

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 is platform independent. Our analysis shows *UPPRESSO* provides a comprehensive privacy protection while achieving the same security guarantees of OIDC.

Keywords—Single sign-on, security, privacy.

I. INTRODUCTION

Single sign-on (SSO) systems, such as OpenID Connect [1], OAuth [2] and SAML [3], have been widely deployed as the identity management and authentication infrastructure in the Internet. SSO enables a website, called the *relying party* (RP), to delegate its user authentication to a trusted third party called the *identity provider* (IdP). Thus, a user visits multiple RPs with only a single explicit authentication attempt at the IdP. With the help of SSO, a user no longer needs to remember multiple credentials for different RPs; instead, she maintains only the user credential for the IdP, which generates *identity proofs* for her visits to these RPs. SSO has been widely integrated with many application services. For example, we find that 80% of the Alexa Top-100 websites [4] support SSO, and the analysis on the Alexa Top-1M websites [5] identifies 6.30% with the SSO support. Meanwhile, many email and social network providers (such as Google, Facebook, Twitter, etc.) are serving the IdP roles in the Internet.

The adoption of SSO also raises privacy concerns regarding online user tracking and profiling [6], [7]. Imagine that, a user

concerning her privacy would avoid to leave her full sensitive informations at an application. The user may use multiple web applications and only leave parts of her sensitive messages at each applications, for example, using real name on social website, the address on shopping website and the phone number on Telecom website. And she would try not to leave any linkable message to avoid applications combining her informations, for example, if she leave the email on each applications, they can combine the parts of informations through the email. However, the privacy leaks in SSO systems make her effort in vain. As long as a user employs the SSO system, such as Google Account, to log in to these applications, the applications providers and Google can combine your informations based on the SSO account.

User privacy leaks in all existing SSO protocols and implementations. Taking a widely used SSO protocol, OpenID Connect (OIDC), as an example, we explain its login process and the risk of user privacy leakage. On receiving a user’s login request, the RP constructs a request of identity proof with its identity and redirects it to the IdP. After authenticating the user, the IdP generates an identity proof binding the identities of the user and the RP, which is forwarded to the RP by the user. Finally, the RP verifies the identity proof and allows the user to log in. From such login instances, any curious IdP or collusive RPs could break the users’ privacy as follows.

- *IdP-based login tracing.* The IdP knows the identities of the RP and the user in each single login instance, to generate the identity proof. As a result, a curious IdP could discover all the RPs that the victim user attempts to visit and profile her online activities.
- *RP-based identity linkage.* The RP learns a user’s identity from the identity proof. When the IdP generates identity proofs for a user, if the same user identifier is bound in identity proofs generated for different RPs, which is the case of several widely deployed SSO systems [8], [9], malicious RPs could collude to not only link the user’s login activities at different RPs for online tracking but also associate her attributes across multiple RPs [6].

Large IdPs, especially the social IdPs such as Google and Facebook, are interested in collecting users’ online behavioral information for various purposes (e.g., Screenwise Meter [10] and Onavo [11]). By simply serving the IdP role, these companies will easily collect a large amount of data to reconstruct users’ online traces. On the other hand, in the Internet, many service providers host a variety of web services and therefore take an advantaged position to link a user’s multiple logins at different RPs. Through the internal information integration, rich information will be obtained from the SSO data for user

profiling. Meanwhile, the technologies of privacy-preserving record linkage [12] and private set intersection [13] allow multiple organizations (e.g., RPs) to share and link the data without directly sharing their clients' data, which pave the path for cross-organizational RP-based identity linkage.

While the privacy problems in SSO have been widely recognized [6], [7], only a few solutions were proposed to protect user privacy [14], [15]. Among them, Pairwise Pseudonymous Identifier (PPID) [1], [16] is a straightforward and commonly adopted solution to defend against RP-based identity linkage. It requires the IdP to create different identifiers for the user when she logs into different RPs, so that the pseudo-identifiers of the same user cannot be used to link the user's logins at different RPs even if they collude. As a recommended practice by NIST [7], PPID has been specified in many widely adopted SSO standards including OIDC [1] and SAML [16]. However, PPID-based approaches cannot prevent the IdP-based login tracing attacks, as the IdP still knows which RP the user visits.

To the best of our knowledge, only two schemes (i.e., BrowserID [14] and SPRESSO [15]) have been proposed so far to defend against IdP-based login tracing. In BrowserID (and its prototypes known as Mozilla Persona [17] and Firefox Accounts [9]), the IdP generates a special "identity proof" to bind the user's unique identifier (i.e., email address) to a public key. With the corresponding private key, the user signs an extra subsidiary identity proof to bind the visited RP's identity and its identity, and sends this pair of identity proofs to that RP. In this way, the IdP does not know the RP's identity when generating identity proofs. SPRESSO requires the RP to create a one-time pseudo-identifier at each login for the IdP to generate an identity proof, and then hides the RP's real identity from the IdP. The RP employs a third-party entity called forwarder, which works as a proxy to relay the identity proof from the IdP to the corresponding RP. In both schemes, the RPs' identities are protected from the IdP; however, the IdP has to know the user's unique identifier (e.g., email address) and includes it in identity proofs so that the visited RP can recognize the user in her multiple logins. As a result, both schemes are still vulnerable to RP-based identity linkage.

As discussed above, none of the existing SSO systems defend against both IdP-based login tracing and RP-based identity linkage at the same time. Before presenting our solution, we first formally analyze the privacy problems and solutions. Let us denote the user's and the visited RP's identities as ID_U and ID_{RP} , respectively. To protect user privacy against RP-based identity linkage, ID_U should not be explicitly included in the identity proof which will be received by the RP. Instead, a privacy-preserving pseudo-identifier PID_U should be used (as in the PPID-based approaches [1], [16]), which can be viewed as the output of a one-way identifier-transformation function $\mathcal{F}_{ID_U \mapsto PID_U}$ at the IdP, which authenticates the user and then knows ID_U . Similarly, to prevent IdP-based login tracing, ID_{RP} should not be explicitly included in the identity proof but be replaced by a pseudo-identifier PID_{RP} (as in SPRESSO [15] and BrowserID [14]), which is obtained by another one-way function $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}$ at the RP. However, if both PID_U and PID_{RP} are used in identity proofs to replace ID_U and ID_{RP} at the same time, assuming they can be securely exchanged between the IdP and the RP in an SSO login process, the RP will allow the user to log in as

PID_U , which will be different in the user's multiple logins at a same RP; otherwise, the IdP might be able to associate these RPs visited by the user. As a result, the RP has no clues to derive the user account at the RP but has to treat her as a one-time user every time when she logs in. This violates the basic requirements of SSO services.

In this paper, we propose an Unlinkable Privacy-PREServing Single Sign-On (UPPRESSO) system to provide comprehensive protections against both IdP-based login tracing and RP-based identity linkage. The key idea of UPPRESSO is to design a special identifier-transformation function $\mathcal{F}_{PID_U \mapsto Account}$, which maps *all* PID_U s of a user to *one* unique *Account* in all logins to an RP, where *Account* is created when the user logs into the RP for the first time. Since in every login instance PID_U and PID_{RP} are separately generated by the IdP and the RP, respectively, we have to design associative one-way identifier-transformation functions $\mathcal{F}_{ID_U \mapsto PID_U}$ and $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}$, so that three identifier-transformation functions work cooperatively to ensure: (a) when a user logs into an RP for multiple times, the RP always maps PID_U s to an identical *Account* without knowing the user's identity; moreover, when a user logs into multiple RPs, (b) a curious IdP cannot link multiple PID_{RPs} to a particular RP or associate them together, and collusive RPs (c) cannot link PID_U s to a particular user or associate them together, (d) nor link *Accounts* of a same user at different RPs.

To completely achieve these goals, we design three one-way identifier-transformation functions based on the discrete logarithm problem. We design a one-way trapdoor function $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}(ID_{RP}, T)$ for an RP to generate a random PID_{RP} based on a randomly generated trapdoor T , and a one-way function $\mathcal{F}_{ID_U \mapsto PID_U}(ID_U, PID_{RP})$ for the IdP to generate PID_U based on PID_{RP} . With the trapdoor T , the RP applies $\mathcal{F}_{PID_U \mapsto Account}(PID_U, PID_{RP}, T)$ to identity proofs binding PID_{RP} and PID_U , to derive the unique *Account*. We summarize our contributions as follows.

- We formally analyze the privacy problems in SSO as an identifier-transformation problem, and propose the first comprehensive solution to hide the users' login traces from both the curious IdP and malicious collusive RPs. To the best of our knowledge, UPPRESSO is the first SSO system that provides secure SSO services against IdP-based login tracing and RP-based identity linkage.
- We formally analyze the security of UPPRESSO and show that it meets the secure requirements of SSO systems, while the users' login traces are well protected.
- We have implemented 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. And the prototype is implemented only relying on the HTML 5 features, such that it can be used cross platforms (PC, smart phones and other devices). Unlike BrowserID and SPRESSO, UPPRESSO does not require non-trivial re-designs of SSO services, which makes it more compatible with existing SSO systems.

- We compare the performance of the UPPRESSO prototype with the state-of-the-art SSO systems (i.e., OIDC and SPRESSO), and demonstrate its efficiency.

The rest of the paper is organized as follows. We first introduce the background and preliminaries in Section II. Then, we describe the identifier-transformation based approach, the threat model, and our UPPRESSO design in Sections III, IV and V, followed by a formal analysis of security and privacy in Section ?? We provide the implementation specifics and experiment evaluation in Section VII, discuss the extensions and related works in Section VIII and IX, and conclude our work in Section X.

II. BACKGROUND AND PRELIMINARIES

UPPRESSO is designed to be compatible with OpenID Connect (OIDC) and provide privacy protections based on the discrete logarithm problem. Here, we provide a brief introduction about OIDC and the discrete logarithm problem.

