UPPRESSO: An Unlinkable Privacy-PREserving Single Sign-On System

Abstract

As a widely adopted identity management and authentication mechanism in today's Internet, single sign-on (SSO) allows a user to maintain only the credential for the identity provider (IdP), instead of one credential for each relying party (RP), which shifts the burden of user authentication from RPs to the IdP. However, SSO introduces new privacy leakage threats, since (*a*) a curious IdP could track *all* the RPs a user has visited, and (*b*) collusive RPs could learn a user's online profile by linking her identifiers and activities across multiple RPs. Several privacy-preserving SSO solutions have been proposed to defend against either the curious IdP or collusive RPs, however, none of them can address both privacy leakage threats at the same time.

In this paper, we propose a privacy-preserving SSO system, called *UPPRESSO*, to protect a user's login traces against both the curious IdP and collusive RPs. We first formally analyze the privacy dilemma between SSO security requirements and the new privacy requirements, and convert the SSO privacy problem into an identifier-transformation problem. Then, we design a novel *transformed RP designation* scheme to transform the identifier of the RP, to which the user requests to log in, into a privacy-preserving pseudo-identifier (PID_{RP}) through the cooperation between the user and the RP. Our *trapdoor user identification* scheme allows the RP to obtain a trapdoor from the transformation process and use it to derive a unique account of the user at that RP from her privacy-preserving pseudo-identifier (PID_U) generated by the IdP. The login process of UPPRESSO follows the service pattern of OpenID Connect (OIDC), a widely deployed SSO system, with minimum modifications. And the system is platform independent. Our analysis shows UPPRESSO provides a comprehensive privacy protection while achieving the same security guarantees of OIDC.

1 Introduction

As a widely deployed identity management and authentication mechanism in the current Internet, single sign-on (SSO) systems such as OpenID Connect [1], OAuth [2] and SAML [3] allow a user to log in to a website, called the *relying party* (RP), using the account registered at another website, called the *identity provider* (IdP). The RPs delegate user authentication to a trusted IdP, who generates *identity proofs* for her visits to these RPs. Thus, the user only needs to remember one credential for the IdP, instead of maintaining different credentials for different RPs. SSO has been widely integrated with many application services. For example, we find that 80% of the Alexa Top-100 websites support SSO [4], and the analysis on the Alexa Top-1M websites identifies 6.30% with the SSO support [5]. Meanwhile, many email and social network providers (such as Google, Facebook, Twitter, etc.) are serving the IdP roles in the Internet.

However, SSO systems have been continuously found vulnerable and insecure [6–15]. Moreover, the adoption of SSO raises a public concern about user privacy [16–19], that is whether an adversary is able to track to which RP(s) the user has logged in. For example, one of the most worldwide popular instant messaging applications, WeChat, also working as the IdP service provider, enables a user to create different plain accounts for login on multiple RPs, shown in Figure 1. Unfortunately, almost all the existing SSO protocols leak user privacy in different ways. Take a widely used SSO protocol OpenID Connect (OIDC) as an example. As shown in Fig. 2, the login process starts when a user sends a login request to the RP, who then constructs a request for identity proof with its identity and redirects the request to the IdP. After authenticating the user, the IdP generates an identify proof with the user's and RP's identities, which is returned to the user and forwarded to the RP. Finally, the RP verifies the identity proof to decide if the user is allowed to log in. In such login instances, by design, an IdP can always see when and where its users log in, in order to generate the identity proof. As a result, a curious IdP can always discover the RPs that a target user has visited over time. This data can be further analyzed to profile users' online activities. Thus, we call this privacy attack ***IdP-based login tracing***, which has also been reported by previous research [18, 19]. Similarly, by design, the RPs

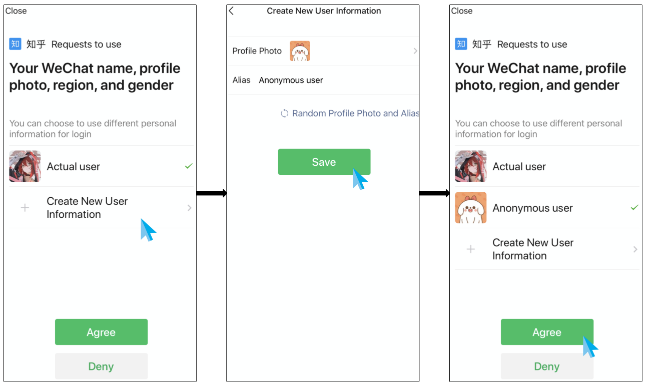

Figure 1: Anonymous accounts in WeChat.

can learn users' identities from the identify proofs. If the IdP binds an unique or relevant user identifier(s) to identity proofs generated for the same user but different RPs [20, 21], these RPs can collude to correlate the identifier(s) with the user's identity. We denote this privacy risk as ***RP-based identity linkage***, which allows the adversaries to not only track the user's online activities but also associate her attributes across multiple RPs by linking her login requests [16].

As SSO becomes a popular safeguard for various privacy-sensitive web services, the privacy concern is considered more prominent and severe than it was in the past. On one hand, privacy-savvy users may provide no or few personal information to web applications to avoid user tracking or profiling. On the other hand, the use of popular SSO services such as Google Account opens a door for IdPs and application providers to recover users' online traces and profiles, which makes users' privacy protection effort in vain. Several large IdPs, especially the social IdPs, are known to be interested in collecting users' online behavioral data for various purposes (e.g., Screenwise Meter [22] and Onavo [23]). Serving the IdP role makes it possible for them to collect such information. Meanwhile, service providers hosting multiple web applications take an advantaged position to correlate users' multiple logins at different RPs through internal information integration. Finally, privacy-preserving record linkage [24] and private set intersection [25] technologies allow multiple RPs to share data without violating their clients' privacy, which pave the path for cross-organizational RP-based identity linkage.

Several solutions have been proposed to protect user privacy in SSO login [16–19]. However, to the best of our knowledge, none of them provides a comprehensive protection to defend against IdP-based login tracing and RP-based identity linkage *at the same time*. For example, as recommended by NIST [17] and specified in several SSO protocols [1, 26], pairwise pseudonymous identifier (PPID) is generated by the IdP to identify a user to an RP, which cannot be correlated with the user's PPID at another RP. Thus, collusive RPs cannot link a user's logins from her PPIDs. However, PPID-based approaches cannot prevent IdP-based login tracing, since the IdP needs to know which RP the user visits in order to generate the correct identify proof. On the contrary, BrowserID [18] and SPRESSO [19] were proposed to defend against IdP-based login tracing. However, both solutions are vulnerable to RP-based identity linkage. In BrowserID (and its prototypes known as Mozilla Persona [27] and Firefox Accounts [21]), the IdP does not know the identity of the requesting RP. Instead, it generates a special "identity proof" to bind the user's unique identifier (e.g., email address) to a public key, so that the user can sign another subsidiary identity proof to bind her identity with the RP's identity and send both identity proofs to the RP. Obviously, when a user logs in to different RPs, the RPs can extract a same user identifier from different identity proofs and correlate these logins. In SPRESSO, the RP creates a one-time pseudo-identifier in each login. Then, the IdP generates an identity proof binding this pseudo-identifier and the user's identity (i.e., email address). Similarly, the RPs can correlate a user's logins using her unique identifier in the identity proofs.

Unfortunately, the techniques proposed by previous research cannot be directly integrated to address the two major types of privacy risks in SSO at the same time. In fact, it requires a non-trivial redesign of the SSO system to defend against IdP-based login tracing and RP-based identity linkage while providing a secure and compatible SSO service. In this paper, we first conceptualize the privacy problem in SSO as *an identifier transformation problem* and explain the reasons that limit existing solutions from fully protecting user privacy against curious IdPs and collusive RPs. Based on our analysis, we propose an Unlinkable Privacy-PREserving Single Sign-On (UPPRESSO) system to provide a comprehensive protection against both types of privacy attacks.

UPPRESSO designs three one-way identifier-transformation functions based on elliptic curve cryptography. Using the one-way trapdoor function $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}(ID_{RP}, T_{RP})$, the RP converts its identity ID_{RP} into a privacy-preserving pseudo-identifier PID_{RP} based on a randomly selected trapdoor T_{RP}. Similarly, the IdP uses the one-way function $\mathcal{F}_{ID_U \mapsto PID_U}(ID_U, PID_{RP})$ to generate a privacy-preserving pseudo-identifier PID_U for the user based on her identity ID_U and PID_{RP}. Finally, using a special identifier-transformation function $\mathcal{F}_{PID_U \mapsto Account}(PID_U, PID_{RP}, T_{RP})$, the RP is able to map all the different privacy-preserving pseudo-identifiers of a user, which are created in her different login sessions to that RP, to a same *Account* that identifies the user to the RP. The three identifier-transformation functions work cooperatively to ensure: (a) when a user logs in to an RP multiple times, the RP can always map PID_Us to a unique *Account* without knowing the user's identity ID_U; moreover, when a user logs in to multiple RPs, (b) a curious IdP learns nothing about the identities of these RPs from PID_{RP}s, and (c) collusive RPs cannot link PID_Us to a particular user (d) nor correlate

*Account*s of a same user at different RPs. We summarize our contributions as follows.

- We are among the first to conceptualize the privacy problem in SSO as an identifier-transformation problem and analyze the strengths and limitations of existing SSO privacy protection solutions.
- We propose a comprehensive solution to hide the users' login traces from curious IdPs and collusive RPs. To the best of our knowledge, UPPRESSO is the first SSO system that secures SSO services against IdP-based login tracing and RP-based identity linkage.
- We provide the reduction from UPPRESSO scheme to **DDH Assumption** proving that it is protected from IdP-based login tracing and RP-based identity linkage, and analyze the security of UPPRESSO based on a formal model of the web infrastructure and formally prove that it provides satisfying security properties.
- We implement a prototype of UPPRESSO based on an open-source implementation of OIDC, which requires only small modifications to support three identifier-transformation functions for privacy protections. Thus, UPPRESSO is compatible with existing SSO systems. Moreover, our prototype leverages HTML 5 features in the implementation so that it can be used across platforms (e.g., PCs, smart phones and other devices).
- We compare the performance of the UPPRESSO prototype with the state-of-the-art SSO systems (i.e., OIDC [1] and SPRESSO [19]) and demonstrate its efficiency.

