UPPRESSO: Untraceable and Unlinkable Privacy-PREserving Single Sign-On Services

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Abstract

Single sign-on (SSO) allows a user to maintain only the credential at an identity provider (IdP), to login to numerous relying parties (RPs). However, SSO introduces extra privacy threats, compared with traditional authentication mechanisms, as (*a*) the curious IdP could track all RPs which a user is visiting, and (*b*) colluding RPs could learn a user's online profile by linking his identities across these RPs. This paper presents a privacy-preserving SSO system, called *UPPRESSO*, to protect a user's online profile against both a curious IdP and colluding RPs. We propose an identity-transformation approach. In each SSO login instance, an *ephemeral pseudo-identity* of an RP (denoted as PID_{RP}), is negotiated between a user and the RP. PID_{RP} is sent to an IdP and designated in an identity token, so the IdP is not aware of the visited RP. Then, PID_{RP} is used by the IdP to transform the *permanent user identity* ID_U into an *ephemeral user pseudo-identity* (denoted as PID_U) in the token. On receiving the identity token, the RP transforms PID_U into a *permanent account* of the user (denoted as *Acct*). Given a user, the account at each RP is unique and different from ID_U, so colluding RPs cannot link his identities across RPs. We build the prototype on top of MITREid Connect, an open-source SSO system. The extensive evaluations show that UPPRESSO fulfills the requirements of both security and privacy and introduces reasonable overheads.

1 Introduction

Single sign-on (SSO) protocols such as OpenID Connect (OIDC) [53], OAuth 2.0 [36] and SAML [35, 37], are widely deployed for identity management and authentication. With the help of SSO, a user logins to a website, referred to as the *relying party* (RP), using his account registered at a trusted web service, known as the *identity provider* (IdP). An RP delegates user identification and authentication to the IdP, which issues an *identity token* (e.g., id token in OIDC or identity assertion in SAML) for a user to visit the RP. For example, in an OIDC system, a user sends a login request to an RP, and this RP constructs an identity-token request with its identity (denoted as ID_{RP}) and redirects this request to an IdP of this system. After authenticating the user, the IdP issues an identity token binding the identities of both the user and the RP (i.e., ID_U and ID_{RP}), which is returned to the user and forwarded to the RP. Finally, the RP verifies the identity token to decide whether the token holder is allowed to login or not. So a user keeps only one credential for the IdP, instead of several credentials for different RPs.

As the comprehensive solution of identity management and authentication, SSO services allow an IdP to provide more user attributes in identity tokens, along with an authenticated user's identity. Attributes (e.g., age, hobby, education, and nationality) are maintained at the IdP, and enclosed in identity tokens after the user's authorization [36, 53].

The wide adoption of SSO raises concerns on user privacy [25, 26, 31, 47], because SSO facilitates curious parties to track a user's login activities. To issue identity tokens, in each login instance an IdP is aware of when and to which RP a user attempts to login. Therefore, an honest-but-curious IdP could track all the RPs that each user has visited over time [25, 26], called the *IdP-based login tracing* in this paper. Meanwhile, RPs learn user identities from the received identity tokens. If an identical user identity is enclosed in the tokens for a user to visit different RPs [30, 47, 55], colluding RPs could link these login instances across the RPs to learn his online profile [47]. We denote this risk as the *RP-based identity linkage*.

Privacy-preserving SSO schemes try to provide comprehensive identity management and authentication, while protecting user privacy [25, 26, 31, 47]. The following features of SSO are commonly desired: (*a*) *User identity at an RP*, i.e., an identity token enables an RP to identify every user uniquely, (*b*) *User authentication to only a trusted IdP*, i.e., the steps of authentication between a user and the RP are eliminated, and a user only needs to hold the secret credential to authenticate himself to an IdP, and (*c*) *Provision of IdP-confirmed user attributes*, i.e., a user maintains his attributes at the trusted IdP, and RP-requested attributes are provided after authorized by the user. Meanwhile, the privacy threats from different types

of adversaries are considered: (*a*) *an honest-but-curious IdP*, (*b*) *colluding RPs*, and (*c*) *the honest-but-curious IdP colluding with some RPs*. We analyze existing privacy-preserving solutions of SSO and also identity federation in Section 2.2.

We propose *identity transformations* for privacy-preserving SSO, and then design an Untraceable and Unlinkable Privacy-PREserving Single Sign-On (UPPRESSO) protocol. We design identity-transformation algorithms in the SSO login flow. In each login instance, ID_{RP} is transformed to an ephemeral PID_{RP} by a user and an RP. PID_{RP} is then sent to an IdP to transform ID_U into ephemeral PID_U, so an identity token binds PID_U and PID_{RP}, instead of permanent ID_U and ID_{RP}. Finally, on receiving an identity token with matching PID_{RP}, the RP transforms PID_U into an account. Given a user, this account is identical across multiple login instances for an RP but unique at each RP.

UPPRESSO prevents the IdP-based login tracing as only PID_{RP} is sent in identity-token requests, and the RP-based identity linkage for every user account is unique (see Section 5 for details). On the contrary, existing privacy-preserving SSO solutions [25, 26, 31, 55] prevent only one of the two privacy threats. The identity transformations work compatibly with widely-used SSO protocols [31, 36, 37, 53], so the above desirable features of SSO services are well kept in UPPRESSO, while not all these features are supported in privacy-preserving identity federation [17, 21, 38, 43, 51, 73]. Our contributions are as follows.

- An identity-transformation approach is proposed for privacy-preserving SSO services, and we design identity-transformation algorithms with desirable properties.
- The UPPRESSO protocol is proposed based on the identity transformations, with several designs specific for web applications. We prove that UPPRESSO satisfies the security and privacy requirements of SSO services.
- We build the UPPRESSO prototype for web applications, on top of an open-source OIDC implementation. The experimental performance evaluations show that UPPRESSO introduces reasonable overheads.

Section 2 presents the background and related works. The identity-transformation framework is described in Section 3, and Section 4 presents the detailed designs. Security and privacy are analyzed in Section 5. We explain the prototype implementation and evaluations in Section 6, and discuss extended issues in Section 7. Section 8 concludes this work.

2 Background and Related Works

We introduce typical SSO login flows, and discuss existing privacy-preserving solutions and other related works.

2.1 OpenID Connect and SSO Services

OIDC is one of the most popular SSO protocols. Users and RPs initially register at an IdP with their identities and other

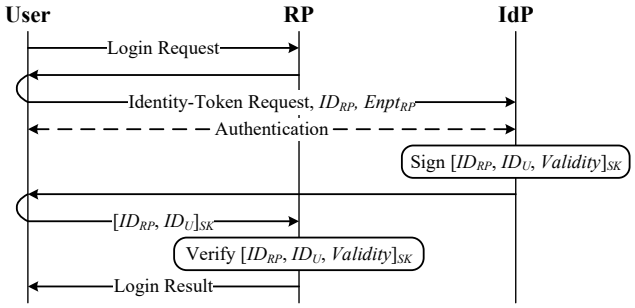


Figure 1: The implicit SSO login flow of OIDC

information such as user credentials (e.g., passwords) and RP endpoints (i.e., the URLs to receive tokens). It supports three types of login flows, i.e., implicit flow, authorization code flow, and hybrid flow (a mix-up of the other two). They work with different steps to request/receive identity tokens, but share the common security requirements of identity tokens. Next, we focus on the implicit flow to present our designs. Section 7 discusses the supports for the authorization code flow.

As shown in Figure 1, when a user initiates a login request to an RP, the RP constructs an identity-token request with its own identity and the scope of the requested user attributes. This request is redirected to a trusted IdP. After authenticating the user, the IdP issues an identity token that will be forwarded by the user to the RP's endpoint. The token contains the identities (or pseudo-identities) of user and RP, a validity period, the requested user attributes, etc. Finally, the RP verifies the received identity token and allows the user to login as the enclosed (pseudo-)identity. The user's operations including redirection, authorization, and forwarding, are implemented in user agents (e.g., a browser for web applications).

Three features are desired in SSO, supported by popular SSO systems [31, 35–37, 53].

User identification at an RP. An RP recognizes each user, as an identity or account *unique* at the RP, to provide customized services across multiple login instances.

User authentication to *only* an IdP. The authentication between a user and an IdP is usually conducted *independently* of the steps of widely-used SSO protocols [36, 37, 53], where RPs verify only the tokens issued by the IdP. This brings advantages. First, the IdP authenticates users by any appropriate means (e.g., password, one-time password, or multi-factor authentication). Meanwhile, a user only maintains his credential at the IdP. If it is lost or leaked, the user only renews it at the IdP. However, if a user proves some *non-ephemeral secret* to RPs, which is valid across multiple login instances (i.e., authentication steps are actually involved), he has to notify each RP when lost or leaked, or additional revocation checking is needed [38, 73].

Selective IdP-confirmed attribute provision. An IdP usually provides user attributes in tokens [36, 53], in addition to user (pseudo-)identities. These attributes are maintained by

Table 1: Privacy-Preserving Solutions of SSO and Identity Federation

Solution	**SSO Feature** - supported ●, unsupported ○, or partially ◐			**Privacy Threat** - prevented ●, or not ○		
	User Identity at an RP	User Authentication to Only an IdP	IdP-Confirmed Selective Attribute Provision	IdP-based Login Tracing	RP-based Identity Linkage	Collusive Attack by the IdP and RPs
OIDC w/ PPID [31]	●	●	●	○	●	-
BrowserID [25]	●	●[1]	○	●	○	-
SPRESSO [26]	●	●	◐[2]	●	○	-
PRIMA [3]	●	○	●	●	○	-
PseudoID [17]	●	○	◐[3]	●	●	●
EL PASSO [73]	●	○	●	●	●	●
UnlimitID [38]	●	○	●	●	●	●
Opaak [43]	◐[4]	○	○	●	●	●
Fabric Idemix [21]	○[5]	○	●	●	●	●
U-Prove [51]	●	○	◐[6]	●	●	●
UPPRESSO	●	●	●	●	●	○

1. A BrowserID user generates an *ephemeral* private key to sign the "subsidiary" token, which is also verified by the RP.
2. SPRESSO can be extended to provide user attributes in the tokens, while the prototype does not implement this feature.
3. Blindly-signed user attributes can be selectively provided using zero-knowledge proofs, but not implemented in the prototype.
4. Opaak supports two exclusive pseudonym options: (*a*) linkable within an RP but unlinkable across multiple RPs and (*b*) unlinkability for any pair of actions.
5. In the original design of Idemix [8], every user logins to an RP with a unique account, but Fabric Idemix implements completely-anonymous services.
6. A U-Prove token may contain some attributes *invisible* to the IdP, in addition the ones confirmed by the IdP.

users at a trusted IdP. The IdP obtains a user's authorization before enclosing any attributes in a token, or provides only attributes pre-selected by the user.