A. OpenID Connect (OIDC)

As an extension of OAuth 2.0 for user authentication, OIDC is one of the most popular SSO protocols [1]. As other SSO protocols [16], OIDC involves three entities, i.e., *users*, the *identity provider (IdP)*, and *relying parties (RPs)*. Both users and RPs register at the IdP with identifiers (ID_U , ID_{RP} and PID_U in some schemes), and the necessary information such as credentials, RP endpoints (e.g., the URLs to receive identity proofs), etc. The IdP is assumed to maintain these attributes securely. In an OIDC login process, a user is responsible for initiating a login request at an RP, redirecting the SSO messages between the RP and the IdP, and checking the scope of user attributes in the identify proof generated by the IdP for the visited RP. Usually, the redirection and checking actions are handled by a user-controlled software, known as *user agent* (e.g., browser). Once receiving a user login request, the RP constructs an identity proof request with its identifier and the scope of requested user attributes, sends the identity proof request to the IdP through the user, and parses the received identity proof to authenticate the user. The IdP authenticates the user based on her ID_U and credential, maps ID_U to PPID (i.e., privacy-preserving pseudo-identifier) based on the RP identity (i.e., ID_{RP}), generates an identity proof containing PPID, ID_{RP} and requested user attributes, and returns the identity proof to the endpoint registered by the RP.

OIDC Implicit Flow. OIDC supports three user login flows, which are the *implicit flow*, *authorization code flow* and *hybrid flow* (i.e., a mix-up of the previous two). In the implicit flow, an *id token* is generated as the identity proof, which contains a user identifier, an RP identifier, the issuer (i.e., IdP), the validity period, and other requested attributes. The IdP signs the id token using its private key to ensure integrity, and sends it to the RP through the user. In the authorization code flow, the IdP binds an authorization code with the RP, and sends it to the RP through the user; then, the RP establishes an HTTPS connection to the IdP and uses the authorization code with the RP's credential to obtain the user's identifier and other attributes. UPPRESSO is compatible with all three flows. For brevity, we will present our design and implementation of

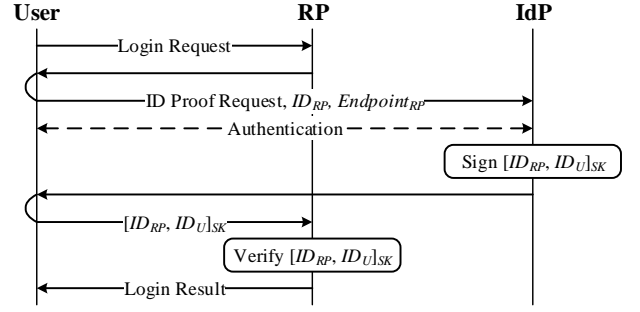


Fig. 1: The implicit flow of OIDC.

UPPRESSO on top of the OIDC implicit flow in details, and discuss the extension to support the authorization code flow in Section VIII.

The original OIDC implicit flow is shown in Figure 1. When a user attempts to log into an RP, the RP constructs an identity proof request and returns it to the user, which gets redirected to the IdP. The request contains ID_{RP} , the RP endpoint to receive the identity proof, and the scope of requested user attributes. If the user has not yet been authenticated, the IdP initiates an authentication process to authenticate her. For a successfully authenticated user, the IdP generates an id token and returns it to the RP endpoint. If the endpoint is not registered for that RP, the IdP will return a warning to notify the user about potential identity proof leakage. Once the RP receives the identity proof, it makes the authentication decision after verifying the identity proof.

RP Dynamic Registration. The RP dynamic registration [18] of OIDC allows an RP to update its information at the IdP. When an RP first registers at the IdP, it obtains a registration token, with which the RP can initiate a dynamic registration process to update its information (e.g., the endpoint). After a successful dynamic registration, the RP obtains a new unique ID_{RP} from the IdP. UPPRESSO leverages this function and slightly modify the dynamic registration process to enable *PID_{RP} registration*, which allows an RP to generate different privacy-preserving identifiers (PID_{RPS}) and register them at the IdP.

B. Discrete Logarithm Problem

Based on the discrete logarithm problem, UPPRESSO designs the identifier-transformation functions. Here, we briefly review the discrete logarithm problem. For the finite field $GF(p)$ where p is a large prime, a number g is called a generator of order q , if it constructs a cyclic group of q elements by calculating $y = g^x \bmod p$. And x is called the discrete logarithm of y modulo p . Given a large prime p , a generator g and a number y , it is computationally infeasible to solve the discrete logarithm (i.e., x) of y [19], which is called the discrete logarithm problem. The hardness of solving discrete logarithms is utilized to design several secure cryptographic primitives, including Diffie-Hellman key exchange and the digital signature algorithm (DSA).

III. THE PRIVACY DILEMMA AND UPPRESSO OVERVIEW

In this section, we first review the security and privacy requirements of SSO services and discuss the privacy dilemma in designing secure privacy-preserving SSO systems. Then, we provide an overview of the identifier-transformation approach of UPPRESSO.

A. Security Requirements of SSO

The primary goal of SSO services is to implement secure user authentication [15], i.e., to ensure that a legitimate user can always log into an honest RP under her unique account. To achieve this, every identity proof generated by the IdP should explicitly specify the user who is authenticated by the IdP (i.e., **user identification**) and the RP which the user attempts to log into (i.e., **RP designation**). User identification also requires an RP to be able to recognize every authenticated user under a unique account registered at that RP in multiple logins of the user. Moreover, the identify proof should be generated by the trusted IdP and correctly transmitted to the dedicated RP and the user in some schemes (i.e., **confidentiality**). In this process, the identify proof should not be modified or forged (i.e., **integrity**). These are the basic security requirements of SSO systems summarized based on theoretical analysis of SSO designs [20]–[22] and practical attacks [23]–[40].

Many attacks exploit vulnerabilities in SSO design or implementation to break at least one of these security requirements, so that the adversaries can log into an honest RP as a victim user (called *impersonation attacks*), or allure a victim user to log into 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) [35], so a malicious RP could replay the identity proof received from a user for itself and log into Friendcaster as the victim user. Or, the adversaries could impersonate the victim user with a leaked identity proof (i.e., a violation of confidentiality) [24], [25], [36]–[38]. 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 potential violation of integrity) [24]. As a result, an adversary could insert arbitrary attributes (e.g., an email address) into the identity proof to impersonate another user at the RP.

B. The Privacy Dilemma in SSO Identity Proofs

As discussed in Section I, existing SSO systems are vulnerable to IdP-based login tracing or RP-based identity linkage privacy leakage. We argue that a secure and privacy-preserving SSO system should prevent *both* types of privacy leakage while satisfying *all* four basic security requirements. However, meeting the security and privacy requirements at the same time incurs a dilemma in the identity proof generation.

In an SSO login instance, the identity proof is generated by the IdP about the authenticated user and the requesting RP. First, to prevent IdP-based login tracing, the identity proof request should not disclose ID_{RP} to the IdP, since the IdP already knows ID_U after authenticating the user. However, to ensure RP designation, the IdP should bind each identify proof with a certain transitional pseudo-identifier of the RP (denoted as PID_{RP}). PID_{RP} can be generated by the user or the RP,

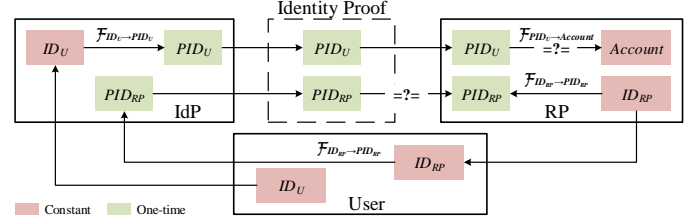


Fig. 2: Identifier transformations in privacy-preserving SSO.

or together, but it should be computationally infeasible for the IdP to derive ID_{RP} from PID_{RP} .

Meanwhile, to prevent RP-based identity linkage, the identity proof should not directly contain ID_U or disclose it in any means. This requires the IdP to generate a certain transitional pseudo-identifier of the user (denoted as PID_U) and bind it to the identity proof. However, to ensure user identification, the requesting RP should be able to recognize the user and associate PID_U to her unique account at the RP (denoted as *Account*). Similarly, it should be computationally infeasible for the RP to derive ID_U from PID_U or *Account*.

We illustrate the relationships between the identifiers, pseudo-identifiers, and the identity proof in Figure 2, where red and green blocks respectively represent long-term identities and one-time pseudo-identifiers known to each entity, and the arrows denote how the pseudo-identifiers are obtained. A *dilemma* exists in the SSO login process, that is, the IdP is expected to generate a PID_U for the authenticated user ID_U that can be linked to her *Account* at the requesting RP, *without knowing any information about the requesting RP*.

C. The Identifier-transformation Framework and UPPRESSO

As shown in Figure 2, we convert the privacy-preserving SSO login problem 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 satisfy the desired security and privacy requirements. To solve the dilemma, the key is to pass some information related to the user's *Account* at the RP to the IdP to assist its generation of PID_U , so that all PID_U s of the same user during her multiple logins at the same RP can be correctly linked to her *Account*. Meanwhile, such information should not provide any additional knowledge for the IdP to infer the RP's identity (i.e., ID_{RP}).

To achieve this goal, UPPRESSO constructs three transformation functions in an integrated way to support *transformed RP designation* and *trapdoor user identification*, where (i) PID_U s and PID_{RP} s are generated dynamically for different logins to protect user privacy; (ii) in each login, PID_{RP} helps to link PID_U to *Account*; and (iii) in a user's multiple logins to the same RP, an invariant *Account* can always be derived from different pairs of PID_U s and PID_{RP} s.

Transformed RP designation. To prevent IdP-based login tracing, the identity proof request should not include ID_{RP} but a PID_{RP} dynamically transformed from ID_{RP} . UPPRESSO designs a novel trapdoor-based transformation function $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}(ID_{RP}, T)$ to compute PID_{RP} based on

TABLE I: 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.

ID_{RP} and a random trapdoor T that is dynamically negotiated between the user and the RP for each login. Then, the user assists the RP to register this PID_{RP} at the IdP (through OIDC dynamic registration). When an RP receives an identity proof, it can verify if the enclosed PID_{RP} is transformed from its own ID_{RP} using the trapdoor it holds.

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 and include it in the identity proof. 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.

D. Existing Privacy-Preserving SSO Solutions

Next, we map three existing privacy-preserving SSO approaches (PPID [1], [16], BrowserID [14] and SPRESSO [15]) to the identifier-transformation framework in Figure 2 and explain their designs and potential privacy issues as shown in Table I. 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_U s for a user to log into different RPs and maintains deterministic one-to-many mappings from ID_U to PID_U s. Therefore, RP-based identity linkage is prevented. At each RP, $Account = PID_U$ ensures user identification. However, since ID_{RP} is directly used in identity proofs ($PID_{RP} = ID_{RP}$), they cannot defend against 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 through the user. With the corresponding nonce, the RP can verify the 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, the IdP uses a constant ID_U to generate identity proofs for each user regardless of which RP she requests to login to. As a result, SPRESSO is vulnerable to RP-based identity linkage, since *Account* always equals to ID_U .