The rest of the paper is organized as follows. We first introduce the background and preliminaries in Section 2. Then, we describe the identifier-transformation-based approach and the threat model in Sections 3 and 4. Section 5 presents the details of our UPPRESSO design, followed by a formal analysis of its privacy and security in Section 6 and 7. We explain the implementation specifics and experiment evaluation in Section 8, discuss the extensions and related works in Section 9 and 10, and conclude our work in Section 11.

2 Background and Preliminaries

UPPRESSO is designed to be compatible with OpenID Connect (OIDC) and provide privacy protections based on the discrete logarithm problem. Next, we briefly introduce OIDC and the discrete logarithm problem.

2.1 OpenID Connect (OIDC)

OIDC is one of the most popular SSO protocols [1]. It involves three entities, i.e., *users*, the *identity provider (IdP)*, and *relying parties (RPs)*. Users and RPs register at the IdP with identifiers and other necessary information such as credentials and RP endpoints (e.g., the URLs to receive identity proofs). The IdP is assumed to maintain these attributes securely.

OIDC Implicit Flow. OIDC supports three types of user login flows: *implicit flow*, *authorization code flow* and *hybrid flow* (i.e., a mix-up of the previous two). UPPRESSO is compatible with all three flows. For brevity, we will present our design and implementation on top of the OIDC implicit flow in the rest of the paper and discuss the extension to support the authorization code flow in Section 9.

As shown in Figure 2, first, the user initiates a login request to an RP. Then, the RP constructs an identity proof request with its identifier, an endpoint to receive the identity proof and a scope of requested user attributes, and sends the request to the user who will redirect it to the IdP. If the user has not been authenticated yet, the IdP initiates an authentication process to authenticate the user based on her identity and credential. If privacy-preserving pseudo-identifier is used, this process also involves mapping ID_U to PID_U based on ID_{RP}. Once successfully authenticating the user, the IdP generates an identity proof (called *id token*) and returns it to the RP endpoint through user redirection. The id token contains a user identifier (ID_U or PID_U), an RP identifier (ID_{RP}), the issuer, a validity period, the requested user attributes, etc. If the RP's endpoint has not been registered at the IdP, the IdP will return a warning to notify the user about potential identity proof leakage. Besides redirecting the messages between the RP and the IdP, the user also checks if the RP is permitted to obtain the user attributes in the identify proof. Usually, the redirection and checking actions are handled by a user-controlled software, called *user agent* (e.g., browser). Finally, the RP verifies the received identity proof and makes the authentication decision.

RP Dynamic Registration. OIDC also supports *RP dynamic registration* [28]. When an RP first registers at an IdP, it obtains a registration token with which the RP can update its information (e.g., endpoints) with the IdP in a later time. After a successful dynamic registration, the RP obtains a new ID_{RP} from the IdP. UPPRESSO leverages this function and slightly modifies the dynamic registration process to implement the PID_{RP} *registration* process (see details in Section 5.C), which allows an RP to generate different privacy-preserving RP identifiers and register them with the IdP.

3 The Privacy Dilemma and UPPRESSO Overview

Next, we overview the required security and privacy properties of an SSO system. Then, we conceptualize the SSO privacy problem as an identifier-transformation problem and explain the privacy dilemma behind existing solutions. Finally, we

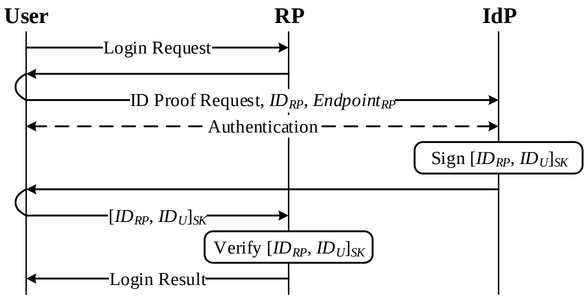

Figure 2: The implicit flow of OIDC.

present the design goals of UPPRESSO. We list the notations used in the discussion in Table 1 for reference.

3.1 Security Properties of SSO

The primary goal of SSO services is to support secure user authentication [19], which ensures that a legitimate user can always log in to an honest RP under her account. To achieve this, the identity proof generated by the IdP should explicitly specify the user who is authenticated by the IdP (i.e., ***user identification***) and the RP to which the user requests to log in (i.e., ***RP designation***). To provide a continuous service, the user identification property also requires an RP to be able to recognize a user and correlate her multiple logins by a unique identifier (or account). Moreover, the identify proof generated by the IdP should be transmitted only to the dedicated RP (through the user) (i.e., ***confidentiality***) and should not be modified or forged (i.e., ***integrity***). We summarize these four security properties from theoretical analysis of SSO designs [29–31] and practical attacks [6–15, 32–39].

Many attacks exploit vulnerabilities in SSO design and implementation to break at least one of the four security properties. The adversary mainly aims to log in to an honest RP as a victim user (called *impersonation attacks*) or allure a victim user to log in to an honest RP under the attacker's account (called *identity injection attacks*). For example, Friendcaster used to accept every received identity proof (i.e., a violation of RP designation) [37]. So, a malicious RP can replay a received identity proof to Friendcaster and log in as the victim user. If identity proofs are leaked (i.e., a violation of confidentiality) [6, 7, 9–11], the adversary can directly impersonate the victim user. It was also reported that some RPs of Google ID SSO accepted user attributes that were not tied to the identity proof (i.e., a violation of integrity) [6]. This allows an adversary to insert arbitrary attributes (e.g., email address of the adversary or another user) into the identity proof for the victim user.

Table 1: The notations used in UPPRESSO.

Notation	Definition	Attribute
q	A large prime, the size of the underlying field.	Long-term
E	An elliptic curve defined over a finite field $\mathbb{F}_q$ $(P-256)$.	Long-term
G	A point in $E(\mathbb{F}_q)$, known as the base point.	Long-term
n	the order of the base point G.	Long-term
SK, PK	The private/public key of IdP.	Long-term
ID_{RP}	An RP's unique identity, a point in cyclic subgroup of $E(\mathbb{F}_q)$ generated by P.	Long-term
$Cert_{RP}$	An RP certificate, containing the RP's identity and endpoint.	Long-term
ID_U	A user's unique identity.	Long-term
$Account$	A user's identifier at an RP: $A = ID_U ID_{RP}$ (denoted as A in equations).	Long-term
PID_{RP}	$PID_{RP} = N_U ID_{RP}$, an RP's pseudo-identifier.	One-time
PID_U	$PID_U = ID_U PID_{RP}$, a user's pseudo-identifier.	One-time
N_U	A user-generated nonce for PID_{RP}.	One-time
T	The trapdoor to derive $Account$: $T = N_U^{-1} \bmod n$.	One-time

3.2 The Privacy Dilemma in SSO Identity Proofs

A secure SSO system should have *all* four security properties discussed above while preventing IdP-based login tracing and RP-based identity linkage privacy leakage. However, meeting the security and privacy requirements at the same time incurs a dilemma in the generation of identity proofs.

An identity proof contains identities/identifiers of a user and an RP, which is to tell the RP that this user has been authenticated by the IdP. Since the IdP always knows the identity of the user (denoted as ID_U), to prevent IdP-based login tracing, we should not reveal RP's long-term identity (denoted as ID_{RP}) to the IdP. Instead, we have to use a transitional pseudo-identifier (denoted as PID_{RP}) that is uniquely associated with the RP in the identity proof request to ensure RP designation. Each RP's PID_{RP}s in different login instances should be different. PID_{RP} can be generated by the user, the RP or together, but it should be computationally infeasible for the IdP to derive the ID_{RP} from a PID_{RP}.

Meanwhile, to prevent RP-based identity linkage, the IdP should not directly include ID_U in the identity proof. So, the IdP has to generate a transitional pseudo-identifier for the user (denoted as PID_U) and bind it to the identity proof. While PID_U should not disclose any information for the RP to derive ID_U, it should also allow the RP to recognize the user and distinguish her from other users in the RP, which means an RP should be able to correlate a user's different PID_Us in different login instances, for example by mapping them to a unique user account (denoted as $Account$) at the RP, to ensure user identification. However, two or more RPs should not be able to correlate a user's $Account$s at different RPs to infer that they belong to the same user.

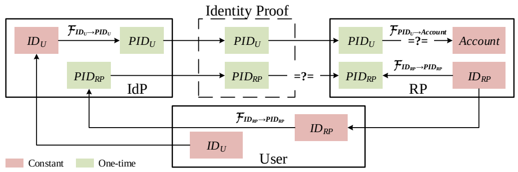

Figure 3: Identifier transformations in privacy-preserving SSO.

Table 2: Identifier-transformation in privacy-preserving SSO.

Solution	PID_U	PID_{RP}	$Account$
PPID	$\mathcal{F}(ID_U, ID_{RP})$	ID_{RP}	PID_U
SPRESSO	ID_U	$Enc(ID_{RP}\|nonce)$	ID_U
BrowserID†	ID_U	$\perp$	ID_U
UPPRESSO	$\mathcal{F}(ID_U, PID_{RP})$	$\mathcal{F}(ID_{RP}, T)$	$\mathcal{F}(PID_U, T)$

†: BrowserID binds null PID_{RP} in the identity proofs by the IdP, but ID_{RP} is bound in the *subsidiary* identity proof signed by the user.

We illustrate the relationships among the identities, pseudo-identifiers and the identity proofs in Figure 3. The red and green blocks represent long-term identities and one-time pseudo-identifiers respectively, and the arrows denote how the pseudo-identifiers are obtained. To comprehensively protect user privacy, the identity proof should only use one-time pseudo-identifiers of the user and the RP, where PID_U and PID_{RP} should satisfy the above requirements. This cause a ***dilemma*** for the IdP: given a user (ID_U) and an unknown RP (PID_{RP}), the IdP is expected to generate a pseudo-identifier (PID_U), which is correlated with a long-term account that uniquely identifies the user at that RP, *without knowing anything about the RP's identity nor the user account at the RP*.

