversaries from guessing passwords. We leave details of such a solution as future work.

### E. Privacy

The PDID framework does not introduce any message flows or mechanisms violating the user’s privacy when compared with the traditional password-based authentication (users interact only with servers, except for the registration). The messages exchanged between servers and the GPM are encrypted, thus do not reveal anything about the authenticating user. Moreover, the server’s keys used in the GPM-server communication are ephemeral and unknown to an observer, therefore, the observer investigating the blockchain logs would not be able to determine the server’s identity (we do not consider network-level deanonymization attacks). Finally, all usernames are stored as part of the encrypted state and processed only by trusted enclaves confidentially.

## V. Implementation and Evaluation

### A. Implementation

We fully implemented the PDID framework and our implementation consists of a supported user’s client (executing the user’s logic as in Fig. 2 and Fig. 3), a server (authenticating users as in Fig. 3), and the GPM handling registrations and assisting servers in user authentication. The user and server functionalities are implemented in C. To realize the GPM, we used a recent Hyperledger Fabric Private Chaincode (FPC) framework [16] which extends Hyperledger Fabric by confidential smart contracts. The GPM is implemented in C++ as a smart contract of this platform by using Intel SGX SDK to run the contract within an enclave. For encryption and hashing, use the NaCl library [20] with its defaults for the user and server implementations, and the TweetNaCl library for the GPM. We implemented the modified OPAQUE and HMQV protocols with elliptic curve cryptography for the group operations. Our implementation bases upon and extends the Easy-ECC library and we used the secp256r1 curve by default. Our code is publicly available at https://github.com/pszal/pdid.

### B. Evaluation

To evaluate our PDID implementation we conducted a series of experiments. First, we evaluated computational overheads introduced by the PDID framework. We set up an FPC tested and executed full PDID registration and authentication operations 1000 times each. In every run, we measured the time required to complete different protocol steps. To measure execution times, we used a commodity laptop equipped with SGX-enabled Intel i7-7600U (2.80GHz) CPU, 8GB of RAM, and run under Linux. In our experiments, we used a conservative setting measuring the computational overhead of specific procedures executed sequentially on ‘fresh’ registration and authentication requests. We did not use any caching strategies, parallelization, sophisticated parametrization, or request/transaction batching, which would amortize the execution time, although we see these techniques as desired in a deployment-ready implementation. The results of our experiments are presented in Tab. 1 reporting total execution times and times for different authentication phases (see Fig. 3).

|                | Registration | Authentication |
|----------------|--------------|----------------|
|                | min | max | avg | min | max | avg | min | max | avg |
| User           | 7.3 | 14.0 | 7.5 | 10.4 | 16.2 | 10.6 | 5.7 | 10.9 | 5.9 |
| Server         | N/A | 1.5 | 3.8 | 1.6 | 1.5 | 3.7 | 1.6 | 0.1 | 0.1 | 0.1 |
| GPM            | 5.9 | 9.4 | 6.5 | 18.0 | 22.7 | 19.0 | N/A | N/A | N/A |
As presented, even in our unoptimized setting PDIDs introduce a small computational overhead. The registration on the user side requires around 7ms on average, while the authentication process takes in total around 10ms on average, and requires the user to keep only a 97 byte long state. More importantly, the server’s side is even faster, requiring only 1.63ms per authentication (in total, on average), dominated by its first phase. It allows a server to conduct around 613 authentications per second. A server needs to store only 64 byte long state (an ephemeral secret key $s_k$) per authentication. Similarly, our protocol introduces a small transmission overhead with message sizes are between 74 and 300 bytes.

To improve performance and allow higher flexibility, Hyperledger Fabric separates contract execution and consensus layers, with distinct node functions responsible for ordering and executing transactions. Given that, the performance of the PDID framework is bounded by the consensus layer (since only once transactions are ordered they can be executed). Fortunately, the performance of this layer has been extensively investigated in previous studies, and even in large-scale distributed deployments, a Hyperledger Fabric network yields throughput between 2000 and 3000 transactions per second [17], introducing the end-to-end latency between 500 and 800 ms, respectively.