The identity proofs in the BrowserID system include ID_U but no RP information (i.e., $PID_{RP} = \perp$), therefore, it 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 and passed to the RP. Therefore,

$Account = ID_U$, which makes BrowserID vulnerable to RP-based identity linkage.

As we can see, none of these approaches prevents 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 arbitrarily designed and function separately, which causes either $PID_{RP} = ID_{RP}$ or $Account = ID_U$.

IV. THREAT MODEL AND ASSUMPTIONS

Similar as other SSO systems (e.g., SAML and OIDC), UPPRESSO consists of an IdP and multiple RPs and users. Next, we describe the threat model and some assumptions.

A. 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 specifications, but may be interested in users' login activities at multiple RPs. It is assumed to be well-protected and never leaks sensitive information. For example, the IdP is trusted to maintain the private key for signing identity proofs and RP certificates (see Section V-B for details), so that the adversaries can never forge an identity proof or an RP certificate. An honest IdP should never collude with other entities (e.g., malicious RPs or users), while a curious IdP tries to break user privacy without violating the protocol. For example, it may store all the received messages to infer the relationship among ID_U , ID_{RP} , PID_U and PID_{RP} and trace a user's login activities.

Malicious Users. We assume the adversary can control a set of users, by stealing users' credentials [41], [42] or directly registering sybil accounts at the IdP and RPs, to break the security of UPPRESSO. They may impersonate a benign user at honest RPs, or trick a victim user to log into an honest RP under the account of a malicious user. For example, the malicious users 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 could also control a set of RPs 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. For example, a malicious RP may manipulate its PID_{RP} and trick the users to submit identity proofs for other honest RPs to itself and reply them, 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 together, attempting to break the security and privacy guarantees. For example, the adversary may firstly acts the RP and allures the honest user to upload her identity proof. Then this adversary may attempt to log in to other honest RPs with this identity proof as the honest user.

B. Assumptions

We assume the user agent deployed at honest users is correctly implemented and transmits messages to the dedicated receivers as expected. We also assume the IdP and benign RPs and users adopt TLS to ensure confidentiality and integrity in the communications. Meanwhile, the cryptographic algorithms (such as RSA and SHA-256) and building blocks (such as random number generators and the discrete logarithm problem) used in UPPRESSO are assumed to be correctly implemented.

As we consider IdP is always honest, therefore, all the parameters provided by the IdP are assumed to be honest. All the calculations and verifications conducted by IdP are correct. Meanwhile, the collusion between RPs and IdP is not considered in this paper.

In UPPRESSO, we study the RP-based identity linkage caused by a same user identifier used across different RPs. In this paper, we consider the user attributes hold by IdP can be separated as distinctive and indistinctive message, which is labelled based on whether it can be only associated with specific user. While the RPs may be able to re-identify a user from some distinctive user attributes, such as telephone numbers, addresses, or driver licenses, we consider it out of the scope of UPPRESSO. However, other attributes, such as nickname, birthday and sex can be provided to RPs with the explicit consent from user. Also, we focus on IdP-based login tracing attacks that are enabled by SSO protocols, but do not consider other network attacks such as traffic analysis that trace a user's logins at different RPs.

V. THE DESIGN OF UPPRESSO

Next, we present the main design of UPPRESSO. First, we describe our design for the three identifier-transformation functions and the details of the transformed RP designation and trapdoor user identification schemes. Then, we provide an overview of the UPPRESSO system and its login flow. Finally, we discuss the compatibility of UPPRESSO with OIDC. The notations used in this paper are listed in Table II.

A. Identifier-transformation Functions in UPPRESSO

As discussed in Section III, the identifier-transformation functions are essential for privacy-preserving SSO systems. In UPPRESSO, the three functions, $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}$, $\mathcal{F}_{ID_U \mapsto PID_U}$ and $\mathcal{F}_{PID_U \mapsto Account}$, are all constructed based on the discrete logarithm problem with public parameters p, q , where p is a large prime defining the finite field $GF(p)$, and q is a prime factor of $(p - 1)$.

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 $1 < ID_U < q$, and ID_{RP} is a generator of order q in $GF(p)$.

RP Identifier Transformation. In each login session, the user negotiates with the RP she tries to log in, and computes a pseudo-identifier PID_{RP} for the RP cooperatively. The user chooses a random number N_{RP} ($1 < N_{RP} < q$), and RP provides the ID_{RP} for user to calculate PID_{RP} following Equation 1.

$$\mathcal{F}_{ID_{RP} \mapsto PID_{RP}} : PID_{RP} = ID_{RP}^{N_U} \mod p \quad (1)$$

TABLE II: The notations used in UPPRESSO.

Notation	Definition	Attribute
p	A large prime.	Long-term constant
q	A large prime factor of $(p - 1)$.	Long-term constant
SK, PK	The private/public key of IdP.	Long-term constant
$Cert_{RP}$	An RP certificate, containing the RP's identity and endpoint.	Long-term constant
ID_U	A user's unique identity.	Long-term constant
$Account$	$Account = ID_{RP}^{ID_U} \mod p$, a user's identifier at an RP.	Long-term constant
PID_{RP}	$PID_{RP} = ID_{RP}^{N_U} \mod p$, an RP's pseudo-identifier.	One-time variable
PID_U	$PID_U = PID_{RP}^{ID_U} \mod p$, a user's pseudo-identifier.	One-time variable
N_U	A user-generated nonce for PID_{RP} .	One-time variable
T	$T = N_U^{-1} \mod q$, the trapdoor to derive $Account$.	One-time variable

The transformation function $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}$ satisfies the following requirements. First, 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 valid only for this login and for the identity proof generated in this login, and (b) PID_{RP} is dynamically generated for this login and is different from other PID_{RPs} generated in other login session between the same user and RP. Therefore, the IdP cannot associate multiple PID_{RPs} of a same RP.

User Identifier Transformation. When the IdP receives an identity proof request for ID_U and PID_{RP} from an authenticated user, it follows the transformation function in Equation 2 to calculate PID_U and includes it in the identity proof.

$$\mathcal{F}_{ID_U \mapsto PID_U} : PID_U = PID_{RP}^{ID_U} \mod p \quad (2)$$

From Equations 1 and 2, we see that $PID_U = ID_{RP}^{N_U ID_U} \mod p$. The discrete logarithm problem ensures that the RP cannot derive ID_U from PID_U .

User Account Transformation. The RP can derive a unique $Account$ for each user following Equation 3.

$$\mathcal{F}_{PID_U \mapsto Account} : Account = PID_U^T \mod p \quad (3)$$

Here, we define $T = N_U^{-1} \mod q$ as the RP's trapdoor. As q is a prime number and $1 < N_U < q$, q is coprime to N_U . Also, there always exists a T that satisfies $T N_U = 1 \mod q$. Moreover, from Equations 1, 2 and 3, we have $Account = ID_{RP}^{ID_U} \mod p$, derived as below.

$$\begin{aligned} Account &= PID_U^T = (PID_{RP}^{ID_U})^{N_U^{-1} \mod q} \\ &= ID_{RP}^{ID_U N_U N_U^{-1} \mod q} = ID_{RP}^{ID_U} \mod p \end{aligned} \quad (4)$$

Therefore, when a user logs in at an RP multiple times, the RP can always derives the same $Account$ to identify the user. Finally, the transformation function $\mathcal{F}_{PID_U \mapsto Account}$ satisfies the following requirements: (a) due to the discrete logarithm problem, the RP cannot derive ID_U from $Account$, and (b) collusive RPs cannot link a user's $Accounts$ at different RPs.

These three identifier-transformation functions enable *transformed RP designation* and *trapdoor user identification* to satisfy all the security and privacy requirements of an SSO.

Transformed RP Designation. $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}$ ensures that the user and RP cooperatively generate a fresh PID_{RP} in each login, while $\mathcal{F}_{ID_U \mapsto PID_U}$ ensures that the IdP generates the exact PID_U for the ID_U who logs in at PID_{RP} . The IdP will bind PID_U with PID_{RP} in the identity proof, which designates this identity proof to PID_{RP} . Finally, the transformed RP designation is provided through two phases. The function $\mathcal{F}_{ID_{RP} \mapsto PID_{RP}}$ prevents the curious IdP from linking PID_{RP} s of different logins at an RP, and therefore avoids IdP-based login tracing.

Trapdoor User Identification. In a user's multiple logins, the RP expresses different PID_U s and has the corresponding T s, so that derives the identical *Account*. The comprehensive design of identifier-transformation functions prevents collusive RPs from linking a user's PID_U s and *Accounts* at different RPs, and therefore prevents RP-based identity linkage.

B. UPPRESSO Overview

The UPPRESSO system has four procedures, namely system initialization, RP initial registration, user registration, and SSO login.

System Initialization. System initialization is conducted once by the IdP to establish the entire system. In particular, the IdP generates a large prime p , and a prime factor q of $p - 1$ as the parameters of the discrete logarithm problem. The IdP also generates one key pair (SK, PK) to sign identity proofs and RP certificates. The lengths of p , q and (SK, PK) should satisfy the required security strength. Then, the IdP keeps SK secret, while announcing p , q and PK are public parameters.

RP Initial Registration. RP initial registration is launched by each RP to obtain the necessary configurations from the IdP, including a unique identifier ID_{RP} and its corresponding RP certificate $Cert_{RP}$. Each RP launches this procedure only once. In particular, an RP registers itself at the IdP and requests ID_{RP} and $Cert_{RP}$ as follows:

- The RP sends a registration request to the IdP, including the RP endpoint (e.g., URL) to receive identity proofs.
- The IdP generates the unique generator ID_{RP} , signs $[ID_{RP}, Endpoint_{RP}, *]$ using SK , where $*$ denotes the supplementary information such as the RP's common name, and returns $Cert_{RP} = [ID_{RP}, Endpoint_{RP}, *]_{SK}$ to the RP, where $[\cdot]_{SK}$ means the message is signed using SK .
- The RP verifies $Cert_{RP}$ using PK and accepts ID_{RP} and $Cert_{RP}$ if they are valid.