To solve the dilemma, we should provide the IdP some information related to the user's *Account* at the RP to assist the generation of PID_U, so that PID_U can be correctly correlated with the *Account*. Meanwhile, such information should not provide any additional knowledge for the IdP to derive the RP's identity, or for two RPs to correlate two *Account*s belonging to the same user. Therefore, the privacy protection problem can be converted into an identifier-transformation problem, which aims to design three identifier-transformation functions $\mathcal{F}_{ID_U \mapsto PID_U}$, $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}$, and $\mathcal{F}_{PID_U \mapsto Account}$ to compute PID_U, PID_{RP} and *Account* that provide the above desired properties.

3.3 The Identifier-transformation Framework of UPPRESSO

To achieve this goal, UPPRESSO constructs three transformation functions in an integrated way to support *transformed RP designation* and *trapdoor user identification*, where (a) different PID_Us and PID_{RP}s are dynamically generated in different logins; (b) in each login session, PID_{RP} is used to assists the generation of PID_U, which helps to link PID_U to *Account* using the trapdoor of this session.

Transformed RP designation. To prevent IdP-based login tracing, the RP includes a PID_{RP} dynamically transformed from ID_{RP}, instead of ID_{RP}, in the identity proof request. UPPRESSO designs a novel trapdoor-based transformation function $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}(ID_{RP}, T)$ to compute PID_{RP} based on ID_{RP} and a random trapdoor T, which is dynamically negotiated between the user and the RP in each login. Then, the user assists the RP to register PID_{RP} at the IdP through OIDC dynamic registration. When an RP receives an identity proof, it verifies if the enclosed PID_{RP} is transformed from its ID_{RP} and the trapdoor of this session.

Trapdoor user identification. To prevent RP-based identity linkage, we design a transformation function $\mathcal{F}_{ID_U \mapsto PID_U}(ID_U, PID_{RP})$ for the IdP to generate PID_U. When an RP receives an identity proof, another transformation function $\mathcal{F}_{PID_U \mapsto Account}(PID_U, PID_{RP}, T)$ is designed to help the RP to derive the *Account* from PID_U and PID_{RP} using the trapdoor it holds. Intuitively, the trapdoor T plays a role in the generations of PID_{RP} and PID_U, directly or indirectly.

3.4 Existing Privacy-Preserving SSO Solutions

We map three existing privacy-preserving SSO approaches (PPID [1], BrowserID [18] and SPRESSO [19]) to the identifier transformation framework in Figure 3 and summarize their potential privacy issues in Table 2. It is worth noting that when $PID_U = ID_U$ and $PID_{RP} = ID_{RP}$, this framework depicts the basic SSO services with no privacy protection.

In PPID approaches, the IdP generates different PID_Us for a user to log in to different RPs and maintains deterministic one-to-many mappings from ID_U to PID_Us. Therefore, they can prevent RP-based identity linkage. At each RP, a user is identified by a same PID_U (i.e., $Account = PID_U$), which ensures user identification. However, since ID_{RP} is directly used in identity proofs (i.e., $PID_{RP} = ID_{RP}$), these approaches are vulnerable to IdP-based login tracing.

In SPRESSO, the RP generates PID_{RP} by encrypting ID_{RP} padded with a nonce for each login session and forwards PID_{RP} to the IdP. With the corresponding nonce, the RP can verify PID_{RP} in the identity proof to ensure RP designation, while hiding ID_{RP} from the IdP to defend against IdP-based login tracing. However, a same ID_U is used to generate identity proofs for a same user, no matter which RPs she requests to log in. So, SPRESSO is vulnerable to RP-based identity linkage, since different RPs can correlate login requests of a same user by ID_U (i.e., $Account = ID_U$).

Identity proofs in BrowserID include ID_U but no RP information (i.e., $PID_{RP} = \perp$), therefore, it directly prevents IdP-based login tracing. To ensure RP designation, BrowserID requires the user to append a *subsidiary* identity proof and sign it, where the identity proof signed by the IdP authorizes the user to sign the subsidiary identity proof. Obviously, ID_U is tied to a pair of identity proof and subsidiary identity proof. Similarly, a user's login requests to different RPs can be linked by ID_U (i.e., $Account = ID_U$), which makes BrowserID vulnerable to RP-based identity linkage.

None of the three approaches can defend against IdP-based login tracing and RP-based identity linkage at the same time. This is because in each approach, three transformation functions $\mathcal{F}_{ID_U \mapsto PID_U}$, $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}$ and $\mathcal{F}_{PID_U \mapsto Account}$ are designed arbitrarily and function separately, which causes either $PID_{RP} = ID_{RP}$ or $Account = ID_U$.

4 Threat Model and Assumptions

4.1 Threat Model

In UPPRESSO, we consider the IdP is curious-but-honest, while some users and RPs could be compromised by adversaries. Malicious users and RPs may behave arbitrarily or collude with each other, attempting to break the security and privacy guarantees for benign users.

Curious-but-honest IdP. A curious-but-honest IdP strictly follows the protocol, while being interested in learning user privacy. For example, it may store all the received messages to infer the relationship among ID_U, ID_{RP}, PID_U and PID_{RP} to trace a user's login activities at multiple RPs. We also assume the IdP is well-protected. For example, the IdP is trusted to maintain the private key for signing identity proofs and RP certificates, so, the adversaries cannot forge an identity proof or an RP certificate.

Malicious Users. We assume the adversary can control a set of users, for example by stealing users' credentials [40,41] or directly registering sybil accounts at the IdP and RPs. They may impersonate a victim user at honest RPs, or trick a victim user to log in to an honest RP under the adversary's account. For example, a malicious user may modify, insert, drop or replay a message, or deviate arbitrarily from the specifications when processing ID_{RP}, PID_{RP} and identity proofs.

Malicious RPs. The adversary can also control a set of RPs, for example, by directly registering at the IdP as an RP or exploiting software vulnerabilities to compromise some RPs. The malicious RPs may behave arbitrarily to break security and privacy guarantees. To do so, a malicious RP may manipulate its PID_{RP} to trick the users to submit identity proofs generated for an honest RP to itself. or it may manipulate its PID_{RP} to affect the generation of PID_U and analyze the relationship between PID_U and $Account$.

Collusive Users and RPs. Malicious users and RPs may collude with each other to break the security and privacy guarantees. For example, acting as an RP, the adversary first lures a victim user to submit a valid identity proof to itself, and then logs in to the honest RPs as the victim user using this identity proof.

4.2 Assumptions

We also make a few assumptions about the information and implementation of the SSO system under study. First, we consider user attributes as distinctive and indistinctive attributes, where distinctive attributes contain identifiable information about a user such as telephone number, address, driver license, etc. We assume the RPs cannot obtain distinctive attributes in an SSO login, since a privacy-savvy user is less likely to permit the RPs to access such information, or even not register such information with the IdP at all. Thus, privacy leakage due to user re-identification is considered out of the scope of this work. Also, we focus only on privacy attacks enabled by SSO protocols, but not network attacks such as traffic analysis that can trace a user's logins at different RPs.

Secondly, we assume the user agent deployed at honest users is correctly implemented so that it can transmit messages to the dedicated receivers as expected. We also assume TLS is adopted to secure the communications between honest entities. Moreover, we assume the cryptographic algorithms (such as RSA and SHA-256) and building blocks (such as random number generators) are correctly implemented.

5 The Design of UPPRESSO

Once we conceptualize the privacy problem into a identifier-transformation problem, the design of UPPRESSO is mainly about designing three identifier-transformation functions to generate pseudo-identifiers for the user and RP as well as link the user's pseudo-identifier to her account at an RP. In this section, we first present our design of these three functions to support *transformed RP designation* and *trapdoor user identification* properties, and then describe the details of the UPPRESSO system and its login flow.

5.1 Identifier-transformation Functions in UPPRESSO

We construct the three functions, $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}$, $\mathcal{F}_{ID_U \mapsto PID_U}$ and $\mathcal{F}_{PID_U \mapsto Account}$, based on NIST elliptical curve $P-256$. where q is a large prime defining the finite field $\mathbb{F}_q$, G is a point on the curve known as the base point, and n the order of the base point G. Without loss of generality, we assume the IdP assigns long-term identifiers ID_U to a user and ID_{RP} to an RP when they first register at the IdP. In particular, the IdP assigns a unique random number to each user as ID_U, where $1 < ID_U < n$, and ID_{RP} is a point on the curve generated based on G.

The RP Identifier Transformation Function. In each login session, the user assists the RP to convert ID_{RP} into a pseudo-identifier PID_{RP}. In particular, the user selects a random number N_{RP} ($1 < N_U < n$) and calculates PID_{RP} as:

$$\mathcal{F}_{ID_{RP} \mapsto PID_{RP}} : PID_{RP} = N_U ID_{RP} \tag{1}$$

This transformation function $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}$ is a one-way function so that it is computationally infeasible for the IdP to derive ID_{RP} from PID_{RP} due to the discrete logarithm problem. Moreover, the nonce N_U ensures that: (*a*) PID_{RP} is a one-time pseudo-identifier of a login that is valid only for the identity proof generated in this login; and (*b*) PID_{RP} is dynamically generated in each login. When a user visits a same RP multiple times, different PID_{RP}s will be generated, which cannot be correlated or linked to a same RP.

The User Identifier Transformation Function. Now, the identity proof request to the IdP contains a user identity ID_U and a pseudo-identifier of the RP PID_{RP}. Therefore, the IdP can convert ID_U into a pseudo-identifier for the user as follows and use it in the identity proof:

$$\mathcal{F}_{ID_U \mapsto PID_U} : PID_U = ID_U PID_{RP} \tag{2}$$

From Equations 1 and 2, we see that $PID_U = (N_U ID_U) ID_{RP}$. So, PID_U is a one-time pseudo-identifier that is valid only in one login session and one identity proof. The discrete logarithm problem ensures that the RP cannot derive ID_U from PID_U. Moreover, although the IdP does not know how the RP identifies the user (i.e. the user's *Account* at the RP), involving PID_{RP} in the generation of PID_U indirectly links a user's one-time pseudo-identifier at the IdP (PID_U) to her long-term identifier at the RP (*Account*) through a trapdoor.