The GPM’s NewPDID() code, executed within an SGX enclave, handles a PDID registration in around 6.54ms on average. Therefore, a single core executing the GPM’s registration can handle around 153 registrations per second (around 0.55 million per hour). This throughput seems to be sufficient to handle even a global-scale registration load using only a single core. Each registered PDID requires only 260 byte password metadata in the GPM’s contract state. Due to the elliptic curve operations, the authentication on the GPM is relatively slower, requiring 19.00ms on average, which yields the throughput of around 52 authentications per second on a single core. To shed a light on this number, we refer to Thomas et al. [21] who report that for 670,000 users, Google has experienced 21 million authentications for 28 days in early 2019 with a peak 2 192 authentications per 100 seconds (i.e., around 22 authentications per second). Approximating their results, a single core executing GPM’s AuthPDID() can handle around 1.58 million users in the peak and around 4 million for the averaged load. We note, that this throughput can be scaled horizontally (to the limits of the consensus layer).

VI. RELATED WORK

A. Password-authenticated Identities

Username and password pairs, as described in § II, are arguably the most popular credentials for user authentication [1]. Typically, the identity is expressed as a user-selected username (i.e., login) which is local to the server and cannot be used for authenticating to other servers. To make such ‘local’ logins more universal and useful, decentralized authentication was proposed. For instance, with OpenID [3] users can use their identities registered with a single server (i.e., identity provider) to authenticate with other servers with no need of creating a new dedicated identity for them. Password-authenticated identities provide critical advantages, contributing to their surprising domination over seemingly superior alternatives [2]. Firstly, they are expressed as human-meaningful names, limiting the need of additional devices or infrastructures for storing or processing them. Secondly, passwords, broadly considered as memorable secrets, significantly simplify the secret managements (especially, on the user’s side). Lastly, they have a particularly long history as authentication means, thus they typically do not introduce any adoption or operation overheads. They come with some limitations, however. The main drawback is that users do not control their own identities and a malicious server could impersonate or terminate any identities at its will. In fact, not only servers have to be trusted. For example, identities expressed with e-mail addresses rely on DNS. OpenID, although convenient, enables identity providers to learn what servers (and when) users contact. Lastly, most of these schemes use the standard insecure authentication (discussed in § II).

B. Public-Key-authenticated Identities

Systems described in this part require users to establish and manage public-private keypairs. Although it may improve security and enable new applications, in practice, the public-private keypair management has been proved to be a challenging task, not only for users but even for allegedly more tech-savvy server operators [22].

1) Certificate-based: Authority-based public-key infrastructures (PKIs), like X.509 PKI [4], are designed to manage mappings between identities and their public keys. Typically, they introduce trusted certification authorities (CAs) that verify bindings between identities and their claimed public keys and assert this fact in signed certificates. X.509 is prominently used together with TLS for authenticating web services (identified by domain names); however, it is also adopted for user identities (expressed by full names and/or e-mail addresses) [23]. These PKIs require trust in CAs, which usually trust DNS for identity verification, and there have been multiple real-world attacks on CAs reported to date [5]. Although many recent approaches try to improve these PKIs, they usually target CAs’ accountability, transparency, and attack detection [24]–[28], but without changing the fundamental CA trust assumptions.

Relaxing the assumption of trusted authorities is a design goal of decentralized PKIs, where no trusted party is needed to verify identities, which in turn, are verified and asserted by other system participants. In those systems, trust decisions are made solely by users, depending on their trust estimation of the quality and length of ‘trust chains’. Such a web-of-trust model was prominently proposed in PGP [7] for securing e-mails (which still rely on the DNS hierarchy). SDSI/SPKI [29] is a distributed PKI with local namespaces extending the web-of-trust paradigm by introducing groups, access control, and security policies. These systems eliminate trusted parties, but their namespaces either allow collisions or are local. Moreover, they require an infrastructure for distributing trust relations.