2.2 Privacy-Preserving SSO and Identity Federation

Table 1 summarizes existing privacy-preserving solutions for SSO and identity federation. Widely-adopted SSO protocols [35–37, 53] allow a user to login to an RP *without holding any permanent secret verified by the RP or by himself maintaining an account at the RP*. While providing these convenience features, existing privacy-preserving SSO approaches [25, 26, 31] prevent either the IdP-based login tracing or the RP-based identity linkage, and UPPRESSO prevents both of them.

Identity federation enables a user registered at a trusted IdP to be accepted by other parties, with different accounts sometimes, but *more user operations* are involved than those in SSO. Privacy-preserving identity federation protects user privacy against even collusive attacks by the IdP and RPs, but requires a user [17, 21, 38, 43, 51, 73] to (*a*) hold long-term secrets verified by RPs, in addition to the authentication credential for the IdP, and (*b*) locally manage the accounts at different RPs. That is, there are actually some authentication steps between a user and RPs (called asynchronous authentication [73]).

Pairwise pseudonymous identifiers (PPIDs) are specified in SSO protocols [35, 53] and recommended [31] to protect user privacy against curious RPs. When issuing an identity token, an IdP encloses a user PPID (but not the identity at the IdP). Given a user, the IdP assigns a unique PPID based on the target RP, so colluding RPs cannot link the user's identities (or accounts). PPIDs cannot prevent the IdP-based login tracing because the IdP needs the RP's identity to assign PPIDs.

Several solutions prevent the IdP-based login tracing but are vulnerable to the RP-based identity linkage. In BrowserID [25] (formerly known as Firefox Accounts [55] and Mozilla Persona [48]), an IdP issues a special token (called user certificate) to bind a user identity to an ephemeral public key. With the corresponding private key, the user signs a "subsidiary" token (called identity assertion) to bind a target RP's identity and sends both tokens to the RP. In SPRESSO [26] an RP creates a verifiable one-time pseudo-identity for itself in each login instance, which is enclosed in the identity token issued by an IdP. A PRIMA IdP signs a credential binding a verification key and user attributes [3], where the key is considered as a user's identity. Then, the user selectively provides IdP-confirmed attributes to an RP using his signing key [58]. In these schemes [3, 25, 26], colluding RPs could link a user based on his unique identity in the tokens (or credentials).

PseudoID [17] introduces another independent service in addition to an IdP to *blindly* sign [12] an access token binding a pseudonym and a user secret. Then, the user unblinds this token and the IdP will assert it, which allows the user to login to an RP using his secret. Two kinds of privacy threats are prevented, because (*a*) the RP's identity is not enclosed in the tokens and (*b*) the user selects different pseudonyms when visiting RPs. Collusive attacks by the IdP and RPs are also prevented, for they cannot link two blindly-signed tokens.

In EL PASSO [73], after authenticating a user, an IdP signs an *anonymous credential* [11] binding a secret, both of which are securely kept on the user's device. When attempting to login to an RP, the user proves that he is the owner of this credential using the secret, and discloses selective attributes in the credential. Although one credential is proved to multiple RPs, *user-managed pseudonyms* and *anonymous credentials* prevent the RPs, even when collusive with the IdP, from link-

ing the users across the RPs. UnlimitID [38] presents similar designs based on anonymous credentials [11], to prevent collusive attacks by the IdP and RPs. NEXTLEAP [32] builds anonymous messaging on top of UnlimitID.

Anonymous credentials [9, 11] are used in flexible ways. Opaak [43] designs IdP-signed anonymous credentials as pseudonym tokens, which bind a user's secret key. Idemix anonymous credentials [8] are integrated in Hyperledger Fabric [21] to implement completely-unlinkable pseudonyms and IdP-confirmed selective attribute disclosure. With a U-Prove token [49, 51] from an IdP, a user is enabled to authenticate himself to an RP and selectively disclose attributes.

2.3 Related Works

Anonymous Token. PrivacyPass and TrustToken allow a user to receive tokens [15, 69], each of which is denoted as (T, T^k), where k is the token server's private key. These tokens are used to access resources anonymously. To unlink token signing and redemption, a user generates a random number e for each token, blinds T into T^e, and sends it to request (T^e, T^{ek}) from the token server. The user then utilizes e to obtain T^k from T^{ek}, and then only (T, T^k) is redeemed to access resources. This cryptographic skill [39] is adopted in UPPRESSO similarly: a user transforms ID_{RP} to $PID_{RP} = [t]ID_{RP}$ by a random number t, and PID_{RP} is transformed again by an IdP to $[tu]ID_{RP}$. The visited RP calculates $Acct = [u]ID_{RP}$ from $[tu]ID_{RP}$ by using t (see Table 3 for detailed descriptions of these notations).

UPPRESSO differs from PrivacyPass and TrustToken as below. Firstly, PrivacyPass and TrustToken work as anonymous SSO to some extent, where one consistent private key serves all users, but UPPRESSO identifies each user at an RP. Secondly, the above cryptographic skill [39] is differently utilized. UPPRESSO integrates it to transform identities in SSO: scalar u is known by the IdP and a user as his user identity, and random number t is shared by the user and the RP. Meanwhile, exponent k is held only by the PrivacyPass/TrustToken server as a private key, and random number e is only known to a user. Lastly and most importantly, more privacy requirements are satisfied in UPPRESSO. The unlinkability between token signing and redemption [15, 69], or (T^e, T^{ek}) and (T, T^k), roughly corresponds to only the IdP-untraceability in UPPRESSO: an IdP cannot link any pair among $[t_i]ID_{RP}$ and ID_{RP}, $i = 1, 2, \cdots$. UPPRESSO also supports the unlinkability across RPs: given multiple users, e.g., identified as u and u', $(ID_{RP}, t, [u]ID_{RP})$ and $(ID_{RP'}, t', [u']ID_{RP'})$ are indistinguishable to colluding RPs. This property of the adopted cryptographic skill is not considered in anonymous tokens [15, 69] or oblivious pseudorandom functions (OPRFs) [39].

Anonymous SSO. Such schemes allow authenticated users to access a service protected by an IdP, without revealing their identities. Anonymous SSO was proposed for GSM communications [20], and formalized [66]. Privacy-preserving primitives, such as group signature, zero-knowledge proof, Chebyshev Chaotic Maps and proxy re-verification, were adopted to design anonymous SSO [33, 34, 40, 66]. Anonymous SSO schemes work for some special applications, but are unapplicable in most systems that require user identification for customized services.

Privacy-Preserving Credential. ZKlaims [54] allows users to prove statements on the credentials issued by a server using zero-knowledge proofs, but the credential contents are not revealed. Crypto-Book [44] coordinates servers to generate a ring-signature private key, and a user picks up his key through a list of Email addresses. Then the key pair works as an untraceable pseudonym. Two-party threshold schemes are implemented with a central server, to protect a user's private keys [6, 7]: to sign/decrypt a message, a user needs a token from the server. Tandem [42] decouples the obtaining and using of such tokens, for the privacy of key usage.

Formal Analysis on SSO Protocols. Fett et al. [27, 28] formally analyzed OAuth 2.0 and OIDC using a Dolev-Yao style model [24], and presented the attacks of 307 redirection and IdP mix-up. SAML-based SSO was analyzed [2], and it is found that RP identities were not correctly bound in the identity tokens of a variant designed by Google.

SSO Implementation Vulnerabilities. Vulnerabilities were found in SSO implementations for web applications, resulting in effective attacks by breaking confidentiality [1, 4, 41, 60, 67], integrity [41, 45, 46, 59, 64, 67] or RP designation [41, 45, 46, 64, 70] of identity tokens. Integrity of identity tokens was violated in SSO systems due to software flaws such as defective verification by RPs [46, 64, 67], XML signature wrapping [59], and IdP spoofing [45, 46]. RP designation is broken for incorrect binding by an IdP [64, 70] or insufficient verification by RPs [45, 46, 70].

Automatic tools such as SSOScan [74], OAuthTester [72] and S3KVetter [70], detect the violations of confidentiality, integrity, or RP designation of SSO identity tokens. Wang et al. [68] detect the vulnerable applications built with authentication/authorization SDKs, due to the implicit assumptions of these SDKs. Navas et al. [50] discussed the possible attack patterns against OIDC services.

In a mobile system, browsers, IdP Apps, or IdP-provided SDKs are responsible for forwarding identity tokens, but none of them ensures an identity token is sent to the designated RP only [14, 65]. Vulnerabilities were found in Android Apps, to break confidentiality [14, 57, 65, 71], integrity [14, 71], and RP designation [14, 57] of identity tokens. A flaw was found in Google Apps [1], allowing a malicious RP to hijack a user's authentication attempt and inject a payload to steal the cookie or identity token belonging to another RP.

If a user is compromised, attackers will login to RPs on behalf of him. Single sign-off helps the victim user to revoke all his tokens accepted and logout from the RPs [29]. FedCM [23] attempts to disable iframe and third-party cookies in SSO, which might be exploited to track users.