The User Account Transformation Function. We define the trapdoor T of each login session as $T = N_U^{-1} \bmod n$. As n is a prime number and $1 < N_U < n$, n is coprime to N_U. So, there always exists a T that satisfies $TN_U = 1 \bmod n$. Using this trapdoor, the RP can easily derive a unique account (denoted as A in the equation) for the user in each login session as:

$$\mathcal{F}_{PID_U \mapsto Account} : A = T PID_U \tag{3}$$

From Equations 1, 2 and 3, we can further derive:

$$A = T PID_U = (ID_U N_U N_U^{-1} \bmod n) ID_{RP} = ID_U ID_{RP}$$

This means, when a user logs in to an RP multiple times, the RP can always derive the same *Account* from different PID_Us to uniquely identity the user. However, the RP cannot derive ID_U from *Account* due to the discrete logarithm problem. Finally, *Account* provides no clue for different RPs to correlate the users.

With three identifier-transformation functions, UPRESSO supports two desirable properties discussed in Section 3.C to satisfy *all* the security and privacy requirements of an SSO. ***(i) Transformed RP designation:*** using $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}$, the user and RP cooperatively generate a dynamic PID_{RP} for each login. The identify proof request contains PID_{RP} instead of ID_{RP}, so, the RP can verify PID_{RP} is associated with ID_{RP} using the trapdoor but the IdP cannot tell to which RP the user attempts to log in. Also, since PID_{RP}s of a same RP are different in different login sessions, the IdP cannot even tell if a same RP is visited. Therefore, it prevents IdP-based login tracing. ***(ii) Trapdoor user identification:*** For each user, different PID_Us are generated by the IdP in different login sessions, no matter she requests to log in to a same RP multiple times or to different RPs. However, using $\mathcal{F}_{ID_U \mapsto PID_U}$ and $\mathcal{F}_{PID_U \mapsto Account}$, UPRESSO guarantees that an RP can always derive the unique *Account* for each user using the dynamically generated PID_U and the corresponding trapdoor in each login session. Meanwhile, collusive RPs cannot link a user's PID_Us and *Account*s at different RPs, and therefore prevents RP-based identity linkage.

5.2 UPPRESSO Procedures

System Initialization. UPPRESSO consists of four procedures. First, the IdP calls system initialization once to establish the entire system. In particular, the IdP generates one key pair (SK, PK) to sign identity proofs and RP certificates. The lengths of (SK, PK) should satisfy the required security strength. Then, the IdP keeps SK secret, while announcing PK as public parameters.

RP Initial Registration. Each RP calls an initial registration process once to obtain the necessary configurations from the IdP. In particular, an RP registers itself at the IdP to obtain a unique identifier ID_{RP} and the corresponding RP certificate $Cert_{RP}$ as follows: (i) The RP sends a registration request to the IdP, including the RP endpoint (e.g., URL) to receive identity proofs; (ii) The IdP generates a unique ID_{RP} and signs $[ID_{RP}, Endpoint_{RP}, *]$ using SK, where $*$ denotes supplementary information such as the RP's common name; then, the IdP returns $Cert_{RP} = [ID_{RP}, Endpoint_{RP}, *]_{SK}$ to the RP, where $[\cdot]_{SK}$ means the message is signed using SK; (iii) The RP verifies $Cert_{RP}$ using PK and accepts ID_{RP} and $Cert_{RP}$ if they are valid. Note that, in UPRESSO, ID_{RP} must be generated by the IdP but cannot be chosen by the RP.

User registration. UPPRESSO adopts a similar user registration process as the ones in other SSO systems. Each user registers once at the IdP to set up a unique user identifier ID_U and the corresponding user credential.

SSO Login. An SSO login procedure is launched when a user requests to log in to an RP, which calls three identifier-transformation functions following the login flow as shown in Figure **??**. It consists of five phases, namely scripts downloading, RP identifier transformation, PID_{RP} registration, identity proof generation and *Account* calculation.

1. Scripts Downloading. The scripts downloading phase is for the user's browser to download the scripts from the RP and IdP servers. The browser and two scripts work together to play the user agent role.

1.1 The user visits the RP's script site to download the RP script.

1.2 The RP script opens a new window in the browser to visit the login path at the RP server.

1.3 The visit is redirected to the IdP's script site.

1.4 The new window visits the IdP's script site and downloads the IdP script.

2. RP Identifier Transformation. The user and RP cooperate to generate $PID_{RP} = N_U ID_{RP}$. To hide the RP's endpoint from the IdP, the user needs to create a new endpoint to replace the real endpoint of the RP.

2.1 The IdP script chooses a random N_U ($1 < N_U < n$) and sends it to the RP script through postMessage. Then, the RP script sends N_U to the RP server.

2.2 The RP verifies $N_U \neq 0 \bmod q$, calculates PID_{RP} and derives the trapdoor $T = {N_U}^{-1} \bmod q$. To acknowledge the negotiation of PID_{RP}, the RP replies with $Cert_{RP}$, which is transmitted from the RP script to the IdP script through postMessage.

2.3 The IdP script verifies $Cert_{RP}$, extracts ID_{RP} from $Cert_{RP}$ and calculates $PID_{RP} = N_U ID_{RP}$ and $nonce = hash(N_U)$. It also creates a one-time endpoint for the RP. If $Cert_{RP}$ is invalid, the user halts the negotiation.

It is important to ensure that the RP's endpoint is not tampered by the adversary. In other OIDC systems, the IdP knows the RP's endpoint during RP registration and thus can verify the endpoint in an identity proof request. However, in UPPRESSO, the IdP sees only a one-time endpoint. So, we let the user verify the correctness of the RP's endpoint using the RP certificate.

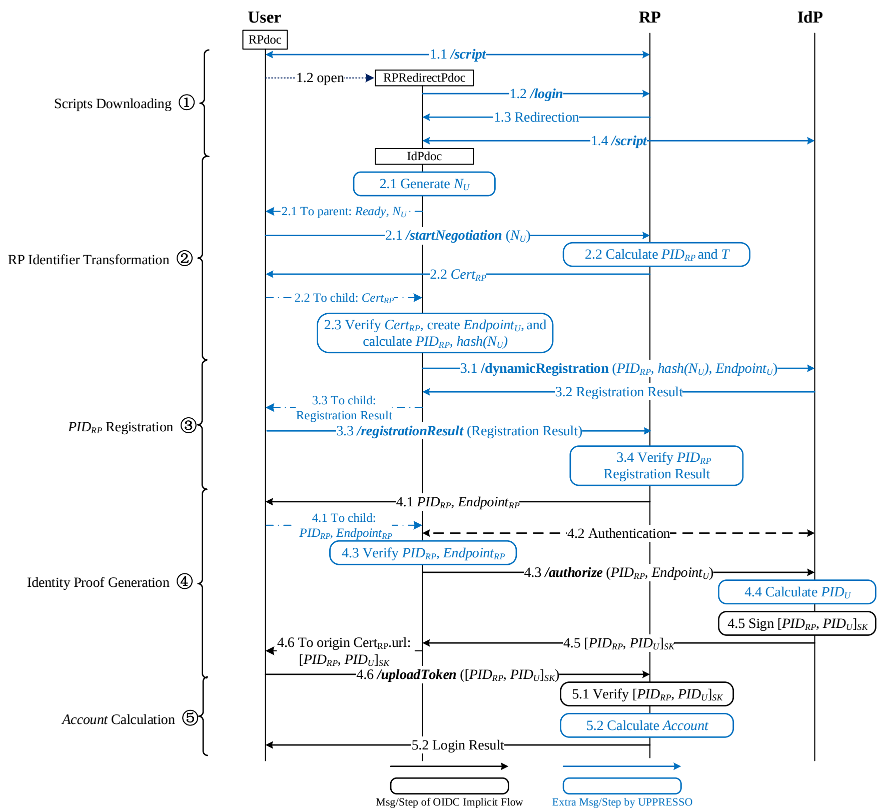

Figure 4: The flow of a user login in UPPRESSO.

3. $\mathbf{PID_{RP}}$ *Registration.* In this phase, the user registers a new RP with PID_{RP} at the IdP using OIDC's dynamic registration. This step has to be conducted by the user but not the RP. Otherwise, the IdP can associate PID_{RP} and ID_{RP}.

3.1 The IdP script sends the PID_{RP} registration request $[PID_{RP}, Hash(N_U), Endpoint_U]$ to the IdP.

3.2 The IdP checks the unexpired PID_{RP}s to verify if the received PID_{RP} is unique. Then, it signs the response as $[PID_{RP}, hash(N_U), validity]_{SK}$, where $validity$ denotes when the PID_{RP} will expire.

3.3 The IdP script forwards the registration result to the RP server through the RP script.

3.4 The RP verifies the IdP's signature, and accepts the result only if PID_{RP} and $hash(N_U)$ match those in the negotiation and PID_{RP} is not expired.

$hash(N_U)$ is a nonce to distinguish different login sessions, because there is a very small chance that a same PID_{RP} is generated for two RPs using different ID_{RP}s and N_Us. This nonce avoids a registration result is acceptable to two RPs.

4. ID Proof Generation. In this phase, the IdP calculates

$PID_U = ID_U PID_{RP}$ and signs the identity proof.

4.1 The RP constructs an identity proof request containing its PID_{RP} and $Endpoint_{RP}$, which is then forwarded to the IdP script through the RP script.

4.2 The IdP authenticates the user if she has not been authenticated yet.

4.3 First, the user checks the scope of the requested attributes, while the IdP script verifies PID_{RP} and $Endpoint_{RP}$ in the request are valid. Then, the IdP script replaces the RP's endpoint with the newly registered one-time $Endpoint_U$ and sends the modified identity proof request to the IdP server.

4.4 The IdP verifies if PID_{RP} and $Endpoint_U$ are registered and unexpired, and then calculates $PID_U = ID_U PID_{RP}$ for the authenticated user.

4.5 The IdP constructs and signs the identity proof $[PID_{RP}, PID_U, Iss, ValTime, Attr]_{SK}$, where Iss is the identifier of the IdP, $ValTime$ is the validity period, and $Attr$ contains the requested attributes.