Petnames [30] is an anti-phishing system where users themselves can assign local (private) names to keys of parties they interact with, distrusting names placed in certificates.
The intention of those local names is that, if a certificate for a lexically-similar phishing website is presented, it will not be trusted by the user by default, since the website will not have its petname. The system requires users to keep maintaining correct bindings between petnames and keys, which in a dynamic or multi-key environment, like the Internet, can be troublesome and harm usability [31].

2) Certificate-less: Since certificates introduce substantial overheads and their management poses significant challenges, especially for security-unaware users, eliminating digital certificates was a design goal of certificate-less systems. Self-certifying identifiers [8] base on the idea of deriving identity directly from the public-key, usually, by simply hashing it. Such hash-names are short (20-32 bytes), global, and collision-secure, and users can create them by themselves. Unfortunately, these names are represented by pseudorandom strings which, despite being relatively short, are not easily memorable by humans, thus they require a dedicated name distribution infrastructure.

Identity-based cryptography enables to generate public-private keypairs in a way where private keys are freely selected by users [32]. Since the public keys can be human-meaningful identities themselves, these systems do not need certificates or name discovery infrastructures. The main drawback of this approach is that keypairs have to be generated by a trusted party that learns secret keys.

3) Blockchain-based: Blockchain platforms were early seen as promising infrastructures for implementing distributed identities. Namecoin [11] is a blockchain-based PKI platform allowing users to register arbitrary identities and associate them with public keys. The system refutes the Zookoo’s conjecture, providing memorizable names associated with key pairs, without trusted parties. The community followed the Namecoin’s design, proposing systems with additional features [33] or extended trust models [34, 35].

Baars [36] discusses the applicability of blockchain technology to provide self-sovereign Identities, while Goodell and Aste [37] propose an architecture where besides technical aspects they point out importance of a careful regulation in such systems. AttriChain [38] is a holistic scheme using a permissioned blockchain to offer self-sovereign identities with threshold traceability and on-chain access control. All these systems require users to create and manage cryptographic keys.

Decentralized Identifiers (DIDs) [39] is an attempt to unify the management of decentralized digital identities. With DIDs, users can create their self-sovereign identities (associating them with their public keys) and anchor them with a blockchain platform their trust. DIDs are under heavy development, and are implemented and experimentally deployed as part of the Hyperledger project.

C. Comparison

In Tab. II we compare different name systems with ours in terms of the desired properties. For the row ‘Collision-secure Names’, we put a negative mark, if the system introduces trusted party(ies) managing identities. Systems providing this property differ in assumptions under which the property is achieved. For instance, self-certifying identifiers require a collision-resistant hash function, web-of-trust PKIs need a trusted ‘fragment’ of a peer-to-peer network, and blockchain-based systems require that a (super)majority of a Sybil-resistant network is honest. We also note that our instantiation of the PDID framework requires the TEE assumption. Our comparison shows that PDIDs is the only system to achieve all the desired properties.

VII. Conclusions

In this work, we presented PDIDs, a framework providing password-authenticated decentralized identities with global and human-meaningful names. Up to our best knowledge, it is the first system achieving these properties, and in comparison to the state-of-the-art systems, PDID does not require users to use and manage cryptographic keys for authentication. In our system, a user registers his username and password-derived information with a confidential smart contract and then can use these credentials to authenticate to any server. For authentication, we combine our framework with the OPAQUE protocol, resulting in an authentication system where even the server cannot learn the user’s password or any information leading to offline dictionary attacks against it. We report on the implementation of our system and evaluation results. In the future, we plan to investigate PDID management and extend our system beyond authentication (e.g., to decentralized storage).

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REFERENCES

[1] Joseph Bonneau, Cormac Herley, Paul C Van Oorschot, and Frank Stajano. Passwords and the evolution of imperfect authentication. Communications of the ACM, 58(7), 2015.
[2] Joseph Bonneau, Cormac Herley, Paul C Van Oorschot, and Frank Stajano. The quest to replace passwords: A framework for comparative evaluation of web authentication schemes. In 2012 IEEE Symposium on Security and Privacy. IEEE, 2012.