Table 2: The (pseudo-)identities in privacy-preserving SSO

Notation	Description	Lifecycle
ID_U	The user's unique identity at the IdP.	Permanent
ID_{RP_j}	The j-th RP's unique identity at the IdP.	Permanent
$PID^i_{U,j}$	The user's pseudo-identity, in the user's i-th login instance to the j-th RP.	Ephemeral
$PID^i_{RP_j}$	The j-th RP's pseudo-identity, in the user's i-th login instance to this RP.	Ephemeral
$Acct_j$	The user's identity (or account) at the j-th RP.	Permanent

3 The Identity-Transformation Framework

We discuss the security requirements of privacy-preserving SSO, and present the identity-transformation framework.

3.1 Security Requirements of SSO

The primary goal of non-anonymous SSO services [31, 35–37, 53] is to ensure that a *legitimate* user is able to login to an *honest* RP as his permanent account at this RP, by presenting *identity tokens* issued by a *trusted* IdP.

To achieve this goal, an identity token issued by a trusted IdP [31, 35–37, 53] specifies (*a*) the RP to which the user requests to login (i.e., *RP designation*) and (*b*) the user who is authenticated by the IdP (i.e., *user identification*). Therefore, an honest RP compares the designated RP identity (or pseudo-identity) in identity tokens with its own before accepting the tokens; otherwise, a malicious RP could replay a received identity token to some honest RP and login as the victim user. The RP allows the token holder to login as the user (pseudo-)identity specified in an accepted token.

The SSO login flow also requires *confidentiality* and *integrity* of identity tokens. An identity token should be forwarded by the authenticated user to the target RP only, not leaked to any other parties; otherwise, an eavesdropper who presents the token, would successfully login to the designated RP. Integrity is also necessary to prevent adversaries from tampering with a token. So identity tokens are usually signed by a trusted IdP and transmitted over HTTPS [36, 37, 53].

The security requirements (i.e., RP designation, user identification, confidentiality, and integrity) of SSO identity tokens are well analyzed [2, 27, 28], and vulnerabilities breaking any of the properties result in attacks [1, 4, 10, 14, 41, 45, 46, 56, 57, 59, 60, 64, 65, 67, 70–72, 74].

3.2 Identity Transformation

We aim to design a privacy-preserving SSO system with the four security properties as above, while preventing both the IdP-based login tracing and the RP-based identity linkage. In UPPRESSO these requirements are satisfied through *transformed identities* in the identity tokens. Table 2 lists the notations in the following explanations, and the subscript j and/or the superscript i may be omitted when there is no ambiguity.

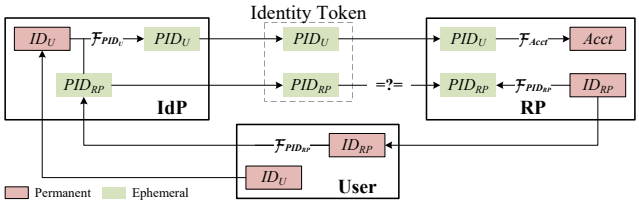


Figure 2: Identity transformations in privacy-preserving SSO

In an SSO login flow, a user firstly negotiates *ephemeral* PID_{RP} with a target RP, and sends an identity-token request enclosing PID_{RP} to an IdP. After authenticating the user as ID_U, the IdP calculates *ephemeral* PID_U based on ID_U and PID_{RP}, and issues an identity token binding PID_U and PID_{RP}. On receiving a token with matching PID_{RP}, the RP calculates *permanent* $Acct$ and allows the token holder to login as $Acct$. The relationship among (pseudo-)identities is illustrated in Figure 2. The *red* and *green* blocks represent *permanent* and *ephemeral* (pseudo-)identities, respectively. The labeled arrows denote the transformations of (pseudo-)identities.

To ensure RP designation, PID_{RP} should be *uniquely* associated with the target RP. To ensure user identification, an *ephemeral* PID^i_U in each login instance should enable the RP to derive a *permanent* account (i.e., $Acct$) at this RP.

To prevent the IdP-based login tracing, the IdP does not obtain any information about ID_{RP} from any PID^i_{RP}, thus, in multiple login instances to a given RP, (*a*) PID^i_{RP} should be independent of each other,[1] and (*b*) PID^i_U should be independent of each other.[2] To prevent the RP-based identity linkage, the RP does not obtain any information about ID_U from any $PID_{U,j}$, which implies $PID_{U,j}$ for different RPs should be independent of each other.

The following identity transformations are needed:

- $\mathcal{F}_{PID_{RP}}(ID_{RP}) = PID_{RP}$, calculated by the user and the RP. From the IdP's view, $\mathcal{F}_{PID_{RP}}()$ is a one-way function and PID_{RP} is *indistinguishable* from random variables.
- $\mathcal{F}_{PID_U}(ID_U, PID_{RP}) = PID_U$, calculated by the IdP. From the target RP's view, $\mathcal{F}_{PID_U}()$ is a one-way function and PID_U is *indistinguishable* from random variables.
- $\mathcal{F}_{Acct}(PID_U, PID_{RP}) = Acct$, calculated by the RP. Given ID_U and ID_{RP}, $Acct$ is *permanent* and *unique* to other accounts at this RP. In a user's any i-th and i'-th ($i \neq i'$) login instances to the RP, $\mathcal{F}_{Acct}(PID^i_U, PID^i_{RP}) = \mathcal{F}_{Acct}(PID^{i'}_U, PID^{i'}_{RP})$.

4 The Designs of UPPRESSO

This section gives the threat model and assumptions, followed by the identity-transformation algorithms and the protocols.

[1] Even when the target RP is kept unknown to the IdP, the IdP should not link multiple login instances to this RP.

[2] If PID^i_U is not completely independent of each other, it implies the IdP could link multiple login instances to a given RP.

4.1 Threat Model

The system consists of an honest-but-curious IdP, a number of RPs and users which could be compromised. This model is consistent with the widely-used SSO services [31, 35–37, 53].

Honest-but-curious IdP. An IdP follows the protocols strictly, while being interested in learning user profiles. For example, it might store all received messages to infer the relationship among ID_U, ID_{RP}, PID_U, and PID_{RP}. It never actively violates the protocols, so a script downloaded from the IdP also strictly follows the protocols (see Section 4.4 about the specific designs for web applications). The IdP maintains the private key well for signing identity tokens and RP certificates, so adversaries cannot forge such tokens or certificates.

Malicious Users. Adversaries could control a set of users, by stealing users' credentials or registering Sybil users in the system. They want to impersonate a victim user at honest RPs, or allure an honest user to login to an honest RP under another user's account. A malicious user might modify, insert, drop or replay messages, or behave arbitrarily in login flows.

Malicious RPs. Adversaries could control a set of RPs, by registering at the IdP as an RP or exploiting vulnerabilities to compromise some RPs. Malicious RPs might behave arbitrarily to break the security and privacy guarantees; e.g., manipulate PID_{RP} in a login instance, attempting to (a) allure honest users to return an identity token that might be accepted by some honest RP, or (b) influence the generation of PID_U to analyze the relationship between ID_U and PID_U.

Colluding Users and RPs. Malicious users and RPs might collude, attempting to break the security and privacy guarantees for honest users. For example, a malicious RP might collude with malicious users to steal another user's identity token, to impersonate the victim user at some honest RP.

Finally, we do *not* consider the collusion of the IdP and RPs. If the IdP could collude with some RPs, a user will finish login flows completely with colluding entities and then in principle we need a long-term user secret to protect (or transform) the permanent accounts across these RPs. This secret is held *only* by the user; otherwise, the colluding IdP and RPs could always link these accounts. However, such accounts derived from the user secret have to be updated, if it is lost or leaked (see discussions in Section 7).

4.2 Assumptions

HTTPS is adopted to secure the communications between honest entities, and the adopted cryptographic primitives are secure. The software stack of an honest entity is correctly implemented, to transmit messages to receivers as expected.

UPPRESSO is designed for users who care about privacy, so a user never authorizes the IdP to enclose any *distinctive* attributes in identity tokens, such as telephone number, Email address, etc. A user does not configure distinctive attributes at any RP, either. So the privacy leakage due to re-identification by distinctive attributes across RPs, is out of our scope.

Table 3: The notations in the UPPRESSO protocols

Notation	Description
$\mathbb{E}$, G, n	$\mathbb{E}$ is an elliptic curve over a finite field $\mathbb{F}_q$. G is a base point (or generator) of $\mathbb{E}$, and the order of G is a prime number n.
ID_U	$ID_U = u \in [1,n)$, is the user's unique identity at the IdP; u is kept unknown to RPs.
ID_{RP_j}	$ID_{RP} = [r]G$, is the j-th RP's unique identity, publicly known; $r \in [1,n)$, is known to only the IdP.
t	$t \in [1,n)$, is a user-generated random integer in a login instance; t is kept secret to the IdP.
$PID^i_{RP_j}$	$PID_{RP} = [t]ID_{RP} = [tr]G$; the j-th RP's pseudo-identity, in the user's i-th login instance to this RP.
$PID^i_{U,j}$	$PID_U = [ID_U]PID_{RP} = [utr]G$; the user's pseudo-identity, in the user's i-th login instance to the j-th RP.
$Acct_j$	$Acct = [t^{-1} \bmod n]PID_U = [ID_U]ID_{RP} = [ur]G$; the user's account at the j-th RP.
SK, PK	The IdP's key pair, a private key and a public key, to sign and verify identity tokens and RP certificates.
$Enpt_{RP_j}$	The j-th RP's endpoint, to receive the identity tokens.
$Cert_{RP_j}$	A signed RP certificate binding ID_{RP_j} and $Enpt_{RP_j}$.

We focus on the privacy threats introduced by SSO protocols. The traffic analysis tracking a user's activities from network packets and the active account linkage through malicious web pages, exist in SSO scenarios but also in other web systems. If a user visits multiple RPs concurrently from one browser, a malicious RP might actively redirect his account to another RP server by crafted web pages. Such attacks are prevented by other defenses, not considered in our work.