4.6 The IdP sends the identity proof to the one-time endpoint. The IdP script forwards the identity proof to the RP script that holds the origin $Endpoint_{RP}$. Finally, the RP script sends it to the RP server.

In this phase, if any check fails, the process will be halted. For example, the user halts the process if PID_{RP} in the identity proof request is inconsistent with the negotiated one. The IdP rejects the identity proof request, if the pair of PID_{RP} and $Endpoint_U$ has not been registered.

5. **Account** *calculation.* The RP verifies the identity proof, derives the user's unique $Account$, and allows her to log in.

5.1 The RP verifies the identity proof, including the signature, validity period, and the consistency between PID_{RP} and the negotiated one. If any fails, the RP rejects this login.

5.2 The RP extracts PID_U, calculates $Accout = T PID_U$, and allows the user to log in.

5.3 Compatibility with OIDC

As described above, UPPRESSO does not introduce any new role nor change the security assumptions for each role. It follows a similar logic flow as OIDC in SSO login and only requires small modifications to perform identifier transformation. Here, we explain the modification in each of the five phases of its SSO login flow to show that UPPRESSO is compatible with OIDC, which indicates UPPRESSO can be easily integrated with other commonly used SSO systems.

Among the five phases, the *scripts downloading* and *RP identifier transformation* phases are newly introduced by UPPRESSO. The browser is required to download two scripts from the IdP and RP and most of the designed operations in these two phases are performed by the scripts in the browser. So, we requires minimal modifications to the user agent. The other three phases adopt a similar communication pattern as OIDC. In particular, the *PID_{RP} registration* phase can be viewed as a variant of the RP dynamic registration flow of OIDC [28], which allows an entity to register its identity and endpoint at the IdP. Different from OIDC in which only RPs can call a dynamic registration, UPPRESSO allows any authenticated user to launch this process and register an RP identifier with the IdP. The *identity proof generation* and *Account calculation* phases adopt the same steps and functions as the implicit protocol flow of OIDC, while using a few different parameters. First, in identity proof generation, PID_U transformed from ID_U is used to replace ID_U, which is directly supported by OIDC, similar as in the PPID approaches that also convert ID_U into PID_U. The calculation of $Account$ from PID_U can be viewed as a customized step by the RP to derive its user account after the implicit protocol flow of OIDC ends. So,the identity proof generation and $Account$ calculation phases of UPPRESSO can be viewed as a particular but compatible implementation of the implicit protocol flow of OIDC. It is worth noting that the identity proof generation and $Account$ calculation phases of UPPRESSO can be also implemented as the authorization code flow of OIDC with small modifications, which will be discussed in Section 9.

6 Provable Security Analysis of Privacy

In this section, we will give the proof that UPPRESSO is defensive to both IdP-based login tracing and RP-based identity linkage, based on DDH assumption [42], the computational problem.

DDH Assumption. $\mathbb{G}$ is a n-order cyclic additive group of $E(\mathbb{F}_q)$, where q and n are large primitive number, and P is the generator of $\mathbb{G}$. For any probabilistic polynomial time (PPT) algorithm D, the distributions, $\{P, aP, bP, abP\}_{a,b \in \mathbb{Z}_n}$ and $\{P, aP, bP, cP\}_{a,b,c \in \mathbb{Z}_n}$, are computationally indistinguishable. There is a negligible $\sigma(k)$, where k is the security parameter.

$$Pr[D(P, aP, bP, abP) = 1] \\ - Pr[D(P, aP, bP, cP) = 1] = \sigma(k)$$

IdP-based identity linkage. It can be found in figure **??** that PID_{RP} is the only data related with RP's identity accessible to IdP. Moreover, PID_{RP} is created based on ID_{RP} and the IdP uncontrolled random number N_U. As N_U is randomly chosen in $\mathbb{Z}_n$, PID_{RP} can be also seemed randomly chosen in $\mathbb{G}$ to IdP. Therefore, obviously IdP cannot trace the user's login RPs, so that IdP-based identity linkage is not possible in UPPRESSO.

RP-based identity linkage.

In the *RP-based identity linkage* scenario, collusive RPs conduct the malicious behavior against IdP and users to relate the user in different RPs. It can be considered as a *Game* guessing whether PID_Us for different RPs belong to the same

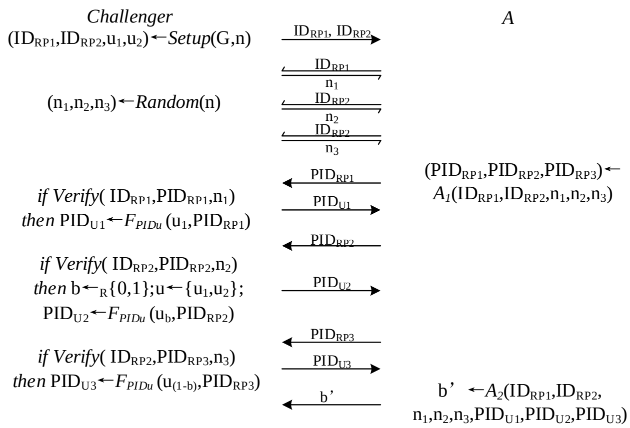

Figure 5: Game 0.

user. In this *Game* IdP and users act as the challenger, and RPs act as the adversary.

If only the adversary cannot take any advantage on guessing whether PID_Us belong to same user, RP-based identity linkage is considered impossible in UPPRESSO.

Following, we are going to build the model of Game to show how the adversary interactive with the challenger. Here we describe the challenger's actions in the Game.

- Initialization: In the initialization phase, the challenger generates the ID_{RP}s and ID_Us for multiple RPs and users, based on the initialization algorithm $Setup(G,n)$ where G and n have been already defined in table 1.

- Random number generation: While challenger receives the ID_{RP}s from adversary, it generates random numbers $N_U \in \mathbb{Z}_n$ for each ID_{RP}s creating PID_{RP} using algorithm $Random(n)$.

- PID_U generation: In this phase, challenger firstly receives and verifies whether PID_{RP} is correctly generated based on ID_{RP} and corresponding n (i.e., the algorithm $Verify(ID_{RP}, PID_{RP}, N_U)$). Then it generates the PID_U using the algorithm $F_{PID_U}(ID_U, PID_{RP})$ and sends it to adversary.

Firstly we give the realistic model of the ID_U-guessing Game, shown as figure 5. In this Game, adversary firstly achieves 2 IR_{RP}s and 3 N_Us and generates 3 PID_{RP}s. In the challenger's view, these PID_{RP}s are related with 3 N_Us respectively. Following the challenger generates PID_Us for different PID_{RP}s based on the 2 ID_Us generated in initialization phase. Then challenger generates the random b=0 or 1. PID_{U1} is generated based on ID_{U1}. However PID_{U2} and PID_{U3} are generated according to b. That is, $PID_{U2} = ID_{Ub}PID_{RP2}$, and $PID_{U3} = ID_{U(1-b)}PID_{RP3}$

Finally adversary returns the b'. While $b = b'$ is true, we consider the adversary succeeds, that means the RP-identity-linkage is possible in UPPRESSO. We define the event $[b' = b]$ in Game 0 as Γ. The probability $Pr[\Gamma]$ must be 1/2 as if the adversary cannot take any advantage of guessing b (i.e. whether PID_Us belong to same ID_U). Therefore, it is proved that UPPRESSO is protected from RP-based identity linkage only if $Pr[\Gamma] = 1/2$.

Then we build the ideal model of Game, of which the probability that an adversary succeeds to guessing b is 1/2. The model is shown as figure 6. We use z and r for generating PID_{U2} and PID_{U3} instead of ID_{U1} and ID_{U2}. As z and r is randomly generated and unknown to A, the adversary has no information about b. We define the event $[b' = b]$ in Game 1 as Γ_1. $Pr[\Gamma_1]$ must be equal to 1/2.

Therefore, we only need to prove that $|Pr[\Gamma_1] - Pr[\Gamma]| = \sigma(n)$, where $\sigma(n)$ is negligible. Here we give another model of Game, shown as figure 7. We can find that in fact it only sets the exact values of the parameters defined in Game 0, such as $ID_{RP2} = xID_{RP1}$, $u_1 = y$ and $u_2 = r$(r is a random number). Here we define the event $[b' = b]$ in Game 2 as Γ_2. There should be $Pr[\Gamma_2] = Pr[\Gamma]$.

We are going to prove that $|Pr[\Gamma_1] - Pr[\Gamma_2]| = \sigma(n)$. In each Games, adversary derives the b' from collected data, $\{ID_{RP1}, ID_{RP2}, n_1, n_2, n_3, PID_{U1}, PID_{U2}, PID_{U3}\}$, with the algorithm A_2. Now we replace the parameters in Game 1 and Game 2 with exact values. In Game 1, $b'_{game1} \leftarrow A_2(P, xP, n_1, n_2, n_3, yn_1P, zP, rP)$, and in Game 2, $b'_{game2} \leftarrow A_2(P, xP, n_1, n_2, n_3, yn_1P, xyn_2P, rn_3P)$ or $b'_{game2} \leftarrow A_2(P, xP, n_1, n_2, n_3, yn_1P, rn_2P, xyn_3P)$. However, n_1, n_2, n_3 are randomly chosen unrelated with ID_U by challenger and able to be eliminated by adversary. Therefore, there is, in Game 1, $b'_{game1} \leftarrow A_2(P, xP, yP, zP, rP)$, and in Game 2, $b'_{game2} \leftarrow A_2(P, xP, yP, xyP, xrP)$. As r is randomly chosen and unknown to adversary, both rP and xrP are random points and cannot bring any extra advantage for adversary to guessing b. The final procedure is $b'_{game1} \leftarrow A_2(P, xP, yP, zP)$ and $b'_{game2} \leftarrow A_2(P, xP, yP, xyP)$. Therefore, there must be no non-negligible difference value between the success probability in Game 1 and Game 2 according to DDH assumption. Otherwise, we can build the PPT distinguishing algorithm breaking DDH assumption based on the adversary.