Note that, ID_{RP} cannot be chosen by the RP. It must be generated by the IdP.

User registration. UPPRESSO takes the same user registration process as other SSO systems to set up a unique user identifier ID_U and the corresponding user credential. User registration is launched only once by each user. ID_U can be chosen by either the user or the IdP, as long as it is unique for each user.

SSO Login. Finally, an SSO login procedure will be launched when a user attempts to log into an RP. It is designed on top of the identifier-transformation functions. As shown in Figure 3, the SSO login consists of five phases, namely, scripts downloading, RP identifier transformation, PID_{RP} registration, identity proof generation and *Account* calculation. At the scripts downloading phase, browser firstly downloads the scripts from RP and IdP server. In RP identifier transformation, the user and the RP negotiate $PID_{RP} = ID_{RP}^{N_U} \mod p$. Next, the user registers PID_{RP} at the IdP. It is worth noting that this step has to be conducted by the user but not the RP. Otherwise, the IdP can associate PID_{RP} and ID_{RP} . To register PID_{RP} , the user needs to create a new endpoint and submit it with PID_{RP} to the IdP. Then, the RP requests the identity proof, and the IdP calculates $PID_U = PID_{RP}^{ID_U} \mod p$ and signs the identity proof. Finally, in *Account* calculation, the RP derives $Account = PID_U^{(N_U)^{-1} \mod q} \mod p$ after verifying the identity proof and allows the user to log in under *Account*.

Moreover, as the IdP is unaware of the visited RP and also the RP's endpoint to receive the identity proof, this endpoint shall be queried by the user from the trusted IdP indirectly to ensure confidentiality; otherwise, an incorrect endpoint leaks the identity proofs. In UPPRESSO this is implemented as an RP certificate signed by the IdP, which is composed of ID_{RP} , the RP's endpoint and other supplementary information. Then, the user determines the correct endpoint by itself, while in commonly-used OIDC systems, the endpoint is configured by the IdP.

C. SSO Login Flow of UPPRESSO

We illustrate the steps of the SSO login protocol of UPPRESSO in Figure 3, and describe the detailed processes as follows.

Scripts Downloading. At the beginning, the user downloads the scripts from RP server and IdP server as follows:

- 1.1 The user visits the RP's script site and downloads the script.
- 1.2 The script opens a new window in the browser visiting the login path at RP server.
- 1.3 The visit to RP's login path is redirected to IdP's script.
- 1.4 The new window visits the IdP's script site and downloads the script.

RP Identifier Transformation. In this phase, the user and the RP cooperate to generate PID_{RP} as follows:

- 2.1 The IdP script chooses a random number N_U ($1 < N_U < q$) and sends it to RP script through postMessage, then RP script sends N_U to RP server.
- 2.2 The RP verifies $N_U \neq 0 \mod q$, calculates PID_{RP} with N_U , derives the trapdoor $T = (N_U N_{RP})^{-1} \mod q$; and acknowledges the negotiation by responding with $Cert_{RP}$. The $Cert_{RP}$ is transmitted from RP script to IdP script through postMessage.

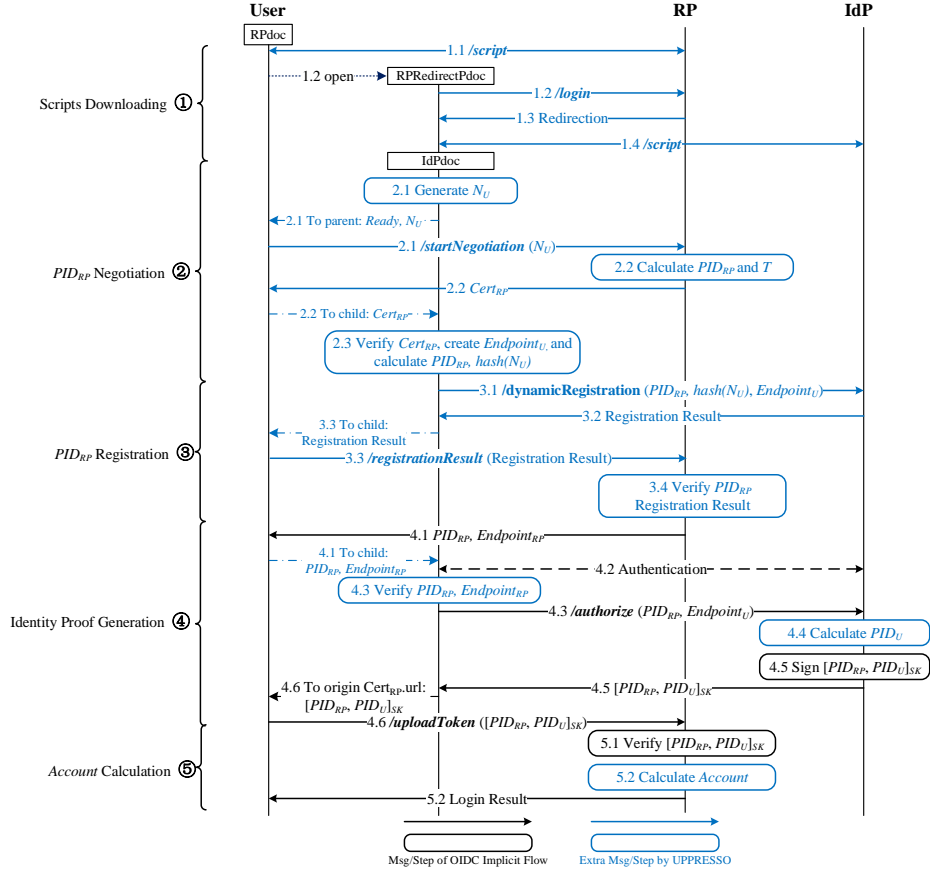


Fig. 3: The flow of a user login in UPPRESSO.

- 2.3 The IdP script verifies $Cert_{RP}$, extracts ID_{RP} from the valid $Cert_{RP}$, calculate $PID_{RP} = ID_{RP}^{N_U} \bmod p$, creates a one-time endpoint to hide the RP's endpoint from the IdP and calculates $Nonce = Hash(N_U)$.

The user halts the negotiation, if $Cert_{RP}$ is invalid.

PID_{RP} Registration. The user registers PID_{RP} at the IdP.

- 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 verifies that PID_{RP} is unique among unexpired PID_{RPs} , and then signs the response $[PID_{RP}, Hash(N_U), Validity]_{SK}$, where $Validity$ is the validity period.
- 3.3 The IdP script forwards the registration result to the RP server through RP script.
- 3.4 The RP verifies the IdP's signature, and accepts it only if PID_{RP} and $Hash(N_U)$ match those in the negotiation and it is in the validity period.

$Hash(N_U)$ is attached as the nonce to avoid the registration result is accepted by two or more RPs, which have different ID_{RPs} but generate a same PID_{RP} . The IdP ensures PID_{RP} is unique among unexpired ones; otherwise, one

identity proof for one PID_{RP} might be accepted by other RPs. More details are analyzed in Section ??.

ID Proof Generation. In this phase, the user login continues and the IdP signs the identity proof.

- 4.1 The RP uses PID_{RP} and $Endpoint_{RP}$ to construct an identity proof request for a set of user's attributes, and the request is forwarded to IdP script through RP script.
- 4.2 The IdP authenticates the user if she has not been authenticated yet.
- 4.3 The user first confirms the scope of the requested attributes. IdP script verifies the PID_{RP} with the negotiated one and $Endpoint_{RP} \in Cert_{RP}$, replaces the endpoint with the registered one-time $Endpoint_U$ and then sends the modified identity proof request to the IdP server.
- 4.4 The IdP verifies whether PID_{RP} and $Endpoint_U$ have been registered and unexpired, and calculates $PID_U = PID_{RP}^{ID_U} \bmod p$ 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, $Attr$ contains the requested attributes.

- 4.6 Then, the IdP sends the identity proof to the one-time endpoint at the user. The IdP script forwards the identity proof to RP script with the origin $Endpoint_{RP}$ and RP script sends it to the server.

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.

Account calculation. Finally, RP derives the user's *Account* and completes the user login as follows.

- 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 $Account = PID_U^T \bmod p$, and allows the user to log in.

D. Compatibility with OIDC

As described above, the SSO login protocol of UPPRESSO follows a same logic flow of OIDC login protocol with small modifications to transform the identifiers. Next, we will discuss these necessary modifications and demonstrate its compatibility with OIDC. This indicates that it can be easily integrated with other commonly adopted SSO systems.

First, UPPRESSO does not introduce any new role nor change the security assumptions for each role. Moreover, among the five phases of its SSO login flow, only the scripts downloading and RP identifier transformation phase are newly introduced by UPPRESSO, while the other three (PID_{RP} registration, identity proof generation and *Account* calculation) adopt similar communication pattern as OIDC flows.

In particular, the PID_{RP} registration phase can be viewed as a variant of the RP dynamic registration flow of OIDC [18], where an entity registers its identity and endpoint at the IdP. The RP endpoint is the required parameter for dynamic registration, therefore, here we add the $Endpoint_U$ to meet the requirement of registration process. Different from OIDC, in UPPRESSO, this process can be launched by any authenticated user who obtains an RP identifier, the registration response includes a signature by the IdP, and the registration will become invalid after a validity period. However, these changes only require small modifications to the RP dynamic registration flow of OIDC.

The identity proof generation and *Account* calculation phases adopt the same steps and functions as the implicit protocol flow of OIDC but calling 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 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 VIII.

VI. WEB MODEL

Our formal analysis of UPPRESSO is based on the Dolev-Yao style web model [15], which has been widely used in formal analysis of SSO protocol, e.g., OAuth 2.0 [21] and OIDC [22]. To make the description cleaner, we focus on our modification on OIDC, and assume DNS and HTTPS are secure, which has already been analyzed in [15].

The main entities in the model are *atomic processes*, which represent the essential nodes in the web systems, such as browsers, web servers and attackers. The atomic processes communicate with each other through the *events* containing the receiver atomic process's address (IP), the sender atomic process's address (IP) and the transmitted *message*. Moreover, there are also dependent *scripting processes* which runs on the client-side environment relying on the browsers such as JavaScript. The scripting provides the server defined function to the browser. The web system mainly consists of the set of atomic processes and scripting processes. The operation of a system is described as that the system converts its states via step of runs. The state of web system is called *configuration* which consists of all the states of the atomic processes in the system and all the event can be accepted by the processes.