4.3 Identity-Transformation Algorithms

We design identity-transformation algorithms, on an elliptic curve $\mathbb{E}$. Table 3 lists the notations, and the subscript j and/or the superscript i may be omitted in the case of no ambiguity.

For a user, a unique random integer u is assigned by the IdP (i.e., $ID_U = u$). When an RP is registering, the IdP generates a random number r, and $ID_{RP} = [r]G$, a unique point on $\mathbb{E}$, is assigned. Here, $[r]G$ is the addition of G on the curve r times.

ID_{RP}-PID_{RP} Transformation. A user selects a random number t ($1 \le t < n$) as the trapdoor and calculates PID_{RP}.

$$PID_{RP} = \mathcal{F}_{PID_{RP}}(ID_{RP}) = [t]ID_{RP} = [tr]G \quad (1)$$

ID_U-PID_U Transformation. On receiving an identity-token request with ID_U and PID_{RP}, the IdP calculates PID_U.

$$PID_U = \mathcal{F}_{PID_U}(ID_U, PID_{RP}) = [ID_U]PID_{RP} = [utr]G \quad (2)$$

PID_U-$Acct$ Transformation. The trapdoor t is sent to the target RP, which checks that PID_{RP} in identity tokens is equal to $[t]ID_{RP}$. After verifying a token binding PID_U and PID_{RP}, it calculates $Acct$ as below.

$$Acct = \mathcal{F}_{Acct}(PID_U) = [t^{-1} \bmod n]PID_U \quad (3)$$

From Equations 1, 2 and 3, it is derived that

$$Acct = [t^{-1}utr \bmod n]G = [ur]G = [ID_U]ID_{RP}$$

The RP derives an *identical permanent* account from the identity tokens in different login instances, with the help of t. Given a user, the accounts at different RPs are inherently unique; while, given an RP, the accounts of different users are also unique. It is impossible for the RP to derive ID_U from either PID_U or $Acct$ due to the elliptic curve discrete logarithm problem (ECDLP). Because t is random in $\mathbb{Z}_n$ and unknown to the IdP, from the IdP's view, PID_{RP} is indistinguishable from a random variable on $\mathbb{E}$, and the IdP learns nothing about ID_{RP} from PID_{RP}.

Note that r is kept secret to the RP; otherwise, two colluding RPs with $ID_{RP_j} = [r]G$ and $ID_{RP_{j'}} = [r']G$ could link a user's accounts by checking whether $[r']Acct_j = [r]Acct_{j'}$ or not.

$PID_{RP} = [t]ID_{RP}$ is negotiated between a user and an RP, while t is a random number known only to them. The user and the RP need to calculate PID_{RP} independently; or, more exactly, one computes $PID_{RP} = [t]ID_{RP}$, and the other checks if PID_{RP} is equal to $[t]ID_{RP}$ or not. In the above descriptions, the user generates t, calculates $PID_{RP} = [t]ID_{RP}$ and sends t to the RP. After receiving t from the user and extracting PID_{RP} from a token, the RP checks that $PID_{RP} = [t]ID_{RP}$, because the correct account $[ID_U]ID_{RP}$ is derived *only if* this equation holds (i.e., $PID_{RP} = [t]ID_{RP}$); otherwise, attacks happen as below. To login as any $Acct$, a malicious user with $ID_{U'} = u'$ might generate a random number t', and calculate $[t'u'^{-1}]Acct$ as PID_{RP} to request an identity token. Then, the IdP will calculate $PID_{U'} = [u'][t'u'^{-1}]Acct = [t']Acct$. Without checking $PID_{RP} = [t']ID_{RP}$ or not, the RP will finally allow the malicious user to login as $[t'^{-1}]PID_{U'} = Acct$.

Meanwhile, if the RP generates t, calculates PID_{RP} and sends t, the user still needs to by himself check that $PID_{RP} = [t]ID_{RP}$; otherwise, attacks happen as below. A malicious user U' initiates a login request to an honest RP, and receives PID_{RP} from this RP. Then U' colludes with a malicious RP denoted as RP', which intentionally sends PID_{RP} to an honest user U in some login instance. Without checking $PID_{RP} = [t']ID_{RP'}$ or not, this honest user will present a token binding PID_U and PID_{RP} to RP'. Finally, this token enables malicious U' to login as the honest user's account at the honest RP.

4.4 The Designs Specific for Web Applications

UPPRESSO works with commercial-off-the-shelf (COTS) browsers as the SSO user agent. First of all, in UPPRESSO an IdP is not aware of visited RPs, so user agents (or browsers) have to deal with the forwarding of an identity token to the target RP, as well as the calculation of PID_{RP}. On the contrary, in commonly-used SSO protocols [35–37, 53] an IdP needs this information to ensure *confidentiality* of identity tokens. For instance, in the OIDC services, when an RP registers itself at the IdP, the `redirect_uri` parameter is set as its endpoint URL to receive tokens [53]. When the IdP is transmitting identity tokens to an RP, it utilizes HTTP 302 redirection with this endpoint as the target URL in HTTP responses, so a browser forwards it to the designated RP.

In UPPRESSO such user-agent functions are implemented by web scripts in COTS browsers, and the scripts downloaded from an honest entity are also *honest*. Two scripts are from the visited RP and the IdP respectively, and each is responsible for the communications with the origin web server. Only the RP script is not enough to implement a user agent; otherwise, the script will leak its origin to the IdP web server, because an HTTP request sent by the RP script automatically carries an HTTP `referer` header that discloses the RP's domain. Moreover, a trusted script from the honest IdP ensures confidentiality of identity tokens (i.e., a token is sent to only the designated RP) and interacts with users for attribute authorization, for the RP (and also the RP script) might be malicious. Thus, on receiving an identity-token request, the IdP checks the `referer` header to ensure it is sent by the IdP script.

The RP script prepares ID_{RP} and $Enpt_{RP}$ for the IdP script, through *RP certificates*. An RP certificate is signed by the IdP during the RP registration, binding the RP's identity and its endpoint. In a login instance the RP provides its certificate through the RP script, to the IdP script. The IdP script verifies the RP certificate to extract ID_{RP} and $Enpt_{RP}$. The IdP's public key is set in the IdP script, so a user does not configure anything locally, as it does in widely-adopted SSO systems [35–37, 53].

After receiving an identity token from the IdP, the IdP script needs to ensure the RP script will forward this token to $Enpt_{RP}$, which is bound along with ID_{RP} in the RP certificate. The scripts communicate with each other within the user browser through the `postMessage` HTML5 API, and the receiver (i.e., the RP script) is restricted by the `postMessage` targetOrigin mechanism [61]: when the IdP script sends messages, the receiver's origin is set as a parameter, e.g., `postMessage(tkn, 'https://RP.com')`. It consists of the protocol (i.e., `https`), the domain (i.e., `RP.com`) and a port which may be implicit. Only the script downloaded from this targetOrigin is a legitimate receiver.

As mentioned in Section 4.3, a user needs to calculate (or check) $PID_{RP} = [t]ID_{RP}$, so this function should be implemented by *honest* scripts. Thus, t is processed in the IdP script, to calculate PID_{RP} with ID_{RP} which is extracted from $Cert_{RP}$. Since $ID_{RP} = [t^{-1} \bmod n]PID_{RP}$, this design relies on an honest IdP that does not steal t, ID_{RP} or the RP's domain through malicious scripts, for any of them leaks the RP identity. This leakage risk may be mitigated by implementing a user agent with trusted browser extensions, but users need to install the extension before visiting RPs.

Finally, the browser downloads the RP script when visiting an RP, and this RP script opens a new window that downloads the IdP script. We should prevent referer leakages when the IdP script is downloaded. Generally, when a browser window visits another website not belonging to its opener's origin, the HTTP request to this website automatically carries a `referer` header (i.e., the opener's origin). Such an HTTP

header leaks the visited RP's domain to the IdP. Fortunately, in UPPRESSO this newly-opened window is a *redirection* from the RP to the IdP, but not a direct visit by browsers (Figure 3, Steps 1.2-1.3). This leakage is prevented by setting a `referrer-policy=no-referrer` header in the HTTP response from the RP, as it is redirected to the IdP. So the HTTP request to download the IdP script carries no `referer` header. This method is specified by W3C [19] and widely supported. We tested it in browsers such as Chrome, Safari, Edge, Opera and Firefox, and confirmed no referer leakage.

4.5 The UPPRESSO Protocols

System Initialization. An IdP generates a key pair (SK, PK) to sign/verify identity tokens and RP certificates. The IdP keeps SK secret, and PK is publicly known.

RP Initial Registration. Each RP registers itself at the IdP to obtain ID_{RP} and its RP certificate $Cert_{RP}$ as follows:

1. An RP sends a registration request, including the endpoint to receive identity tokens and other information.
2. The IdP randomly generates $r \in [1,n)$, until $ID_{RP} = [r]G$ is unique. It signs $Cert_{RP} = [ID_{RP}, Enpt_{RP}, *]_{SK}$, where $[\cdot]_{SK}$ is a message signed using SK and $*$ is supplementary information such as the RP's common name.
3. The RP verifies $Cert_{RP}$ using PK, and accepts ID_{RP} and $Cert_{RP}$ if they are valid.

User Registration. Each user registers once at the IdP to set up a unique random identity $ID_U = u \in [1,n)$ and the corresponding credential. ID_U is kept unknown to RPs.

SSO Login. A login instance consists of four steps, namely script downloading, RP identity transformation, identity-token generation, and *Acct* calculation, as shown in Figure 3. In this figure, the IdP's operations are linked by a vertical line, so are the RP's. Two vertical lines split the user operations into two groups (i.e., in two browser windows), one of which is to communicate with the IdP, and the other is with the target RP. Each solid horizontal line means some messages between the user and the IdP (or the RP), and each dotted line means a `postMessage` invocation between two scripts (or browser windows) within the browser.