Distinguishing algorithm. The distinguishing algorithm D is shown as figure 8. The inputs of the algorithm is $\{P, X, Y, Z\}$. While the input is in the form $\{P, xP, yP, zP\}_{x,y,z \in \mathbb{Z}_n}$, for the adversary it is the Game 1. As the input is $\{P, xP, yP, xyP\}_{x,y \in \mathbb{Z}_n}$, for the adversary it is the Game 2. So, there is,

$$Pr[D(P, xP, yP, zP) = 1] = Pr[\Gamma_1]$$

$$Pr[D(P, xP, yP, xyP) = 1] = Pr[\Gamma_2]$$

Therefore, $|Pr[\Gamma_1] - Pr[\Gamma_2]| = \sigma(n)$, where $\sigma(n)$ is negligible, and n is the security parameter. So, the adversary has no advantage to guessing b in Game 0, that means he cannot distinguish whether two PID_Us for different RPs belong to the same user or not.

The RP-based identity linkage attack is not possible in UPPRESSO.

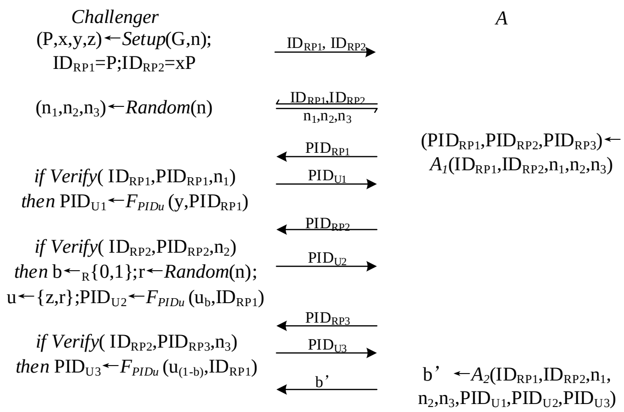

Figure 6: Game 1.

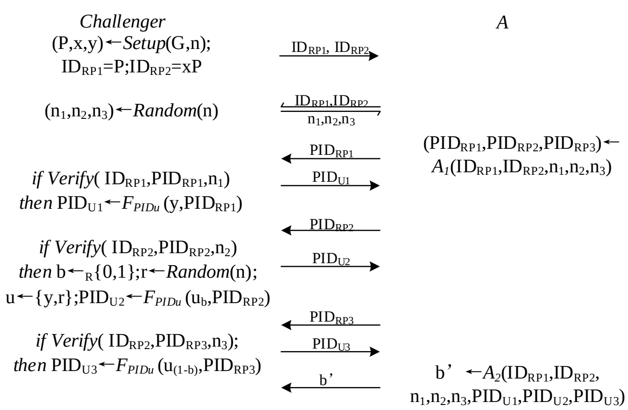

Figure 7: Game 2.

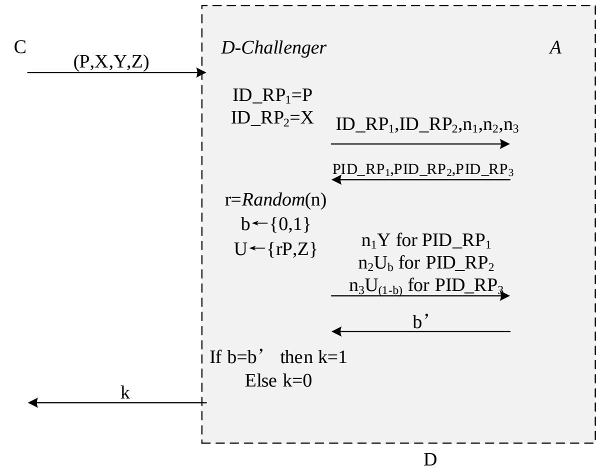

Figure 8: Distinguishing algorithm.

7 Security Analysis

We formally analyze security properties of UPPRESSO based on the Dolev-Yao style web model [19], which has been widely used in the formal analysis of SSO protocols such as OAuth 2.0 [30] and OIDC [31]. For brevity, we focus on the modifications introduced by UPPRESSO in this paper and neglect the proofs for the security of DNS and HTTPS requests. We refer interested readers to [19] for details.

7.1 The Web Model

The Dolev-Yao model abstracts the entities in a system, such as browsers and web servers, as *atomic processes*, which communicate with each other through the *events*. [19] also defines *scripting processes* to model client-side scripting such as JavaScript, so a web system consists of a set of atomic and scripting processes. The state of a system, called a *configuration*, consists of the current states of all atomic processes and all the events that can be accepted by these processes. We list the definitions of these notations as below [19].

Messages are defined as formal terms without variables (i.e., ground terms) over a *signature*. The signature Σ consists of a finite set of function symbols (with arity). For messages in this mode, the signature Σ contains constants such as ASCII strings and nonce, sequence symbols such as n-ary sequences $\langle\rangle$, $\langle.\rangle$, $\langle.,.\rangle$, and function symbols that model cryptographic primitives such as `encrypt`, `decrypt` and digital signatures. For example, an HTTP request can be modeled as a ground term containing a type (e.g., `HTTPReq`), a nonce, a method (e.g., `GET` or `POST`), a domain, a path, URL parameters, request headers and a message body, over the Σ in the sequence symbol format. So, an HTTP GET request for the domain exa.com/path?para=1 with empty header and body can be represented as: $m := \langle \mathtt{HTTPReq}, n, \mathtt{GET}, exa.com, /path, \langle\langle para, 1\rangle\rangle, \langle\rangle, \langle\rangle\rangle$.

Events are the basic communication elements in the model. An event is of the form $\langle a, f, m\rangle$, where a and f represent the addresses of the sender and receiver respectively, and m is the message to be transmitted.

Atomic Processes. An *atomic Dolev-Yao (DY) process* is a tuple $p = (I^p, Z^p, R^p, s_0^p)$, where I^p is the set of addresses that the process listens to, Z^p is the set of states (i.e., terms) that describes the process, s_0^p is an initial state, and R^p is the mapping from an input state $s \in Z^p$ and an event e to a new state s' and an event e'. Each atomic process also contains a set of nonces that it may use.

Scripting Processes represent client-side scripts loaded by the browser to provide server-defined functions to the browser. However, a scripting process must rely on an atomic process, such as the browser, and provide the relation R called by this atomic process.

Web system. We can represent the web infrastructure as a web system of form ($\mathcal{W}$, $\mathcal{S}$, `script`, E^0), where $\mathcal{W}$ is the set of atomic processes containing both honest and malicious processes, $\mathcal{S}$ is the set of scripting processes including honest and malicious scripts, `script` is the set of concrete script codes related to specific scripting processes in $\mathcal{S}$, and E^0 is the set of events acceptable to the processes in $\mathcal{W}$.

A *configuration* of this web system is a tuple (S,E,N), where S is the current states of all processes in $\mathcal{W}$, E is the set of events that the processes accept, and N is a global sequence of nonces that have not been used by the processes yet.

A *run step* is the system migrating from configurations (S,E,N) to (S',E',N') by processing an event $e \in E$.

7.2 The Formal Model of UPPRESSO

Accordingly, we model UPPRESSO as a web system, which is defined as $\mathcal{UWS} = (\mathcal{W}, \mathcal{S}, \texttt{script}, E^0)$. $\mathcal{W}$ is a finite set of atomic processes in UPPRESSO, which contains an IdP server process, a finite set of web servers for the honest RPs, a finite set of honest browsers, and a finite set of attacker processes. Here, we consider all the RP processes and browser processes are honest, and model an RP or a browser controlled by an adversary as an atomic attacker process. $\mathcal{S}$ is a finite set of scripting processes, which contains script_rp, script_idp and script_attacker, where script_rp and script_idp are honest scripts downloaded by an RP process and the IdP process, and script_attacker denotes a script downloaded by an attacker process that exists in all browser processes. Below is a brief description about the processes and scripts in UPPRESSO.

- A browser is an atomic process, which is responsible for sending HTTP requests, receiving HTTP responses, handling user actions, and transmitting messages between scripting processes. As the browsers are considered honest, in the remaining analysis, we focus only on the scripting processes running in the browsers. We refer interested readers to Appendix C and [19] for more details about the browser process.

- The IdP server process (defined as p^i) only accepts the events whose message is an HTTP request with a path in the set of {/script, /dynamicRegistration, /login, /loginInfo, /authorize}. All the events can be accepted by p^i in any state, but the output may vary.

- The RP server process (denoted as p^r) only accepts the events whose message is an HTTP request with a path in {/script, /login, /startNegotiation, /registrationResult, /uploadToken}. However, an event with a path in { /script, /login, /startNegotiation} can be accepted in any state, while an event with a path $\equiv$ /registrationResult is accepted only when the state s is the output of an event whose path $\equiv$ /startNegotiation. Similarly, the following accepted events should have a path in {/registrationResult, /uploadToken}.

- The IdP and RP scripting processes accept the events in the form of HTTP response and postMessage.

7.3 Security of UPPRESSO

At the very beginning, it is to be emphasized that, whether an RP accepted *Acount* can be controlled by an adversary may be the most noticeable question for readers, as it can caused the essential attack that the adversary can impersonate other honest users by controlling the *Acount*. For example, the adversary may try to make the conflict $Account_1 = ID_{U_1} ID_{RP_1}$, $Account_2 = ID_{U_2} ID_{RP_2}$ and $Account_1 = Account_2$ possible, where ID_{U_1} and ID_{RP_1} belong to the honest user and RP. Here we give the direct conclusion and brief proofs in advance and the details are shown in the following analysis. **The** *Account* **accepted by an RP must be consist with ID_{RP} and ID_U, where ID_{RP} belongs to this RP and ID_U is decided by IdP according to the requesting user.** That is, while an RP R receive an identity proof related with an honest user u's *Account*, this identity proof must be issued to u for r.

Proof. An identity proof contains the PID_{RP} and PID_U, and it follows the relation $PID_U = ID_U PID_{RP}$. RP is going to transform into *Account* with the trapdoor N^{-1}. However, during the registration phase in authentication, the RP received the registration token including PID_{RP} and $hash(N)$, which confirms that $N^{-1} PID_{RP} = ID_{RP}$. Therefore, the RP would achieve the $Account = ID_U R$ (R is the real ID of this RP). As ID_U is unique for each user, the efforts of the adversary in making the conflicted $Account_1$ and $Account_2$ is impossible.