A. Communication Description

Here we give a brief presentation of generic Dolev-Yao-style communication model proposed by [15] on which our web model is based.

A *signature* Σ consists of a finite set of function symbols, such as *encrypt*, *decrypt*, and *pair*, each with an arity. A function symbol with arity 0 (with no arguments) is a constant symbol. The set of *terms* is defined over a signature Σ , an infinite set of names, and an infinite set of variables.

Messages are defined as formal terms without variables (called ground terms). The signature Σ for the messages in the model is considered containing constants (such as ASCII strings and nonce), sequence symbols (such as n-ary sequences $\langle \rangle$, $\langle . \rangle$, $\langle ., . \rangle$ etc.) and further function symbols (such as encryption/decryption and digital signatures). An HTTP request is a common message in the web model, containing a type HTTPReq, a nonce n , a method GET or POST, a domain, a path, URL parameters, request headers, and the body over the Σ in the sequence symbol format. Here is an example for an HTTP GET request for the domain *exa.com/path?para=1* with the headers and body empty.

$$m := \langle \text{HTTPReq}, n, \text{GET}, \text{exa.com}, /path, \langle \langle para, 1 \rangle \rangle, \langle \rangle, \langle \rangle \rangle$$

Events are the basic communication elements in the model. An event is the term in the format $\langle a, f, m \rangle$, where the a and f represent the address of sender and receiver, and m is the message transmitted.

Atomic Processes. An *atomic Dolev–Yao* (DY) process is constructed as the tuple $p = (I^p, Z^p, R^p, s_0^p)$ representing the single node in the web model, such as the server and browser. I^p is the set of addresses a process listens to, and Z^p is the set of states (terms) which describes the process. R^p is the mapping between the pairs $\langle s, e \rangle$ and $\langle s', e' \rangle$ where $s, s' \in Z^p$. It's worth noting that for one process in a state only a finite set of events can be accepted by the process as the state and event are defined as the input of R^p .

Scripting Processes. The web model also contains the scripting process representing the client-side script loaded by browser such as JavaScript code. However, the *scripting process* must rely on an *atom process* such as browser and provide the relation R which is called by this *atomic process*.

Equational theory is defined as usual in Dolev-Yao models which introduces the symbol \equiv representing the congruence relation on terms. For instance, $dec(enc(m, k), k) \equiv m$.

B. Web System

The web system contains a set of processes (including atomic processes and scripting processes) and represents the web infrastructure. A web system is defined as a tuple $(\mathcal{W}, \mathcal{S}, \text{script}, E^0)$. \mathcal{W} is the set of atomic processes containing honest processes and malicious processes, \mathcal{S} is the set of scripting processes including honest scripts and malicious scripts, script is the set of concrete script code related with specific scripting process in \mathcal{S} , and E^0 is the set of events which could be accepted by the processes in \mathcal{W} .

Configuration. We firstly define the set of states S of a system, consists of all the current states of processes in \mathcal{W} . And the set of events E , for each event $e \in E$, there is always a state $s \in S$, e and s can be accepted by one of the processes as the input. A *configuration* of the system is defined as the tuple (S, E, N) where N is the mentioned sequence of unused nonces.

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

C. Model Of UPPRESSO

The UPPRESSO model is a web system which is defined as

$$\mathcal{UWS} = (\mathcal{W}, \mathcal{S}, \text{script}, E^0),$$

\mathcal{W} is the finite set of atom processes in UPPRESSO system including a single IdP server process, multiple honest RP server processes, the browsers representing the users, and the attacker processes. We assume that all the honest RPs are implemented following the same rule so that the process are considered consistent besides of the addresses they listen to. The browsers controlled by user are considered honest. That is, the browser controlled by attackers can behave as an independent atomic process. \mathcal{S} is the finite set of scripting processes consists of script_{rp} , script_{idp} and $\text{script}_{attacker}$. The script_{rp} and script_{idp} are downloaded from honest RP and IdP processes and the $\text{script}_{attacker}$ is downloaded from attacker process considered existing in all browser processes.

We now give a brief description about UPPRESSO model.

- The browser is responsible to send HTTP request, receive HTTP response, handle user behaviour and transmit message between scripting process. As the browser is honest, we only focus on the scripting process running on the browser. The detailed model of browser is shown in [15]
- IdP server process (defined as p^i) only accepts the events whose messages are HTTP request and the $\text{path} \in \{ /script, /dynamicRegistration, /login, /loginInfo, /authorize \}$. The function of each path is shown in Section V. All the events are accepted by p^i in any state but the output may be different. The detailed R^i is shown in *.
- RP server process (defined as p^r) only accepts the events whose messages are HTTP request and the $\text{path} \in \{ /script, /login, /startNegotiation, /registrationResult, /uploadToken \}$. The function of each path is shown in Section V. The event with $\text{path} \in \{ /script, /login, /startNegotiation \}$ are accepted in any state. However, the event with $\text{path} \equiv /registrationResult$ is accepted only when the state s is the output for event $\text{path} \equiv /startNegotiation$. In the same way the following accepted events must be arranged as path in the sequence $/registrationResult, /uploadToken$.
- IdP and RP scripting process accepts the events in the formate as HTTP response and postMessage. The details about accepted events are shown in ??.

D. Security Of UPPRESSO

As we assume that the HTTP requests and responses are well protected by TLS, and the postMessage are securely implemented in browser, therefore, web attackers are not considered. In this section, we are going to prove the following theorem,

Theorem 1. Let \mathcal{UWS} be a UPPRESSO web system, then \mathcal{UWS} is secure.

Firstly, an SSO system is considered secure **iff** only the legitimate user can always log into an honest RP under her unique account. Based on the model of UPPRESSO, we found that an attacker can visit an honest RP as the honest user only when the attacker own the cookie which is bound to the honest user by RP. Therefore, the definition of a secure UPPRESSO system is,

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

Therefore, to prove theorem 1, we are going to prove that an authenticate cookie c is unknown to attacker a . The proof can be separated as two parts, initially a does not know any authenticated cookie, and the following requirements must be met.

- If c is the authenticated cookie owned by u , c cannot be obtained by a .

- If c is an unauthenticated cookie owned by a , c cannot be authenticated by r for u .

Proof Outline. Here we introduce the lemmas briefly to prove that UWS follows the requirements by Definition 1 so that UWS is secure. And the detailed proofs to these lemmas are in ??.

Lemma 1. The cookie owned by honest user will not be leaked to any attacker.

Proof: That is, due to the Same-Origin policy, the honest browser will not leak the cookies to any attacker. And based on the UPPRESSO model, it is to prove that RP server and RP script will not send any cookies to other processes either. Therefore, the attackers cannot obtain the u 's authenticated cookie. ■

Based on the model of UPPRESSO about RP server process, the procedure of the cookie being authenticated is described as follows.

Definition 2. In UWS , the cookie c is to be set authenticated for user u only when RP r receives a valid u 's identity proof from the owner of c .

Then we are going to prove that UWS follows the requirements that the cookie of the attacker cannot be set authenticated.

Here we propose the lemmas

Lemma 2. Attackers cannot obtain the user u 's password in UWS .

Lemma 3. Attackers cannot forge the IdP issued proofs in UWS .

Proof: Lemma 2 can be easily proved because the password is only sent by honest IdP scripting process to IdP server. Lemma 3 is proved as the IdP issued proofs are well signed and verified. Therefore, the following lemma can be proved base on Lemma 2 and Lemma 3. ■

Lemma 4. Attackers cannot obtain the u 's valid identity proof in UWS .

Proof: We now give a brief proof about Lemma 4. As the attacker attempts to obtain a valid identity proof, he must receive the proof from one of following processes, IdP server process, RP server process, IdP scripting process and RP scripting process. That is, according to the model we find the honest RP scripting process only send identity proof to honest RP server and RP server will not send the proof to any process. It can be proved that only the process who holds u 's password can obtain the u 's identity proof from IdP server. As the attacker does not know u 's password so that he cannot obtain the identity proof from IdP server. To prove that attacker cannot obtain the identity from IdP scripting process is a little complicated so that we here only give a straightforward conclusion. That is when the honest user u sends the identity proof from the IdP scripting process, the receiver is restricted by the RP Certification $cert_r$. And the identity proof is valid in honest RP r only if the $cert_r$ belongs to r (the full proof is in ??). ■

Therefore, UWS satisfies the requirements in Definition ??, such that Theorem 1 is proved.

E. Privacy Of UPPRESSO

Firstly we introduce the definition in [15] about static equivalence.

Definition 3. Two messages t_1 and t_2 are statically equivalent, written $t_1 \approx t_2$, if and only if, for all terms such as $M(x)$ and $N(x)$ which only contain one variable x without nonces, it is true that $M(t_1) \equiv N(t_1)$ **iff** $M(t_2) \equiv N(t_2)$. For instance, there are the messages m and m' , symmetric key k , such that $enc(m, k) \approx enc(m', k)$ is always true to the attackers without the k .

Here we give the new definitions

Definition 4. For a large prime p (2048-bit length) and $p-1$'s prime factor q (256-bit length), there are two constants g_1, g_2 as the generators of p and the constants n_1, n_2 ($n_1, n_2 < q$). We define the function symbol $modpow(a, b, p) = a^b \bmod p$, there are $modpow(g_1, n_1, p) \approx modpow(g_2, n_2, p)$ and $modpow(g_1, n_1, p) \approx modpow(g_1, n_2, p)$ always true due to the discrete logarithm problem as the n_1 and n_2 are unknown.

Definition 5. Equivalence of HTTP requests. There are messages m_1 and m_2 , we say that $m_1 \approx m_2$ **iff** the following conditions are met,

- If m_1 and m_2 are HTTPs requests, they are equivalent to the observers besides of the receiver.
- If m_1 and m_2 are HTTPs requests, they are equivalent for the receiver **iff** the value of the Host, Path, Origin and Referer headers in both requests are same, as well as the value of the Parameters and Body are statically equivalent.
- If m_1 and m_2 are HTTP requests, they are equivalent to all the observers as the equivalent HTTPS requests to receivers.

Definition 6. Equivalence of events. There are events $e_1 := \langle a_1, f_1, m_1 \rangle$ and $e_2 := \langle a_2, f_2, m_2 \rangle$, we say that $e_1 \approx e_2$ **iff**

- $a_1 \equiv a_2$ or a_1 and a_2 belong to random addresses.
- $f_1 \equiv f_2$ or f_1 and f_2 belong to random addresses.
- m_1 and m_2 are equivalent.