1. *Script Downloading.* The browser downloads scripts from the visited RP and the IdP.
   - 1.1 When attempting to visit any protected resources at the RP, the user downloads the RP script.
   - 1.2 The RP script opens a window in the browser to visit the login path at the RP, which is then redirected to the IdP.
   - 1.3 The redirection to the IdP downloads the IdP script.

2. *RP Identity Transformation.* The user and the RP negotiate $PID_{RP} = [t]ID_{RP}$.
   - 2.1 The IdP script locally chooses a random number t in $\mathbb{Z}_n$, and sends it to the RP script through `postMessage`. The RP script forwards t to the RP.
   - 2.2 On receiving t, the RP verifies $1 \leq t < n$ and replies with $Cert_{RP}$, which is then transmitted from the RP script to the IdP script, with the scope of requested user attributes.
   - 2.3 The IdP script locally verifies $Cert_{RP}$, extracts ID_{RP} and $Enpt_{RP}$ from $Cert_{RP}$, and calculates $PID_{RP} = [t]ID_{RP}$.

3. *Identity-Token Generation.* The IdP calculates $PID_U = [ID_U]PID_{RP}$ and signs an identity token.
   - 3.1 The IdP script sends an identity-token request for PID_{RP} on behalf of the user.
   - 3.2 The IdP authenticates the user, if not authenticated yet.
   - 3.3 The IdP script obtains the user's authorization for each requested attribute, and sends the scope of authorized attributes. Then, the IdP calculates $PID_U = [ID_U]PID_{RP}$, and signs $[PID_{RP}, PID_U, Issuer, Validity, Attr]_{SK}$, where $Issuer$ is the IdP's identity, $Validity$ indicates the validity period, and $Attr$ contains the authorized user attributes.
   - 3.4 The IdP replies with the identity token, to the IdP script.

4. *Acct Calculation.* The RP receives the identity token and allows the user to login.
   - 4.1 The IdP script forwards the identity token to the RP script, which sends it to the RP through $Enpt_{RP}$.
   - 4.2 The RP verifies the identity token, including the IdP's signature and its validity period. Then, the RP extracts PID_{RP} from the token, checks that it is equal to $[t]ID_{RP}$, and calculates $Acct = [t^{-1}]PID_U$.
   - 4.3 The RP allows the user to login as $Acct$.

If any verification or checking fails, this flow will be halted immediately. For example, the user halts it on receiving invalid $Cert_{RP}$. The IdP rejects an identity-token request Step 3.3, if the received PID_{RP} is not a point on $\mathbb{E}$. Or, the RP rejects an identity token in Step 4.2, if the signature is invalid or PID_{RP} enclosed in it is not equal to $[t]ID_{RP}$.

4.6 Compatibility with OIDC

First of all, UPPRESSO and OIDC work with COTS browsers. Among the four steps of the login flow in UPPRESSO, *script downloading* prepares the user agent. The user agent is responsible for the communications between the IdP and the RP, which are implemented by HTTP redirections in OIDC. On the contrary, in UPPRESSO the scripts hide $Enpt_{RP}$ from the IdP and forward the identity token to $Enpt_{RP}$ extracted from the RP certificate, so the IdP does not set `redirect_uri` in the HTTP responses. Most operations of *RP identity transformation* are conducted within browsers, while the RP only receives t to prepare an RP pseudo-identity and responds with $Cert_{RP}$. The static $Cert_{RP}$ is viewed as a supplementary message to users. Thus, compared with the original OIDC protocol, in these two steps, the IdP's operations are simplified and an RP customizes its *dynamic* pseudo-identity.

The operations of *identity-token generation* and *Acct calculation*, are actually *identical* to those of OIDC, because (a)

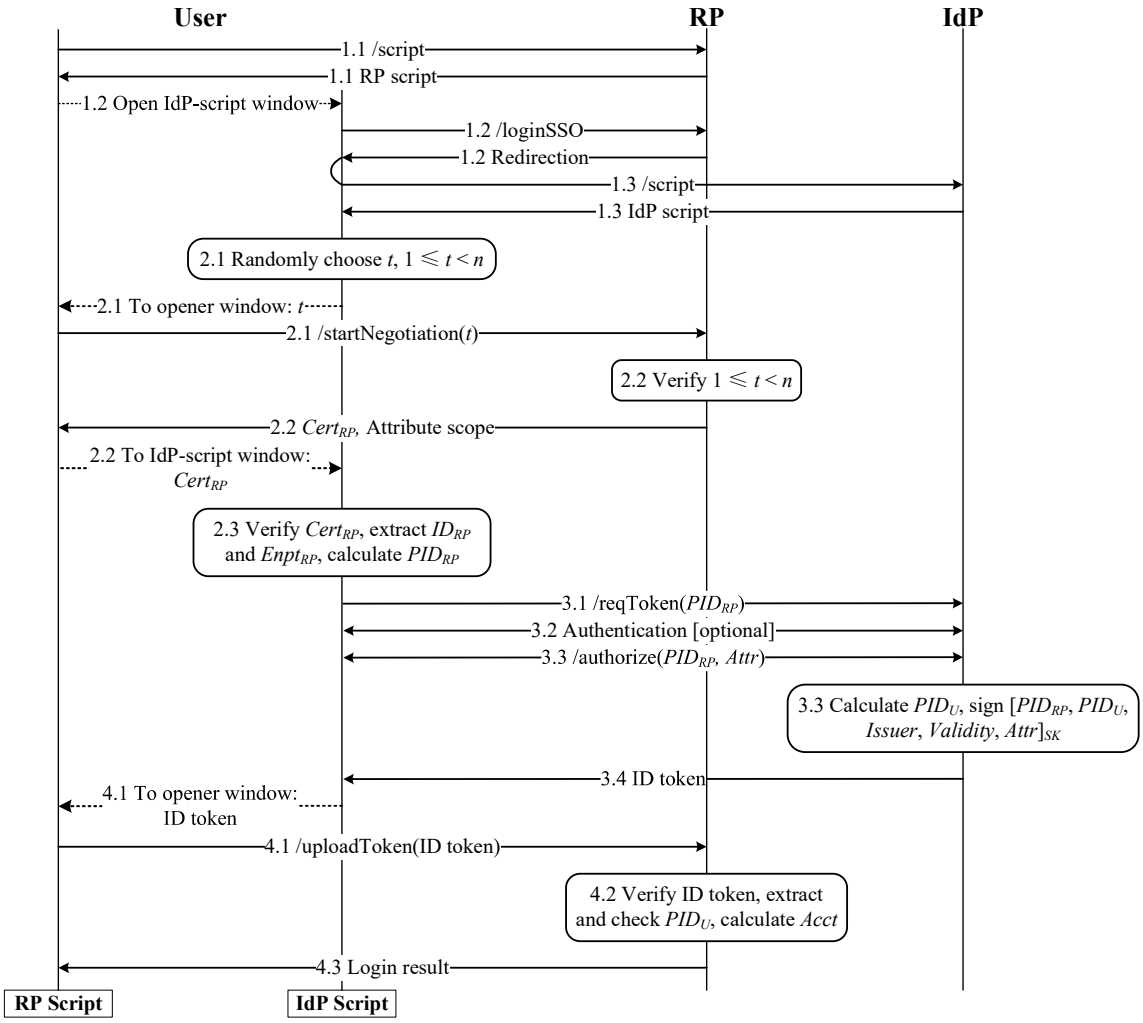


Figure 3: The SSO login flow of UPPRESSO

the calculation of PID_U is viewed as a method to generate PPIDs and (*b*) the calculation of *Acct* is viewed as a mapping from the user identity in tokens to an account at the RP.

Finally, this compatibility is experimentally confirmed by our prototype implementation: only 23 lines of Java code in MITREid Connect [52], an open-source OIDC system, are modified to build an IdP of UPPRESSO (see Section 6.1).

5 The Analysis of Security and Privacy

In this section, we present the analysis that UPPRESSO achieves the required properties of security and privacy.

5.1 Adversarial Model

Based on the threat model and assumptions in Section 4, different adversaries are considered as below. First of all, in the proofs of security, malicious RPs collude with malicious users to break any of the four security properties of SSO identity tokens for an honest user to visit an honest RP. Then, in the analysis of privacy against the IdP-based login tracing, an honest-but-curious IdP is the only adversary. Finally, in the privacy analysis against the RP-based identity linkage, a number of malicious RPs collude to link an honest user's accounts across these RPs.

We analyzed UPPRESSO based on a Dolev-Yao style model [26]. The model abstracts the entities in a web system, such as web servers and browsers, as *atomic processes*. It defines *script processes* to formulate client-side scripts. UPPRESSO contains atomic processes including: an IdP process, a finite set of web servers for honest RPs, a finite set of honest browsers, and a finite set of attacker processes. The processes communicate with each other through events such as HTTPS requests and responses. An RP or a browser controlled by adversaries is modeled as an attacker process. Within a browser, an honest IdP script, an honest RP script, and also attacker scripts which are downloaded from attacker processes, are invoked. Script processes communicate with each other through

`postMessage`, modelled as transmitted-to-itself events of a browser process.

After formulating the system by this model, we analyze the following data for the proofs in Sections 5.2 and 5.3, when there are corresponding adversaries. We (*a*) trace the lifecycle of an identity token for an honest user to visit an honest RP, starting when it is generated and ending when accepted by the RP, to ensure it is not leaked to adversaries, (*b*) locate all places where PID_U, PID_{RP} and other parameters enclosed in the token are processed, to ensure no adversary able to manipulate them, and (*c*) locate the places where PK is transmitted and used in the IdP script, to ensure no adversary tampering with it. These conclusions are necessary to prove security of the UPPRESSO protocols. Then, we ensure t is unaccessible to the honest-but-curious IdP, which is necessary for privacy against the IdP-based login tracing.

5.2 Security

UPPRESSO satisfies four security requirements of SSO identity tokens [2, 27, 28], as listed in Section 3.1.

RP Designation. Provided that r is known to only the IdP, the RP pseudo-identity $PID_{RP} = [t]ID_{RP}$ in the identity token designates the target RP with $ID_{RP} = [r]G$, and only this RP.