In the security analysis, we consider web systems $\mathcal{UWS}$ defined in Section 7.1. In this model, we considers only one network attacker who is able to listen to and spoof all addresses. The network attacker can control (malicious) browsers and RPs. The analysis of the security of UPPRESSO is to prove the below theorem:

Theorem 1. *Let $\mathcal{UWS}$ be a UPPRESSO web system defined above. Then, $\mathcal{UWS}$ is secure.*

In Section 3.1, we describe the fundamental security properties that an SSO system should satisfy. Confidentiality and integrity require that the identity proof from the IdP cannot be intercepted or altered. As we assume tall the messages transmitted using HTTPS, we can prove that the encrypted communications over HTTPS between honest entities cannot be tampered by the network attacker. Therefore, an honest RP can receive correct identity proofs and retrieve the correct key for signature verification from the IdP through the honest browsers. For brevity, we do not include the detailed proofs here, which are similar to the proof in [19].

User identification and RP designation informally require that *an attacker should not be able to log in to an honest RP as an honest user*. To prove this property, we assume there exists a UPPRESSO web system in which an attacker can log in to an honest RP as an honest user, and show this assumption leads to a contradiction. We consider the visits to an RP's resource paths are controlled by the visitors' cookie. So, if such a system exists, the attacker could break the security if and only if he owns the cookie bound to the honest user.

Based on this, we define a secure UPPRESSO as below.

Definition 1. Let $\mathcal{UWS}$ be a UPPRESSO web system. $\mathcal{UWS}$ is secure *iff* any authenticated cookie $c(u,r)$ of an honest user u for an honest RP $r \in \mathcal{W}$ is unknown to the attacker a.

To prove that an attacker a does not know the authenticated cookie $c(u,r)$, we want to show that (A) a cannot obtain any $c(u,r)$ owned by u; (B) if c is an unauthenticated cookie owned by a, c cannot be set as $c(u,r)$, i.e., being authenticated by r for u; and (C) an honest user u should not use the authenticated cookie of the attacker (i.e., $c(a,r)$). $\mathcal{UWS}$ meeting the requirement (A) can be proved by the following Lemma.

Lemma 1. The cookie owned by an honest user cannot be leaked to the attacker.

First, due to the same-origin policy, an honest browser should not leak the cookie to any attacker. Based on the UPPRESSO model, we also prove that the RP server and the RP script will not send any cookie to other processes. Therefore, the attackers cannot obtain the u's authenticated cookie. Next, to prove $\mathcal{UWS}$ satisfies the requirement (B), we define the process that authenticates a cookie as below.

Definition 2. In $\mathcal{UWS}$, a cookie c is set as an authenticated cookie $c(u,r)$ for a user u and an RP r only when r receives a valid identity proof of u from the owner of c.

Lemma 2. In $\mathcal{UWS}$, an attacker cannot obtain the password of an honest user u.

Lemma 3. In $\mathcal{UWS}$, an attacker cannot forge or modify the proofs issued by the IdP.

Lemma 2 can be easily proved because the password is only sent by an honest IdP scripting process to the IdP server. Lemma 3 can be proved by showing that the proofs issued by the IdP process are signed and verified. With Lemma 2 and Lemma 3, we can prove the following lemma.

Lemma 4. In $\mathcal{UWS}$, an attacker cannot obtain a valid identity proof for an honest user u.

Here, we provide a brief proof for Lemma 4. A valid identity proof can only be obtained from one of the four processes: the IdP server process, the RP server process, the IdP scripting process and the RP scripting process. According to the model, the honest RP scripting processes only send identity proofs to an honest RP server, while the RP server never sends the proofs to any other process. So, only the process that holds u's password can obtain u's identity proof from the IdP server. As the attacker does not know u's password, he cannot receive the identity proof of u from the IdP server process. Finally, it is a little complicated to prove that the attacker cannot obtain the identity proof from the IdP scripting process. So, we only describe it intuitively. That is, an honest user u only sends the identity proof from the IdP scripting process to the receiver specified by the RP certificate $cert_r$. And, an identity proof is valid to an honest RP r only if $cert_r$ belongs to r (we include a full proof in the Appendix).

Next, we prove a $\mathcal{UWS}$ system meets the requirement (C). First, the attacker cannot set $c(a,r)$ with the RP's origin in an honest browser due to the same-origin policy. According to Definition 2, the RP r sets $c(a,r)$ in an honest browser u if it receives an identity proof with the attacker's PID_U and a valid PID_{RP} generated by u and r. This requires the attacker to know a valid PID_{RP}. According to the following lemma, the attacker cannot obtain an identity proof with a valid PID_{RP}.

Lemma 5. The attacker cannot know a valid PID_{RP} negotiated by a user u and an RP r.

Finally, we prove $\mathcal{UWS}$ satisfies requirements (A), (B) and (C) in Definition 1. As a result, Theorem 1 is proved. Due to space limit, we include all the detailed proofs of the lemmas and theorems in the Appendix.

8 Implementation and Performance Evaluation

We have implemented the UPPRESSO prototype, and evaluated its performance by comparing with the original OIDC which only prevents RP-based identity linkage, and SPRESSO which only prevents IdP-based login tracing.

8.1 Implementation

We adopt SHA-256 for digest generation, and RSA-2048 for signature generation. We choose the NIST elliptical curve $P-256$ to create ID_{RP} (the point generated based on base point G), N_U and $ID_U \in \mathbb{Z}_n$ (n is the order of G). UPPRESSO includes the processing at the IdP, users and the RPs. The implementations at each entity are as follows.

The implementation of the IdP only needs small modifications on the existing OIDC implementation. The UPPRESSO IdP is implemented based on MITREid Connect [43], an opensource OIDC Java implementation certificated by the OpenID Foundation [44]. We add 3 lines of Java code to calculate PID_U, about 20 lines to modify the way to send identity proof to the RP, about 50 lines to the function of dynamic registration to support PID_{RP} registration, i.e., checking PID_{RP} and adding a signature and validity period in the response. The calculations of ID_{RP}, PID_U and RSA signature are implemented based on Java built-in cryptographic libraries (e.g., BigInteger).

The user-side processing is implemented as a JavaScript code provided by IdP and RP server, respectively containing about 200 lines and 150 lines of codes, to provide the functions in Steps 2.1, 2.3 and 4.3. The cryptographic computations, e.g., $Cert_{RP}$ verification and PID_{RP} negotiation, are implemented based on jsrsasign [45], an efficient JavaScript cryptographic library.

We provide a Java SDK for RPs to integrate UPPRESSO. The SDK provides 2 functions to encapsulate RP's processings: one for RP identifier transformation, PID_{RP} registration and identity proof request generation; while the other for identity proof verification and *Account* calculation. The SDK is implemented based on the Spring Boot framework with about 1000 lines code, and cryptographic computations are implemented based on Spring Security library. An RP only needs to invoke these two functions for the integration.

8.2 Performance Evaluation

Environment. The evaluation was performed on 3 machines, one (3.4GHz CPU, 8GB RAM, 500GB SSD, Windows 10) as IdP, one (3.1GHz CPU, 8GB RAM, 128GB SSD, Windows 10) as an RP, and the last one (2.9GHz CPU, 8GB RAM, 128GB SSD, Windows 10) as a user. The user agent is Chrome v75.0.3770.100. And the machines are connected by an isolated 1Gbps network.

Setting. We compare UPPRESSO with MITREid Connect [43] and SPRESSO [19], where MITREid Connect provides open-source Java implementations [43] of IdP and RP's SDK, and SPRESSO provides the JavaScript implementations based on node.js for all entities [19]. We implemented a Java RP based on Spring Boot framework for UPPRESSO and MITREid Connect, by integrating the corresponding SDK respectively. The RPs in all the three schemes provide the same function, i.e., extracting the user's account from the identity proof. We have measured the time for a user's login at an RP, and calculated the average values of 1000 measurements. For better analysis, we divide a login into 3 phases according to the lifecycle of identity proof: **Identity proof requesting** (Steps 1.1-4.3 in Figure **??**), the RP (and user) constructing and transmitting the request to IdP; **Identity proof generation** (Steps 4.4-4.6 in Figure **??**), the IdP generating identity proof (no user authentication); and **Identity proof acceptance** (Steps 4.5-5.2 in Figure **??**), the RP server receives, verifies and parse the identity proof relayed from the IdP;

Results. The evaluation results are provided in Figure 9. The overall processing times are 113 ms, 308 ms and 310 ms for MITREid Connect, SPRESSO and UPPRESSO, respectively. The details are as follows. The significant overhead in UPPRESSO is opening the new window and downloading the script from IdP, which needs about 104 ms. This overhead could be reduced by implicitly conducting this procedure when the user visits the RP website.

In the requesting, UPPRESSO requires that (1) the user downloads the RP script, opens the IdP window and downloads the IdP script, and (2) the user and RP performs 2 elliptic curve scalar multiplications for RP identifier transformation and complete PID_{RP} registration at the IdP. The total proceeding time is 271 ms (104 ms downloading scripts and opening new window), where SPRESSO needs 19 ms for the

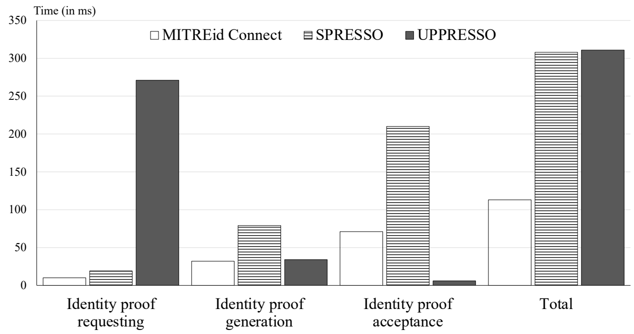

Figure 9: The Evaluation.

RP to obtain IdP's public key and encrypt its domain; while MITREid Connect only needs 10 ms.

In the generation, UPPRESSO needs totally 34 ms including computing PID_U, compared to MITREid Connect which only needs 32 ms. SPRESSO requires 71 ms, as it implements the IdP based on node.js and therefore can only adopt a JavaScript cryptographic library, while others adopt a more efficient Java library. As the processings in SPRESSO and MITREid Connect are the same, the processing time in SPRESSO may be reduced to 32 ms.