Then we are going to prove the following theorem

Theorem 2. Let UWS be a UPPRESSO web system, then UWS is IdP-Privacy and RP-Privacy.

The definitions about IdP-Privacy and RP-Privacy are designed as follows.

Definition 7. IdP-Privacy Let UWS be a UPPRESSO web system, there are honest RPs $r_1, r_2 \in \mathcal{W}$, IdP $i \in \mathcal{W}$ and the honest user u , then UWS is IdP-Privacy **iff** for every event e_1 received by i during the u logging in to r_1 , there is always an event e_2 for the u logging in to r_2 , and e_1 and e_2 are equivalent.

Proof: Here we only give a brief proof that UWS meets the conditions defined in Definition 7. Firstly, it is assumed that the HTTPs transmissions well implemented such that all the events to IdP are regarded as equivalent to web attackers. As we consider IdP server is honest but curious, i can only hold the events to IdP server process and does not attempt to steal parameters from other processes or set any illegal parameters in the system.

Here we only focus on the same user's multiple requests to the IdP. IdP server only accepts the events whose messages are HTTP request and the $path \in \{ /script, /dynamicRegistration, /login, /loginInfo, /authorize \}$. All the path will be visited in each login procedure. It can be easily found that the visits to $/script$ and $/loginInfo$ carrying no parameters and bodies so that the events must be equivalent. The visits to $/login$ only carry u 's username and password so that the events are equivalent. Moreover, the visits to $/dynamicRegistration$ and $/authorize$ carry the PID_{RPs} and $endpoints$ where PID_{RPs} are statically equivalent because of Definition 4 and $endpoints$ are unrelated random constants. Therefore, UWS meets the conditions defined in Definition 1, so that theorem 1 is proved. ■

Definition 8. RP-Privacy Let UWS be a UPPRESSO web system, there are honest RPs $r_1, r_2 \in \mathcal{W}$ and the honest users u_1 and u_2 , then UWS is RP-Privacy iff event through r_1 and r_2 share their states

- for every event e_1 received by r_2 during the u_1 logging in to r_2 , there is always an event e_2 for the u_2 logging in to r_2 , and e_1 and e_2 are equivalent to r_1 .
- for every events received by r_2 , the event cannot be straightforward linked to the existing user's attributes at r_1 .

RP server process only accepts the events whose messages are HTTP request and the $path \in \{ /script, /login, /startNegotiation, /registrationResult, /uploadToken \}$. As the RPs may behave malicious so that the events received by RP scripting process should also be considered. However, all of the messages received by RP scripting process are transmitted to RP server. Therefore, we only need to focus on the events received by RP server.

Firstly, we assume that all the parameters are set legally. We give the brief proof. The events visiting to $/script$ and $/login$ carry no parameters and bodies so that the events must be equivalent. The visits to $/startNegotiation$ only carry the nonce so that the events are equivalent. The visits to $/registrationResult$ carry the IdP signed registration result, however, the contents in the result contains the PID_{RP} , N_U and $endpint$. The contents are all random constants (PID_{RP} is regarded as same as N_U) so that the events are equivalent. The visits to $/uploadToken$ includes the identity proof containing the PID_{RP} , PID_U . According to Definition 4, the PID_U s are statically equivalent to r_1 . Moreover, with the r_2 shared state, $Account_{r_1}$ s are known to r_1 . However, r_1 is unable to transform $Account_{r_1}$ s into the users' account $Account_{r_2}$ at r_2 so that the events cannot be linked to the existing user. Therefore, the requirements of Definition 8 are met.

However, as the RPs are considered maybe malicious, such that they will attempt to steal the data from other process or set the malicious parameters during the login procedure. That is, according to Definition 4, the PID_U the $Accounts$ must be equivalent to the attacker as long as the attacker does not know the ID_U . Therefore the attacker may attempt to steal the ID_U from UPPRESSO system. But it is easy to be found that IdP will not send the plain ID_U to any process so that RPs cannot obtain the ID_U . Another way is that RPs may attempt to treat the $Account$ or PID_U to be generated insecurely, but we are going to prove it is impossible.

- RP may lead the login using the forged ID_{RP} or PID_{RP} so that PID_U s and $Accounts$ are no more equivalent. However, ID_{RP} are provided by the $Cert$, protected by the IdP's signature and verified by IdP script. PID_{RP} is generated by the ID_{RP} and the honest user generated nonce. Therefore, it is impossible to lead the honest user to use the illegal ID_{RP} and PID_{RP} .
- RP may also lead the same user to upload the identity proof with same PID_U or $Account$ so that the system is not RP-Privacy according to Definition 8. However, the PID_U is generated with the user's nonce N_U so that it is not controlled by the RP. $Account$ is generated as the form $ID_{RP}^{ID_U} \bmod p$, while RPs may lead the user to use the same ID_{RP} to generate identity proof. However, the ID_{RP} is bound with $Cert$ which is verified by the user and it is easy for user to find out the login RP does not coincide the RP name shown on her browser.

Therefore, we consider that \mathcal{W} meet all the requests defined in Definition 8 so that theorem 2 is proved.

VII. 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.

A. Implementation

We adopt SHA-256 for digest generation, and RSA-2048 for signature generation. We randomly choose a 2048-bit prime as p , a 256-bit prime as q , and the q -order generators as ID_{RP} . N_U and ID_U are 256-bit random numbers. Then, the discrete logarithm problem provides equivalent security strength (i.e., 112 bits) as RSA-2048 [43]. 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 [44], an open-source OIDC Java implementation certificated by the OpenID Foundation [45]. We add 3 lines of Java code to calculate PID_U , about 20 lines to change the way identity proof responded, 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 jsrsasn [46], 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.

B. 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 [44] and SPRESSO [15], where MITREid Connect provides open-source Java implementations [44] of IdP and RP's SDK, and SPRESSO provides the JavaScript implementations based on node.js for all entities [15]. 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 4 phases according to the lifecycle of identity proof: **Identity proof requesting** (Steps 1.1-4.3 in Figure 3), the RP (and user) constructing and transmitting the request to IdP; **Identity proof generation** (Steps 4.4 and 4.5 in Figure 3), the IdP generating identity proof (no user authentication); **Identity proof extraction** (Steps 4.5 and 4.6 in Figure 3), the RP server extracts the identity proof from the IdP; and **Identity proof verification** (Steps 5.1 and 5.2 in Figure 3), the RP verifying and parsing the identity proof.

Results. The evaluation results are provided in Figure 4. The overall processing times are 113 ms, 308 ms and 492 ms for MITREid Connect, SPRESSO and UPPRESSO, respectively. The part in UPPRESSO takes the longest time is opening the new window and downloading the script which totally cost about 255 ms. The time cost can be cut down as the browser can implicitly conduct this procedure while user visit the RP website. The details are as follows.

In the requesting, UPPRESSO requires firstly user downloads the RP script, opens the IdP window and downloads the

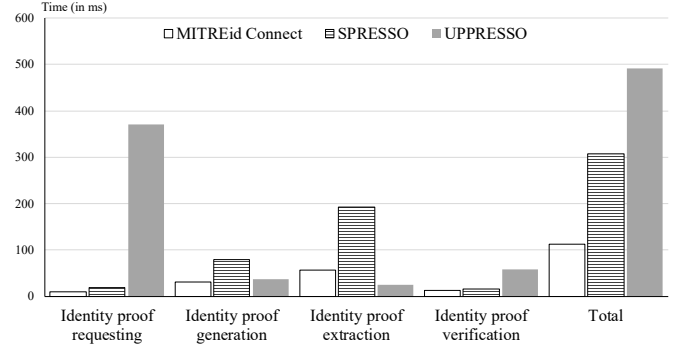


Fig. 4: The Evaluation.

IdP script, then both the user and RP to perform 1 modular exponentiations for RP identifier transformation and complete PID_{RP} registration at the IdP, which totally need 371 ms, where SPRESSO needs 19 ms for the RP to obtain IdP's public key and encrypt its domain; while MITREid Connect only needs 10 ms.

In the generation, UPPRESSO needs an extra 6 ms for 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 extraction, UPPRESSO only needs about 25 ms where the scripts relay the identity proof to the RP server. 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 57 ms. SPRESSO needs the longest time (193 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.

In the verification, UPPRESSO needs an extra calculation for $Account$, which then requires 58 ms, compared to 14 ms in MITREid Connect and 17 ms in SPRESSO.

VIII. 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_{RPs} are different among the unexpired identity proof (the number denoted as n). We assume that IdP doesn't perform the uniqueness check, and then calculate the probability that at least two PID_{RPs} are equal in these n ones. The probability

is $1 - \prod_{i=0}^{n-1} (1 - i/q)$ which increases with n . 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, n is less than 2^{36} , then the probability is less than 2^{-183} for 256-bit q . 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 2.1) and identity proof generation (Step 3.2) 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. The adversary may act as a user requesting to log into an RP, and make the RP perform two modular exponentiations. The RP could previously calculated a set of Y_{RPs} to mitigate this attack.

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 [47] and user's identifier check [15]. With certificate transparency [47], 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 [15].

IX. RELATED WORKS

Various SSO protocols have been proposed, such as, OIDC, OAuth 2.0, SAML, Central Authentication Service (CAS) [48] and Kerberos [49]. These protocols are widely adopted in Google, Facebook, Shibboleth project [50], Java applications and etc. And, plenty of works have been conducted on privacy protection and security analysis for SSO systems.

A. Privacy protection for SSO systems.

Privacy-preserving SSO systems. As suggested by NIST [7], 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 [15] and BrowserID [14] only prevent IdP-based login tracing. BrowserID is adopted in Persona [17] and Firefox Accounts [9], however an analysis on Persona found IdP-based

login tracing could still succeed [14], [51]. UPPRESSO prevents both the RP-based identity linkage and IdP-based login tracing, and could be integrated into OIDC which has been formally analyzed [22].

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 [52]. The notion of anonymous SSO was formalized [53] in 2013. And, various cryptographic primitives, such as group signature, zero-knowledge proof and etc., were adopted to design anonymous SSO schemes [53], [54]. Anonymous SSO schemes are designed for the anonymous services, and not applicable to common services which need user identification.