Proof. $PID_{RP} = [t]ID_{RP}$ in the the identity token is expected by the target RP, because t is also sent to this RP with ID_{RP} and this RP checks that PID_{RP} is equal to $[t]ID_{RP}$.

Based on the ECDLP we prove that, for adversaries, the probability of finding t and t' satisfying $[t]ID_{RP_j} = [t']ID_{RP_{j'}}$ is negligible, where RP_j and $RP_{j'}$ are any two RPs in the finite set of RPs (i.e., $ID_{RP_j} = [r_j]G$ and $ID_{RP_{j'}} = [r_{j'}]G$, while r_j and $r_{j'}$ are kept secret to adversaries). This negligible probability means $PID_{RP_j} = [t]ID_{RP_j}$ designates *only* the target RP with ID_{RP_j}.

Let $\mathbb{E}$ be an elliptic curve, G be a point on $\mathbb{E}$ of order n, and $Q = [x]G$ where x is a random integer in $\mathbb{Z}_n$. Given G and Q, the probability that a probabilistic polynomial time (PPT) algorithm calculates x (i.e., solves the ECDLP) is negligible. For any PPT algorithm $\mathcal{D}$ to calculate x, we define

$$\Pr\{\mathcal{D}(G,[x]G) = x\} = \varepsilon_c(k)$$

Here, $\Pr\{\}$ denotes the probability. So $\varepsilon_c(k)$ becomes negligible with the increasing security parameter k.

Assume a game $\mathcal{G}_c$ between an adversary and a challenger, to describe this PID_{RP}-collision attack: the adversary receives a finite set of RP identities from the challenger, denoted as $(ID_{RP_1}, ID_{RP_2}, ..., ID_{RP_m})$ where m is the amount of all RPs in the system, and then outputs (a,b,t,t'). If $[t]ID_{RP_a} = [t']ID_{RP_b}$, the adversary succeeds in this game. Note that m is a finite integer, and $m \ll 2^k$ as k increases. We define the probability that the adversary succeeds in this game as $\Pr_s$.

Figure 4 shows a PPT algorithm $\mathcal{D}_c^*$ based on this game, to solve the ECDLP. The input of $\mathcal{D}_c^*$ is in the form of (G, Q).

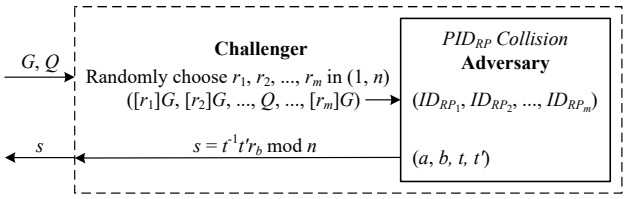


Figure 4: The algorithm based on the PID_{RP} collision, to solve the ECDLP

On receiving an input, the challenger of $\mathcal{G}_c$ randomly chooses $r_1, r_2, \cdots, r_m$ in $\mathbb{Z}_n$, calculates $[r_1]G, [r_2]G, \cdots, [r_m]G$, and randomly replaces some $[r_j]G$ with Q. Then, these m RP identities are sent to the adversary, which returns the result (a, b, t, t'). Finally, the challenger of $\mathcal{G}_c$ calculates $s = t^{-1}t'r_b \bmod n$ and returns s as the output of $\mathcal{D}_c^*$.

If $[r_a]G$ happens to be replaced with Q and the adversary of $\mathcal{G}_c$ succeeds, we find $Q = [s]G$ and then $s = x$ because $[tr_a]G = [t]Q = [t'r_b]G$. As $[r_j]G$ is randomly replaced by the challenger, Q and other RP identities in the input set are indistinguishable to the adversary. Thus,

$$\Pr\{\mathcal{D}_c^*(G,[x]G) = x\} = \Pr\{s = x\} = \Pr\{a = j\}\Pr_s = \frac{1}{m}\Pr_s$$

If the adversary is able to find t and t' satisfying that $[t]ID_{RP_j} = [t']ID_{RP_{j'}}$, it will have advantages in $\mathcal{G}_c$ and then $\Pr_s$ becomes non-negligible as k increases. Because m is a finite integer, $\Pr\{\mathcal{D}_c^*(G,[x]G) = x\} = \frac{1}{m}\Pr_s$ also becomes non-negligible with the increasing k. This violates the ECDLP assumption. Thus, the probability of finding t and t' satisfying that $[t]ID_{RP_j} = [t']ID_{RP_{j'}}$ in UPPRESSO is negligible, so this token binding PID_{RP} is expected by only the target RP. □

User Identification. In the identity token binding PID_U and PID_{RP}, the user pseudo-identity $PID_U = [ID_U]PID_{RP}$ identifies the authenticated user with ID_U, and only this user, at the target RP with $ID_{RP} = [r]G$.

Proof. PID_U in identity token identifies the authenticated user as $Acct = [ID_U][ID_{RP}]$ at the RP with ID_{RP} as follows. $PID_U = [ID_U]PID_{RP}$ is calculated by the IdP based on the user authenticated as $ID_U = u$, which is analyzed in the Dolev-Yao style model. In the meantime, the RP checks that $PID_{RP} = [t]ID_{RP}$ and calculates $Acct = [t^{-1}]PID_U = [t^{-1}][ID_U]PID_{RP} = [t^{-1}][ID_U][t]ID_{RP} = [ID_U]ID_{RP}$. Thus, given a user with ID_U, an RP with ID_{RP} always derives an identical account $[ID_U]ID_{RP}$ from different identity tokens.

$Acct = [ID_U]ID_{RP}$ identifies *only* this user. $\mathbb{E}$ is a finite cyclic group, and then $ID_{RP} = [r]G$ is also a generator of order n. Thus, given any RP, $[u]ID_{RP}$ assigns a *unique* account to the user, provided that $1 \le u < n$ and $ID_U = u$ is unique. □

Integrity. An honest RP accepts only identity tokens binding its pseudo-identity PID_{RP} and the authenticated user's pseudo-identity PID_U, and actually binding ID_{RP} and $Acct = [ID_U]ID_{RP}$, when SK is held by only the IdP.

Proof. A signed identity token binds $PID_{RP} = [t]ID_{RP}$ and $PID_U = [ID_U]PID_{RP}$, and any breaking results in some failed checking or verification in the login flow as below. First of all, the identity token is signed by the IdP and verified by the RP using PK, so any modification will be rejected. According to the proof of RP designation, PID_{RP} identifies only the RP with ID_{RP}; according to the proof of user identification, PID_U identifiers only the user with $Acct = [ID_U]ID_{RP}$ at the RP. Therefore, the identity token explicitly binding PID_U and PID_{RP}, matches *only* one ID_{RP} and *only* one $Acct = [t^{-1}]PID_U$. Thus, $Acct$ and ID_{RP} are actually bound in the token by the IdP's signatures, due to the one-to-one mapping between (a) the pair of $Acct$ and ID_{RP} and (b) the triad of PID_U, PID_{RP}, and t. □

Confidentiality. An identity token is accessible to only the authenticated user and the target RP, in addition to the IdP signing this token.

Proof. As analyzed in the Dolev-Yao style model, no event leaks an identity token to any malicious entity other than the authenticated user and the designated RP. First of all, the communications among the IdP, RPs and users, are protected by HTTPS, and the `postMessage` HTML5 API ensures the dedicated channels between two scripts within the browser, so no other entities can eavesdrop the identity tokens. Further, the IdP sends an identity token only to the authenticated user (i.e., the IdP script). The IdP script forwards the token to the RP script only if it is downloaded from the same origin as $Enpt_{RP}$, and the binding of $Enpt_{RP}$ and ID_{RP} is ensured by a verified RP certificate. So only the RP that owns $Enpt_{RP}$ and ID_{RP}, receives this token. □

5.3 Privacy

UPPRESSO effectively prevents the privacy threats of IdP-based login tracing and RP-based identity linkage.

The information accessible to the IdP and derived from the RP's identity, is only PID_{RP} in identity-token requests, where $PID_{RP} = [t]ID_{RP}$ is calculated by a user. So the prevention against the IdP-based login tracing in UPPRESSO is expressed formally as below.

Privacy against the IdP. If t is random in $\mathbb{Z}_n$ and unknown to the IdP, the IdP cannot infer any information about ID_{RP} or link any pair of PID^i_{RP} and $PID^{i'}_{RP}$ ($i \neq i'$), from an honest user's identity-token requests for PID^i_{RP} ($i = 1, 2, \cdots$).

Proof. Because (a) $ID_{RP} = [r]G$ is also a generator of order n, where G is a generator of finite cyclic group $\mathbb{E}$, and (b) t is a random number in $\mathbb{Z}_n$ and kept unknown to the IdP, from the IdP's view, PID_{RP} is *indistinguishable* from a random variable on $\mathbb{E}$. Thus, the IdP cannot infer any information about ID_{RP} from $PID_{RP} = [t]ID_{RP}$, or distinguish $[t]ID_{RP_j} = [tr]G$ from any other $[t']ID_{RP_{j'}} = [t'r']G$. So the IdP-based login tracing is impossible. □

In every login instance, without knowing u and r, an RP holds ID_{RP} and $Acct$, receives t, calculates PID_{RP}, and verifies PID_{RP} and PID_U in the identity token. After filtering out the redundant information (i.e., $PID_{RP} = [t]ID_{RP}$ and $Acct = [t^{-1}]PID_U$), the RP actually receives $(ID_{RP}, t, Acct) = ([r]G, t, [ur]G)$. So the prevention against the RP-based identity linkage in UPPRESSO is expressed as follows.