In the identity proof acceptance, UPPRESSO only needs about 6 ms where the scripts relay the identity proof to the RP server, and RP server verifies and parses the proof. MITREid Connect requires the IdP to send the identity proof to the RP's web page which then sends the proof to the RP server through a JavaScript function, and needs 71 ms. SPRESSO needs the longest time (210 ms) due to a complicated processing at the user's browser, which needs the browser to obtain identity proofs from the IdP, download the JavaScript program from a trusted entity (forwarder), execute the program to decrypt RP's endpoint, send identity proofs to this endpoint (an RP's web page) who finally transmits the proof to RP server. In the evaluation, the forwarder and IdP are deployed in one machine, which doesn't introduce performance degradation based on the observation.

9 Discussions and Future work

In this section, we discuss some related issues and our future work.

Scalability. The adversary cannot exhaust ID_{RP} and PID_{RP}. For ID_{RP}, it is generated only in RP's initial registration. For PID_{RP}, in practice, we only need to ensure all PID_{RP}s are different among the unexpired identity proof (the number denoted as a). We assume that IdP doesn't perform the uniqueness check, and then calculate the probability that at least two PID_{RP}s are equal in these a ones. The probability is $1-\prod_{i=0}^{a-1}(1-i/q)$ which increases with a. For an IdP with throughput $2*10^8$ req/s, when the validity period of the identity proof (PID_{RP}) is set as 5 minutes, a is less than 2^{36}, then the probability is less than 2^{-183} for 256-bit q (the order of base point G on $P-256$). Moreover, as this probability is negligible, the uniqueness check of PID_{RP}, i.e., the PID_{RP} registration, could be removed in the SSO login process, and this optimization can be adopted when this negligible probability is acceptable by the users and RPs.

Security against DoS attack. The adversary may attempt to perform DoS attack on the IdP and RP. For example, the adversary may act as a user to invoke the PID_{RP} registration (Step 3.1) and identity proof generation (Step 4.3) at the IdP, which requires the IdP to perform two signature generations and one modular exponentiation. However, as the user has already been authenticated at the IdP, the IdP could identify the malicious users based on audit, in addition to the existing DoS mitigation schemes.

OIDC authorization code flow support. The privacy-preserving functions $\mathcal{F}_{ID_U \mapsto PID_U}$, $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}$ and $\mathcal{F}_{PID_U \mapsto Account}$ can be integrated into OIDC authorization code flow directly, therefore RP-based identity linkage and IdP-based login tracing are still prevented during the construction and parsing of identity proof. The only privacy leakage is introduced by the transmission, as RP servers obtain the identity proof directly from the IdP in this flow, which allows the IdP to obtain RP's network information (e.g., IP address). UPPRESSO needs to integrate existing anonymous networks (e.g., Tor) to prevent this leakage.

Malicious IdP mitigation. The IdP is assumed to assign a unique ID_{RP} in $Cert_{RP}$ for each RP and generate the correct PID_U for each login. The malicious IdP may attempt to provide the incorrect ID_{RP} and PID_U, which could be prevented by integrating certificate transparency [46] and user's identifier check [19]. With certificate transparency [46], the monitors check the uniqueness of ID_{RP} among all the certificates stored in the log server. To prevent the malicious IdP from injecting any incorrect PID_U, the user could provide a nickname to the RP for an extra check as in SPRESSO [19].

Identity linkage through cookie. In UPPRESSO, IdP does not provide any distinctive information (such as ID_U) of each user to RP, which avoids RP-based identity linkage. However, the cookie of each user may be exploited by RPs to correlate the same user. For instance, while the user has logged in to RP_A with $Account_A$, RP may redirect user's $Account_A$ to RP_B through the hidden iframe. That is, as long as the user has logged in to RP_B with $Account_B$, the user would be correlated. Moreover, this attack is not only appeared in SSO systems, but also existed in all user-account systems. However, this attack can be easily detected through multiple methods, such as checking the iframe in script, observing redirection flow through browser network tool, and detecting the redirection based on the browser extension.

10 Related Works

Various SSO protocols have been proposed, such as, OIDC, OAuth 2.0, SAML, Central Authentication Service (CAS) [47] and Kerberos [48]. These protocols are widely adopted in Google, Facebook, Shibboleth project [49], Java applications and etc. And, plenty of works have been conducted on privacy protection and security analysis for SSO systems.

10.1 Privacy protection for SSO systems.

Privacy-preserving SSO systems. As suggested by NIST [17], SSO systems should prevent both RP-based identity linkage and IdP-based login tracing. The pairwise user identifier is adopted in SAML [3] and OIDC [1], and only prevents RP–based identity linkage; while SPRESSO [19] and BrowserID [18] only prevent IdP-based login tracing. BrowserID is adopted in Persona [27] and Firefox Accounts [21], however an analysis on Persona found IdP-based login tracing could still succeed [18, 50]. UPPRESSO prevents both the RP-based identity linkage and IdP-based login tracing, and could be integrated into OIDC which has been formally analyzed [31].
Anonymous SSO systems. Anonymous SSO schemes are designed to allow users to access a service (i.e. RP) protected by a verifier (i.e., IdP) without revealing their identities. One of the earliest anonymous SSO systems was proposed for Global System for Mobile (GSM) communication in 2008 [51]. The notion of anonymous SSO was formalized [52] in 2013. And, various cryptographic primitives, such as group signature, zero-knowledge proof and etc., were adopted to design anonymous SSO schemes [52, 53]. Anonymous SSO schemes are designed for the anonymous services, and not applicable to common services which need user identification.

10.2 Security analysis of SSO systems.

Formal analysis on SSO standards. The SSO standards (e.g., SAML, OAuth and OIDC) have been formally analyzed. Fett et al. [30, 31] have conducted the formal analysis on OAuth 2.0 and OIDC standards based on an expressive Dolev-Yao style model [50], and proposed two new attacks, i.e., 307 redirect attack and IdP Mix-Up attack. When the IdP misuses HTTP 307 status code for redirection, the sensitive information (e.g., credentials) entered at the IdP will be leaked to the RP by the user's browser. While, IdP Mix-Up attack confuses the RP about which IdP is used and makes the victim RP send the identity proof to the malicious IdP, which breaks the confidentiality of the identity proof. Fett et al. [30, 31] have proved that OAuth 2.0 and OIDC are secure once these two attacks prevented. UPPRESSO could be integrated into OIDC, which simplifies its security analysis. [29] formally analyzed SAML and its variant proposed by Google, and found that Google's variant of SAML doesn't set RP's identifier in the identity proof, which breaks RP designation.

Single sign-off. In SSO systems, once a user's IdP account is compromised, the adversary could hijack all her RPs' accounts. A backwards-compatible extension, named single sign-off, is proposed for OIDC. The single sign-off allows the user to revoke all her identity proofs and notify all RPs to freeze her accounts [5]. The single sign-off could also be achieved in UPPRESSO, where the user needs to revoke the identity proofs at all RPs, as the IdP doesn't know which RPs the user visits.

Analysis on SSO implementations. Various vulnerabilities were found in SSO implementations, and then exploited for impersonation and identity injection attacks by breaking the confidentiality [6, 7, 9–11], integrity [6, 8, 11–14] or RP designation [11–15] of identity proof. Wang et al. [6] analyzed the SSO implementations of Google and Facebook from the view of the browser relayed traffic, and found logic flaws in IdPs and RPs to break the confidentiality and integrity of identity proof. An authentication flaw was found in Google Apps [9], allowing a malicious RP to hijack a user's authentication attempt and inject the malicious code to steal the cookie (or identity proof) for the targeted RP, breaking the confidentiality. The integrity has been tampered with in SAML, OAuth and OIDC systems [6, 8, 12–14], due to various vulnerabilities, such as XML Signature wrapping (XSW) [8], RP's incomplete verification [6, 12, 14], IdP spoofing [13, 14] and etc. And, a dedicated, bidirectional authenticated secure channel was proposed to improve the confidentiality and integrity of identity proof [38]. The vulnerabilities were also found to break the RP designation, such as the incorrect binding at IdPs [12, 15], insufficient verification at RPs [13–15]. Automatical tools, such as SSOScan [32], OAuthTester [34] and S3KVetter [15], have been designed to detect vulnerabilities for breaking the confidentiality, integrity or RP designation of identity proof.

Analysis on mobile SSO systems. In mobile SSO systems, the IdP App, IdP-provided SDK (e.g., an encapsulated WebView) or system browser are adopted to redirect identity proof from IdP App to RP App. However, none of them was trusted to ensure that the identity proof could be only sent to the designated RP [33, 37], as WebView and system browser cannot authenticate RP App while the IdP App may be repackaged. Moreover, the SSO protocols needed to be modified to provide SSO services for mobile Apps, however these modifications were not well understood by RP developers [35, 37]. The top Android applications have been analyzed [33, 35–37, 39], and vulnerabilities were found to break the confidentiality [33, 35–37, 39], integrity [35, 37], and RP designation [36, 37] of identity proof.

11 conclusion

In this paper, we propose UPPRESSO, an unlinkable privacy-preserving single sign-on system, which protects a user's login activities at different RPs against both curious IdP and collusive RPs. To the best of our knowledge, UPPRESSO is the first approach that defend against both IdP-based login tracing and RP-based identity linkage privacy threats at the same time. To achieve these goals, we convert the privacy problem in SSO services into an identifier-transformation problem and design three transformation functions based on the discrete logarithm problem, where $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}$ prevents curious IdP from knowing the identity of the RP, $\mathcal{F}_{ID_U \mapsto PID_U}$ prevents collusive RPs from linking a user based on her identifier, and $\mathcal{F}_{PID_U \mapsto Account}$ allows each RP to derive an identical account for a user in her multiple logins. The three functions could be integrated with existing SSO protocols, such as OIDC, to enhance the protection of user privacy, without breaking any security guarantee of SSO. Moreover, the evaluation on the prototype of UPPRESSO demonstrates that it supports an efficient SSO service, where a single login takes only 310 ms on average.

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