B. 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. [21], [22] have conducted the formal analysis on OAuth 2.0 and OIDC standards based on an expressive Dolev-Yao style model [51], 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. [21], [22] 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. [20] 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 [24], [25], [36]–[38], integrity [23], [24], [28], [30], [31], [38] or RP designation [28], [30]–[32], [38] of identity proof. Wang et al. [24] 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 [25], 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 [23], [24], [28], [30], [31], due to various vulnerabilities, such as XML Signature wrapping (XSW) [23], RP's incomplete verification [24], [28], [31], IdP spoofing [30], [31] and etc. And,

a dedicated, bidirectional authenticated secure channel was proposed to improve the confidentiality and integrity of identity proof [39]. The vulnerabilities were also found to break the RP designation, such as the incorrect binding at IdPs [28], [32], insufficient verification at RPs [30]–[32]. Automatic tools, such as SSOScan [26], OAuthTester [29] and S3KVetter [32], 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 [27], [35], 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 [33], [35]. The top Android applications have been analyzed [27], [33]–[35], [40], and vulnerabilities were found to break the confidentiality [27], [33]–[35], [40], integrity [33], [35], and RP designation [34], [35] of identity proof.

X. 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 $\mathcal{F}_{ID_{RP} \rightarrow PID_{RP}}$ prevents curious IdP from knowing the identity of the RP, $\mathcal{F}_{ID_U \rightarrow PID_U}$ prevents collusive RPs from linking a user based on her identifier, and $\mathcal{F}_{PID_U \rightarrow Account}$ 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 254 ms on average.

REFERENCES

- [1] Nat Sakimura, John Bradley, Mike Jones, Breno de Medeiros, and Chuck Mortimore, “OpenID Connect core 1.0 incorporating errata set 1,” *The OpenID Foundation, specification*, 2014.
- [2] Dick Hardt, “The OAuth 2.0 Authorization Framework,” *RFC*, vol. 6749, pp. 1–76, 2012.
- [3] John Hughes, Scott Cantor, Jeff Hodges, Frederick Hirsch, Prateek Mishra, Rob Philpott, and Eve Maler, “Profiles for the OASIS Security Assertion Markup Language (SAML) v2.0,” *OASIS standard*, 2005, Accessed August 20, 2019.
- [4] “The top 500 sites on the web,” <https://www.alexa.com/topsites>, Accessed July 30, 2019.
- [5] Mohammad Ghasemisharif, Amrutha Ramesh, Stephen Checkoway, Chris Kanich, and Jason Polakis, “O single sign-off, where art thou? An empirical analysis of single sign-on account hijacking and session management on the web,” in *Proceedings of the 27th USENIX Security Symposium, USENIX Security, Baltimore, MD, USA*, 2018, pp. 1475–1492.

- [6] Eve Maler and Drummond Reed, “The venn of identity: Options and issues in federated identity management,” *IEEE Security & Privacy*, vol. 6, no. 2, pp. 16–23, 2008.
- [7] Paul A Grassi, M Garcia, and J Fenton, “NIST special publication 800-63c digital identity guidelines: Federation and assertions,” *National Institute of Standards and Technology, Los Altos, CA*, 2017.
- [8] “Google identity platform,” <https://developers.google.com/identity/>, Accessed August 20, 2019.
- [9] “About firefox accounts,” <https://mozilla.github.io/application-services/docs/accounts/welcome.html>, Accessed August 20, 2019.
- [10] Sydney Li and Jason Kelley, “Google screenwise: An unwise trade of all your privacy for cash,” <https://www.eff.org/deeplinks/2019/02/google-screenwise-unwise-trade-all-your-privacy-cash>, Accessed July 20, 2019.
- [11] Bennett Cyphers and Jason Kelley, “What we should learn from “facebook research”,,” <https://www.eff.org/deeplinks/2019/01/what-we-should-learn-facebook-research>, Accessed July 20, 2019.
- [12] Rakesh Agrawal, Alexandre V. Evfimievski, and Ramakrishnan Srikant, “Information sharing across private databases,” in *Proceedings of the 30th ACM International Conference on Management of Data (SIGMOD), San Diego, California, USA*, 2003, pp. 86–97.
- [13] Emiliano De Cristofaro and Gene Tsudik, “Practical private set intersection protocols with linear complexity,” in *Proceedings of the 14th International Conference on Financial Cryptography and Data Security (FC), Canary Islands, Spain*, 2010, pp. 143–159.
- [14] Daniel Fett, Ralf Küsters, and Guido Schmitz, “Analyzing the BrowserID SSO system with primary identity providers using an expressive model of the web,” in *Proceedings of the 20th European Symposium on Research in Computer Security (ESORICS)*, 2015, pp. 43–65.
- [15] Daniel Fett, Ralf Küsters, and Guido Schmitz, “SPRESSO: A secure, privacy-respecting single sign-on system for the web,” in *Proceedings of the 22nd ACM SIGSAC Conference on Computer and Communications Security (CCS), Denver, CO, USA*, 2015, pp. 1358–1369.
- [16] Thomas Hardjono and Scott Cantor, “SAML v2.0 subject identifier attributes profile version 1.0,” *OASIS standard*, 2019.
- [17] Mozilla Developer Network (MDN), “Persona,” <https://developer.mozilla.org/en-US/docs/Archive/Mozilla/Persona>.
- [18] Nat Sakimura, John Bradley, Mike Jones, Breno de Medeiros, and Chuck Mortimore, “OpenID Connect dynamic client registration 1.0 incorporating errata set 1,” *The OpenID Foundation, specification*, 2014.
- [19] Taher El Gamal, “A public key cryptosystem and a signature scheme based on discrete logarithms,” in *Proceedings of 4th International Cryptology Conference (CRYPTO), Santa Barbara, California, USA*, 1984, pp. 10–18.
- [20] Alessandro Armando, Roberto Carbone, Luca Compagna, Jorge Cuéllar, and M. Llanos Tobarra, “Formal analysis of SAML 2.0 web browser single sign-on: breaking the SAML-based single sign-on for Google apps,” in *Proceedings of the 6th ACM Workshop on Formal Methods in Security Engineering (FMSE), Alexandria, VA, USA*, 2008, pp. 1–10.
- [21] Daniel Fett, Ralf Küsters, and Guido Schmitz, “A comprehensive formal security analysis of OAuth 2.0,” in *Proceedings of the 2016 ACM SIGSAC Conference on Computer and Communications Security (CCS), Vienna, Austria*, 2016, pp. 1204–1215.
- [22] Daniel Fett, Ralf Küsters, and Guido Schmitz, “The web SSO standard OpenID Connect: In-depth formal security analysis and security guidelines,” in *Proceedings of the 30th IEEE Computer Security Foundations Symposium (CSF), Santa Barbara, CA, USA*, 2017, pp. 189–202.
- [23] Juraj Somorovsky, Andreas Mayer, Jörg Schwenk, Marco Kampmann, and Meiko Jensen, “On breaking SAML: Be whoever you want to be,” in *Proceedings of the 21th USENIX Security Symposium, Bellevue, WA, USA*, 2012, pp. 397–412.
- [24] Rui Wang, Shuo Chen, and XiaoFeng Wang, “Signing me onto your accounts through Facebook and Google: A traffic-guided security study of commercially deployed single-sign-on web services,” in *Proceedings of the 33rd IEEE Symposium on Security and Privacy (S&P), San Francisco, California, USA*, 2012, pp. 365–379.
- [25] Alessandro Armando, Roberto Carbone, Luca Compagna, Jorge Cuéllar, Giancarlo Pellegrino, and Alessandro Sorniotti, “An authentication flaw