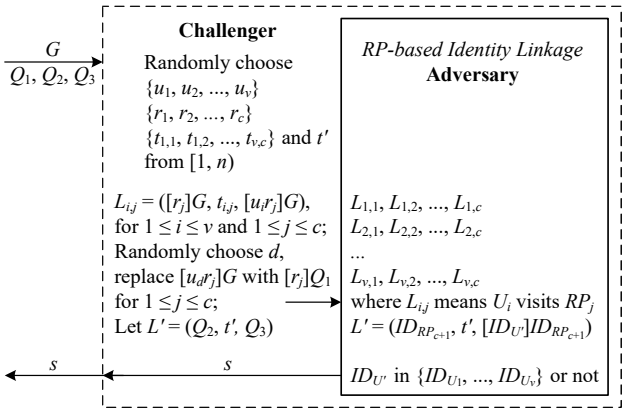


Figure 5: The algorithm based on the RP-based identity linkage, to solve the ECDDH problem

Privacy against Colluding RPs. Provided that u and r are kept unknown to RPs, based on the collected information of login instances by v users, c colluding RPs cannot decide whether a login instance to another RP is initiated by one of these v users or not, where the collected login instances are denoted as $\mathfrak{L} = \begin{Bmatrix} L_{1,1}, & L_{1,2}, & \cdots, & L_{1,c} \\ L_{2,1}, & L_{2,2}, & \cdots, & L_{2,c} \\ \cdots, & \cdots, & \cdots, & \cdots \\ L_{v,1}, & L_{v,2}, & \cdots, & L_{v,c} \end{Bmatrix}$, $L_{i,j} = (ID_{RP_j}, t_{i,j}, [ID_{U_i}]ID_{RP_j}) = ([r_j]G, t_{i,j}, [u_i r_j]G)$, and the login instance to RP_{c+1} is $L' = (ID_{RP_{c+1}}, t', [ID_{U'}]ID_{RP_{c+1}}) = ([r_{c+1}]G, t', [u' r_{c+1}]G)$.

Proof. We prove this privacy property, based on the elliptic curve decisional Diffie-Hellman (ECDDH) assumption. Let $\mathbb{E}$ be an elliptic curve, and G be a point on $\mathbb{E}$ of order n. For any PPT algorithm $\mathcal{D}$, the probability of distinguishing $([x]G, [y]G, [xy]G)$ and $([x]G, [y]G, [z]G)$ is negligible, where x, y and z are integers randomly and independently chosen in $\mathbb{Z}_n$. Let $\Pr\{\}$ denote the probability and we define

$$\Pr_1 = \Pr\{\mathcal{D}(G, [x]G, [y]G, [xy]G) = 1\}$$
$$\Pr_2 = \Pr\{\mathcal{D}(G, [x]G, [y]G, [z]G) = 1\}$$

So $\varepsilon_r(k) = |\Pr_1 - \Pr_2|$ becomes negligible as k increases.

We define the RP-based identity linkage game $\mathcal{G}_r$: after receiving $\mathfrak{L}$ and L' from a challenger, the adversary outputs the result $s = 1$ if it decides $u' \in \{u_1, u_2, \cdots, u_v\}$ or $s = 0$ if u' is randomly chosen in $\mathbb{Z}_n$. The adversary's advantage in $\mathcal{G}_r$

is defined as $\mathbf{Adv}_A$. Then,

$$\begin{aligned}
&\Pr'_1 = \Pr\{\mathcal{G}_r(\mathfrak{L}, L' | ID_{U'} \in \{ID_{U_1}, ID_{U_2}, \cdots, ID_{U_v}\}) = 1\} \\
&\Pr'_2 = \Pr\{\mathcal{G}_r(\mathfrak{L}, L' | ID_{U'} \in \mathbb{Z}_n) = 1\} \\
&\mathbf{Adv}_A = |\Pr'_1 - \Pr'_2|
\end{aligned}$$

We design a PPT algorithm $\mathcal{D}_r^*$ based on $\mathcal{G}_r$, shown in Figure 5, to solve the ECDDH problem. The input is in the form of $(G, Q_1 = [x]G, Q_2 = [y]G, Q_3 = [z]G)$. On receiving the input, the challenger of $\mathcal{G}_r$ randomly chooses $\{u_1, u_2, \cdots, u_v\}$, $\{r_1, r_2, \cdots, r_c\}$, $\{t_{1,1}, t_{1,2}, \cdots, t_{v,c}\}$, and t' in $\mathbb{Z}_n$. Then the challenger constructs $\mathfrak{L}$ and L' as below. It firstly assigns $L_{i,j} = ([r_j]G, t_{i,j}, [u_i r_j]G)$, and randomly chooses $d \in [1, v]$ to replace $[u_d r_j]G$ with $[r_j]Q_1 = [x r_j]G$ for $1 \le j \le c$. So $\mathfrak{L} =$

$$\begin{Bmatrix}
L_{1,1}, & L_{1,2}, & \cdots, & L_{1,c} \\
L_{2,1}, & L_{2,2}, & \cdots, & L_{2,c} \\
\cdots, & \cdots, & \cdots, & \cdots \\
([r_1]G, t_{d,1}, [r_1]Q_1), & \cdots, & \cdots, & ([r_c]G, t_{d,c}, [r_c]Q_1) \\
\cdots, & \cdots, & \cdots, & \cdots \\
L_{v,1}, & L_{v,2}, & \cdots, & L_{v,c}
\end{Bmatrix}.$$

The challenger assigns $L' = (Q_2, t', Q_3) = ([y]G, t', [z/y][y]G)$. Finally, $\mathfrak{L}$ and L' are sent to the adversary, and the output s of $\mathcal{G}_r$ is output by the challenger. According to the above construction of $\mathfrak{L}$ and L', x is actually inserted into $\mathfrak{L}$ as u_d and z/y is assigned to u'. So, if $z = xy$, then $z/y = x$ and $ID_{U'} \in \{ID_{U_1}, ID_{U_2}, \cdots, ID_{U_v}\}$; otherwise, $ID_{U'} \in \mathbb{Z}_n$. Thus,

$$\begin{aligned}
&\Pr_1 = \Pr\{\mathcal{D}_r^*(G, [x]G, [y]G, [xy]G) = 1\} = \Pr'_1 \\
=&\Pr\{\mathcal{G}_r(\mathfrak{L}, L' | ID_{U'} \in \{ID_{U_1}, ID_{U_2}, \cdots, ID_{U_v}\}) = 1\} \\
&\Pr_2 = \Pr\{\mathcal{D}_r^*(G, [x]G, [y]G, [z]G) = 1\} = \Pr'_2 \\
=&\Pr\{\mathcal{G}_r(\mathfrak{L}, L' | ID_{U'} \in \mathbb{Z}_n) = 1\} \\
&\mathbf{Adv}_A = |\Pr'_1 - \Pr'_2| = |\Pr_1 - \Pr_2| = \varepsilon_r(k)
\end{aligned}$$

The ECDDH assumption means that in $\mathcal{G}_r$ the adversary does not have advantages, i.e., cannot distinguish a user U' chosen from $\{U_1, U_2, \cdots, U_v\}$ or randomly from the universal user set. So the RP-based identity linkage is impossible. □

6 Implementation and Evaluation

We implemented the UPPRESSO prototype,[3] and experimentally compared it with two open-source SSO systems: (*a*) MITREid Connect [52] which supports the PPID-enhanced OIDC protocol to prevent the RP-based identity linkage, and (*b*) SPRESSO [26] preventing the IdP-based login tracing.

6.1 Prototype Implementation

The identity transformations are defined on the NIST P256 elliptic curve. RSA-2048 and SHA-256 are used as the signature algorithm and the hash function, respectively.

[3]The prototype is open-sourced at https://github.com/uppresso/.

An IdP is built on top of MITREid Connect [52], an open-source OIDC Java implementation, and only a few modifications are needed. We add only 3 lines of Java code to calculate PID_U, and 20 lines to modify the way to send identity tokens. The calculations of ID_{RP} and PID_U are implemented based on Java cryptographic libraries.

The IdP and RP scripts include about 160 and 140 lines of JavaScript code, respectively. The cryptographic computations such as $Cert_{RP}$ verification and PID_{RP} negotiation, are finished based on jsrsasign [62], an efficient JavaScript cryptographic library.

We finished a Java RP SDK. This SDK provides two functions to encapsulate the protocol steps: one to request identity tokens, and the other to derive the accounts. It is implemented based on the Spring Boot framework with about 500 lines of Java code, and cryptographic computations are done based on the Spring Security library. An RP invokes these functions for the integration, by less than 10 lines of Java code.

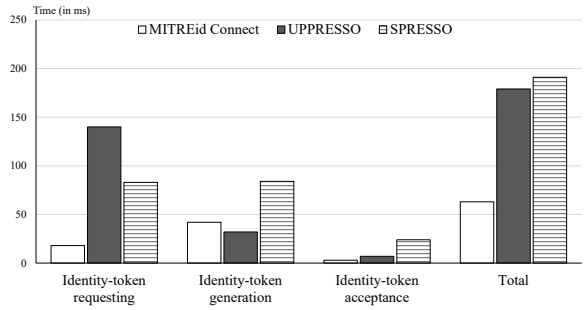
6.2 Performance Evaluation

MITREid Connect runs with the implicit flow of OIDC, and in SPRESSO an identity token is forwarded by a user to the RP, similarly to the implicit flow. In SPRESSO an RP's domain is encrypted as PID_{RP} in identity tokens, while the symmetric key is known to only the RP and the user. They also adopt RSA-2048 and SHA-256 in the generation of tokens.

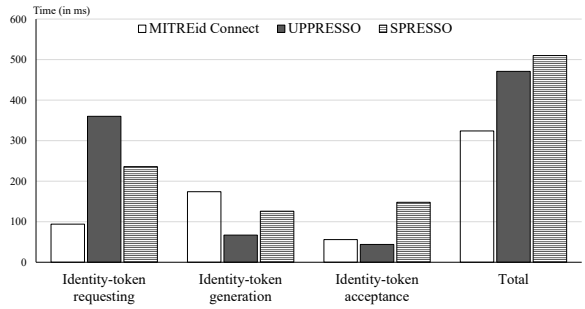
MITREid Connect provides Java implementations of IdP and RP SDK, while SPRESSO implements all entities by JavaScript based on node.js. We implemented RPs based on Spring Boot for UPPRESSO and MITREid Connect, by integrating the corresponding SDKs. The RPs in three schemes provide the same function, i.e., simply obtain the user's account from verified identity tokens.

The IdP and RP servers are deployed on Alibaba Cloud Elastic Compute Service, each of which runs Window 10 with 8 vCPUs and 32 GB memory. The forwarder of SPRESSO runs Ubuntu 20.04.4 with 16 vCPUs and 16 GB memory, also on Alibaba Cloud. We compare the schemes in two scenarios: (*a*) a user browser, Chrome 104.0.5112.81, runs on another virtual machine with 8 vCPUs and 32 GB memory on Alibaba Cloud, and (*b*) a browser runs locally on a PC with Core i7-8700 CPU and 32 GB memory, to remotely visit the servers. In the cloud scenario, all entities are deployed in the same virtual private cloud and connected to one vSwitch, which minimizes the influence of network delays. In any scenario, the IdP server never directly communicates with the RP.

We divide a login flow into three parts: *identity-token requesting* (for UPPRESSO, it includes Steps 1 and 2 in Figure 3), to construct an identity-token request transmitted to the IdP; *identity-token generation* (Step 3 in Figure 3), for the IdP to generate an identity token, while the user authentication and the authorization of user attributes are excluded; and *identity-token acceptance* (Step 4 in Figure 3), as the RP



(a) In a virtual private cloud



(b) With a remotely-visiting browser

Figure 6: The time cost of SSO login

receives, verifies and parses the identity token.

Figure 6 shows the average time cost of 1,000 measurements. The overall time costs of an SSO login instance for MITREid Connect, UPPRESSO, and SPRESSO are (*a*) 63 ms, 179 ms, and 190 ms, respectively, when all entities are deployed on Alibaba Cloud, or (*b*) 312 ms, 471 ms, and 510 ms, respectively, when the user browser runs locally to visit the cloud servers. In the part of identity-token requesting, the RP of MITREid Connect constructs an identity-token request immediately. Compared with MITREid Connect, the main overhead of UPPRESSO is to open a new browser window and download the scripts.[4] The RP in SPRESSO needs to obtain some information on the IdP and encrypt its domain using an ephemeral key, resulting in additional overheads.

In the identity-token generation, UPPRESSO simply retrieves a token from the IdP. On the contrary, in MITREid Connect when a user retrieves the identity token from the IdP, the token must be carried with a URL following the fragment identifier # instead of ?, due to security considerations [16]. So the user needs to first download a script from the RP to process this token, which takes the most time. SPRESSO takes a little more time to generate an identity token, as it implements the IdP based on node.js and adopts a JavaScript cryptographic library, while a more efficient Java library is used in the others.

In the identity-token acceptance, MITREid Connect and UPPRESSO spend the comparable amounts of time to send an identity token to the RP and verify this token. SPRESSO needs the longest time due to the complicated process at the user agent: after receiving identity tokens from the IdP, the browser downloads JavaScript code from the trusted forwarder server, decrypts the RP endpoint, and finally sends identity tokens to this endpoint.

[4] This overhead may be mitigated by implementing a user agent with browser extensions. We tested such a browser extension while the IdP and RPs are kept unmodified, and our experiments show about 90 ms and 260 ms are saved in a login instance, in a virtual private cloud and by a remotely-visiting user, respectively.

7 Discussions

Collusive Attack by an IdP and RPs. Privacy-preserving identity federation solutions [8, 17, 38, 43, 51, 73] prevent the collusive attacks by an IdP and RPs, at the cost of (*a*) a long-term secret held by a user but verified by RPs and (*b*) user-managed accounts [17] for different RPs. Such accounts may be derived from an RP's domain and this secret locally [8, 38, 43, 51, 73], but it still brings inconveniences. For web applications, a user needs to install a browser extension to handle this long-term secret; and if it is lost or leaked, a user has to notify all RPs to update his accounts which are derived from the secret (if the accounts are not masked by the user's secret, the colluding IdP and RPs can eventually link them).

UPPRESSO does not protect user privacy against such collusive attacks, but a user is authenticated to *only* an IdP: the user identity at the IdP are transformed to the accounts at RPs, unrelated to any user credential (e.g., password, one-time password, smart card or FIDO device).

Scalability and Uniqueness. ID_{RP} is generated uniquely in an RP's initial registration, and the capacity of RPs is n (i.e., the order of G). For the NIST P256 elliptic curve, n is approximately 2^{256}. PID_{RP} cannot be exhausted, either. We ensure PID_{RP} is unique in unexpired tokens, the number of which is σ. The probability that at least two PID_{RP}s are identical among the σ ones, is $1-\prod_{i=0}^{\sigma-1}(1-i/n)$. If the system serves 10^8 requests per second and the validity period is 10 minutes, σ is less than 2^{36} and the PID_{RP}-collision probability is negligible (i.e., less than 2^{-183}) for the NIST P256 curve.

The capacity of accounts at any RP is also n, the same as that of user identities at the IdP. $\mathbb{E}$ is a finite cyclic group, so $ID_{RP} = [r]G$ is also a generator of order n. Thus, given any RP, because $Acct = [ID_U]ID_{RP} = [u]ID_{RP}$, a unique account is automatically assigned to every user.

Besides, stronger elliptic curves accommodate more RPs and users; e.g., n is nearly 2^{384} for the NIST P384 curve.

Support for the Authorization Code Flow. In the authorization code flow of OIDC [53], an IdP does not directly response with identity tokens; instead, an authorization code is sent to the RP, which uses this code to ask for identity tokens. The identity-transformation algorithms $\mathcal{F}_{PID_U}$, $\mathcal{F}_{PID_{RP}}$ and $\mathcal{F}_{Acct}$ can be integrated into the authorization code flow:

an authorization code is forwarded to the RP script by the IdP script and this code is used to ask for an identity token binding PID_U and PID_{RP}. An authorization code is usually an index to retrieve identity tokens from the IdP, and does not disclose information about the authenticated user.

After receiving an authorization code, an RP uses it and another secret credential which is issued by the IdP during the initial registration [53], to retrieve identity tokens from the IdP. To protect RP identities from the IdP, anonymous tokens (e.g., ring or group signatures [5, 13], and TrustToken [69]) and anonymous networks (e.g., Tor [18]) need to be adopted for RPs in the retrieval of identity tokens.

Alternative Way to Generate ID_{RP} and Bind $Enpt_{RP}$. In the prototype an RP certificate binds ID_{RP} and $Enpt_{RP}$, verified by the honest IdP script. RP certificates ensure the target RP has already registered itself at the IdP, which prevents unauthorized RPs from accessing the IdP's services.

This binding may be finished in another way: ID_{RP} is *deterministically* calculated based on the RP's unambiguous name. For example, $Hs()$ encodes an RP's domain (or the RP script's origin, e.g., `https://RP.com`) to a point on $\mathbb{E}$ as ID_{RP}, where hashing to elliptic curves $Hs()$ [22] provides collision resistance and does not reveal the discrete logarithm of the output (i.e., $ID_{RP} = [r]G$ is *unique* and r is *unknown*). Then, in Step 2.2 the RP script will send the endpoint but not its RP certificate, and ID_{RP} is calculated by the IdP script. However, if an RP updates its domain, for instance, from `https://RP.com` to `https://theRP.com`, $Acct = [ID_U]ID_{RP}$ will change inevitably. In such cases, it needs special operations by each user to migrate his account to the updated RP system. This account migration requires extra operations explicitly by each user; otherwise, colluding RPs could actually link a user's accounts across RPs.

Restriction of the RP Script's Origin. When identity tokens are forwarded by the IdP script to the RP script, the receiver is restricted by the `postMessage` targetOrigin mechanism [61], to ensure it will forward the tokens to $Enpt_{RP}$ that is bound in RP certificates. A targetOrigin is specified as a pair of protocol and port (if not presented, implicitly 80 for `http` and 443 for `https`) and a domain (e.g., `RP.com`), and it requires the RP script's origin accurately matches the targetOrigin.

Although the URL path part of $Enpt_{RP}$ is not checked by the targetOrigin mechanism, which assumes only one RP runs on a domain, it brings no *extra* risk. For example, if two RPs run on one domain but with different endpoints to receive identity tokens (e.g., `https://RP.com/honest/tkn` and `https://RP.com/malicious/tkn`), they cannot be distinguished by `postMessage`. Meanwhile, browsers enforce the same-origin policy (SOP) in the access control of web resources [63]. So a malicious RP could always access the other RP's resources in browsers, e.g., steal cookies by the script `window.open('https://RP.com/honest').document.cookie`, even if the honest RP restricts only HTTP requests to specific paths carry its cookies. This risk actually results from the SOP design of browsers.

Applicability of Identity Transformations. The proposed identity-transformation algorithms are applicable to various SSO scenarios (e.g., web application, mobile App, and native software), because these algorithms follow the common model of popular SSO protocols and do not depend on any special implementation or runtime.

8 Conclusion

This paper proposes UPPRESSO, an untraceable and unlinkable privacy-preserving SSO system, to protect a user's online profile at different RPs against a curious IdP and colluding RPs. We propose an identity-transformation approach for privacy-preserving SSO, and design algorithms satisfying the requirements, where (*a*) $\mathcal{F}_{PID_{RP}}$ protects an RP's identity from the curious IdP, (*b*) $\mathcal{F}_{PID_U}$ prevents colluding RPs from linking a user across these RPs, and (*c*) $\mathcal{F}_{Acct}$ enables the visited RP to derive an identical account for a user in his multiple logins. These identity transformations are integrated with the widely-adopted OIDC protocol to protect user privacy and keep user convenience, without breaking the security guarantees of SSO services. The experimental evaluations of the UPPRESSO prototype show that it provides efficient SSO services: on average a login instance takes 174 ms when the IdP, the visited RP and users are deployed in a virtual private cloud, or 421 ms when a user visits remotely.

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