- in browser-based single sign-on protocols: Impact and remediations,” *Computers & Security*, vol. 33, pp. 41–58, 2013.
- [26] Yuchen Zhou and David Evans, “SSOScan: Automated testing of web applications for single sign-on vulnerabilities,” in *Proceedings of the 23rd USENIX Security Symposium, San Diego, CA, USA, 2014*, pp. 495–510.
- [27] Hui Wang, Yuanyuan Zhang, Juanru Li, Hui Liu, Wenbo Yang, Bodong Li, and Dawu Gu, “Vulnerability assessment of OAuth implementations in Android applications,” in *Proceedings of the 31st Annual Computer Security Applications Conference (ACSAC), Los Angeles, CA, USA, 2015*, pp. 61–70.
- [28] Hui Wang, Yuanyuan Zhang, Juanru Li, and Dawu Gu, “The achilles heel of OAuth: A multi-platform study of OAuth-based authentication,” in *Proceedings of the 32nd Annual Conference on Computer Security Applications (ACSAC), Los Angeles, CA, USA, 2016*, pp. 167–176.
- [29] Ronghai Yang, Guanchen Li, Wing Cheong Lau, Kehuan Zhang, and Pili Hu, “Model-based security testing: An empirical study on OAuth 2.0 implementations,” in *Proceedings of the 11th ACM on Asia Conference on Computer and Communications Security (AsiaCCS), Xi’an, China, 2016*, pp. 651–662.
- [30] Christian Mainka, Vladislav Mladenov, and Jörg Schwenk, “Do not trust me: Using malicious IDPs for analyzing and attacking single sign-on,” in *Proceedings of the 1st IEEE European Symposium on Security and Privacy (EuroS&P), Saarbrücken, Germany, 2016*, pp. 321–336.
- [31] Christian Mainka, Vladislav Mladenov, Jörg Schwenk, and Tobias Wich, “Sok: Single sign-on security - an evaluation of OpenID Connect,” in *Proceedings of the 2nd IEEE European Symposium on Security and Privacy (EuroS&P), Paris, France, 2017*, pp. 251–266.
- [32] Ronghai Yang, Wing Cheong Lau, Jiongyi Chen, and Kehuan Zhang, “Vetting single sign-on SDK implementations via symbolic reasoning,” in *Proceedings of the 27th USENIX Security Symposium, USENIX Security, Baltimore, MD, USA, 2018*, pp. 1459–1474.
- [33] Ronghai Yang, Wing Cheong Lau, and Shangcheng Shi, “Breaking and fixing mobile app authentication with OAuth2.0-based protocols,” in *Proceedings of the 15th International Conference on Applied Cryptography and Network Security (ACNS), Kanazawa, Japan, 2017*, pp. 313–335.
- [34] Shangcheng Shi, Xianbo Wang, and Wing Cheong Lau, “MoSSOT: An automated blackbox tester for single sign-on vulnerabilities in mobile applications,” in *Proceedings of the 14th ACM Asia Conference on Computer and Communications Security (AsiaCCS), Auckland, New Zealand, 2019*, pp. 269–282.
- [35] Eric Y. Chen, Yutong Pei, Shuo Chen, Yuan Tian, Robert Kotcher, and Patrick Tague, “OAuth demystified for mobile application developers,” in *Proceedings of the 2014 ACM SIGSAC Conference on Computer and Communications Security (CCS), Scottsdale, AZ, USA, 2014*, pp. 892–903.
- [36] San-Tsai Sun and Konstantin Beznosov, “The devil is in the (implementation) details: an empirical analysis of OAuth SSO systems,” in *Proceedings of the 19th ACM SIGSAC Conference on Computer and Communications Security (CCS), Raleigh, NC, USA, 2012*, pp. 378–390.
- [37] Chetan Bansal, Karthikeyan Bhargavan, Antoine Delignat-Lavaud, and Sergio Maffei, “Discovering concrete attacks on website authorization by formal analysis,” *Journal of Computer Security*, vol. 22, no. 4, pp. 601–657, 2014.
- [38] Wanpeng Li and Chris J. Mitchell, “Analysing the security of Google’s implementation of OpenID Connect,” in *Proceedings of the 13th International Conference on Detection of Intrusions and Malware & Vulnerability Assessment (DIMVA), San Sebastián, Spain, 2016*, pp. 357–376.
- [39] Yinzhi Cao, Yan Shoshitaishvili, Kevin Borgolte, Christopher Krügel, Giovanni Vigna, and Yan Chen, “Protecting web-based single sign-on protocols against relying party impersonation attacks through a dedicated bi-directional authenticated secure channel,” in *Proceedings of the 17th International Symposium on Research in Attacks, Intrusions and Defenses (RAID), Gothenburg, Sweden., 2014*, pp. 276–298.
- [40] Mohamed Shehab and Fadi Mohsen, “Towards enhancing the security of OAuth implementations in smart phones,” in *Proceedings of the 3rd IEEE International Conference on Mobile Services, Anchorage, AK, USA, 2014*, pp. 39–46.
- [41] Ding Wang, Zijian Zhang, Ping Wang, Jeff Yan, and Xinyi Huang, “Targeted online password guessing: An underestimated threat,” in *Proceedings of the 23rd ACM SIGSAC Conference on Computer and Communications Security (CCS), Vienna, Austria, 2016*, pp. 1242–1254.
- [42] Hung-Min Sun, Yao-Hsin Chen, and Yue-Hsun Lin, “oPass: A user authentication protocol resistant to password stealing and password reuse attacks,” *IEEE Transactions on Information Forensics and Security (TIFS)*, vol. 7, no. 2, pp. 651–663, 2012.
- [43] Elaine Barker, “Recommendation for key management part 1: General (revision 4),” *NIST special publication*, vol. 800, no. 57, pp. 1–160, 2016.
- [44] “MITREid connect /openid-connect-java-spring-server,” <https://github.com/mitreid-connect/OpenID-Connect-Java-Spring-Server>, Accessed August 20, 2019.
- [45] “Openid foundation,” <https://openid.net/certification/>, Accessed August 20, 2019.
- [46] “jsrsasign,” <https://kjur.github.io/jsrsasign/>, Accessed August 20, 2019.
- [47] Ben Laurie, Adam Langley, and Emilia Käseper, “Certificate transparency,” *RFC*, vol. 6962, pp. 1–27, 2013.
- [48] Pascal Aubry, Vincent Mathieu, and Julien Marchal, “ESUP-portail: Open source single sign-on with CAS (central authentication service),” *Proceedings of EUNIS04—IT Innovation in a Changing World*, pp. 172–178, 2004.
- [49] Jennifer G. Steiner, B. Clifford Neuman, and Jeffrey I. Schiller, “Kerberos: An authentication service for open network systems,” in *Proceedings of the USENIX Winter Conference. Dallas, Texas, USA, 1988*, pp. 191–202.
- [50] “The shibboleth project,” <https://www.shibboleth.net>, Accessed July 30, 2019.
- [51] Daniel Fett, Ralf Küsters, and Guido Schmitz, “An expressive model for the web infrastructure: Definition and application to the BrowserID SSO system,” in *Proceedings of the 35th IEEE Symposium on Security and Privacy (S&P), Berkeley, CA, USA, 2014*, pp. 673–688.
- [52] Kalid Elmufti, Dasun Weerasinghe, Muttukrishnan Rajarajan, and Veselin Rakocevic, “Anonymous authentication for mobile single sign-on to protect user privacy,” *International Journal of Mobile Communications (IJMC)*, vol. 6, no. 6, pp. 760–769, 2008.
- [53] Jingquan Wang, Guilin Wang, and Willy Susilo, “Anonymous single sign-on schemes transformed from group signatures,” in *Proceedings of the 5th International Conference on Intelligent Networking and Collaborative Systems, Xi’an, China, 2013*, pp. 560–567.
- [54] Jinguang Han, Liquan Chen, Steve Schneider, Helen Treharne, and Stephan Wesemeyer, “Anonymous single-sign-on for n designated services with traceability,” in *Proceedings of the 23rd European Symposium on Research in Computer Security (ESORICS), Barcelona, Spain, 2018*, pp. 470–490.

APPENDIX A WEB MODEL

A. Data Formate

Here we provide the details of formate of some messages we use to construct the UPPRESSO model.

HTTP Messages. An HTTP request message is the term of the form

$$\langle \text{HTTPReq}, \text{nonce}, \text{method}, \text{host}, \text{path}, \text{parameters}, \text{headers}, \text{body} \rangle$$

An HTTP response message is the term of the form

$$\langle \text{HTTPResp}, \text{nonce}, \text{status}, \text{headers}, \text{body} \rangle$$

The details are dined as follows:

- **HTTPReq** and **HTTPResp** are the type of messages.
- *nonce* is the constant nonce mapping the response with the specific request.
- *method* is the HTTP method, such as GET and POST.
- *host* is the constant string domain of visited server.
- *path* is the constant string representing the concrete resource of the server.
- *parameters* contains the parameters carried by the url as the form $\langle \langle \text{name}, \text{value} \rangle, \langle \text{name}, \text{value} \rangle, \dots \rangle$, , for example the *parameters* HTTP request sent to the url *http : //www.example.com?type = confirm* is $\langle \langle \text{type}, \text{confirm} \rangle \rangle$.
- *headers* is the header content of each HTTP messages as the form $\langle \langle \text{name}, \text{value} \rangle, \langle \text{name}, \text{value} \rangle, \dots \rangle$, such as $\langle \langle \text{Referer}, \text{http : //www.example.com} \rangle, \langle \text{Cookies}, c \rangle \rangle$.
- *body* is the body content carried by HTTP POST request or HTTP response in the form $\langle \langle \text{name}, \text{value} \rangle, \langle \text{name}, \text{value} \rangle, \dots \rangle$.
- *status* is the HTTP status code defined by HTTP standard.

URL. A URL is a term $\langle \text{URL}, \text{protocol}, \text{host}, \text{path}, \text{parameters} \rangle$, where URL is the type, *protocol* is chosen in {S, P} as S stands for HTTPS and P stands for HTTP. The *host*, *path*, and *parameters* are same as in HTTP message.

Origin. An Origin is a term $\langle \text{host}, \text{protocol} \rangle$ that stands for the specific domain used by the HTTP CORS policy, where *host* and *protocol* are defined as same as in URL.

POSTMESSAGE. PostMessage is used in the browser for transmitting messages between scripts from different origins. We define the postMessage as the form $\langle \text{POSTMESSAGE}, \text{target}, \text{Content}, \text{Origin} \rangle$, where POSTMESSAGE is the type, *target* is the constant nonce which stands the for the receiver, *Content* is the message transmitted and Origin is restricts the receiver's origin.

XMLHTTPREQUEST. XMLHttpRequest is the HTTP message transmitted by scripts in the browser. That is the XMLHttpRequest is converted with the HTTP message by the browser. The XMLHttpRequest in the form $\langle \text{XMLHTTPREQUEST}, \text{URL}, \text{methods}, \text{Body}, \text{nonce} \rangle$ can be converted into HTTP request message by the browser, and $\langle \text{XMLHTTPREQUEST}, \text{Body}, \text{nonce} \rangle$ is converted from HTTP response message.

Data Operation. The data used in UPPRESSO are defined in the following forms:

- **Standardized Data** is the data in the fixed format, for instance the HTTP request is the standardized data in the form $\langle \text{HTTPReq}, \text{nonce}, \text{method}, \text{host}, \text{path}, \text{parameters}, \text{headers}, \text{body} \rangle$. We assume there is an HTTP request $r := \langle \text{HTTPReq}, n, \text{GET}, \text{example.com}, / \text{path}, \langle \rangle, \langle \rangle, \langle \rangle \rangle$, here we define the operation on the *r*. That is the elements in *r* can be accessed in the form *r.name*, such that $r.\text{method} \equiv \text{GET}$, $r.\text{path} \equiv / \text{path}$ and $r.\text{body} \equiv \langle \rangle$.
- **Dictionary Data** is the data in the form $\langle \langle \text{name}, \text{value} \rangle, \langle \text{name}, \text{value} \rangle, \dots \rangle$, for instance the *body* in HTTP request is dictionary data. We assume there is a *body* $:= \langle \langle \text{username}, \text{alice} \rangle, \langle \text{password}, 123 \rangle \rangle$, here we define the operation on the *body*. That is we can access the elements in *body* in the form *body[name]*, such that $\text{body}[\text{username}] \equiv \text{alice}$ and $\text{body}[\text{password}] \equiv 123$. We can also add the new attributes to the dictionary, for example after we set $\text{body}[\text{age}] := 18$, the *body* are changed into $\langle \langle \text{username}, \text{alice} \rangle, \langle \text{password}, 123 \rangle, \langle \text{age}, 18 \rangle \rangle$.

Patten Matching. We define the term with the variable \star as the pattern, such as $\langle a, b, \star \rangle$. That is the pattern matches any terms which is in the same form of the pattern but replacing the \star with other terms. For instance, $\langle a, b, \star \rangle$ matches $\langle a, b, c \rangle$.

B. Browser Model

As we consider that the browsers are honest in UPPRESSO model, therefore, we only focus on how the browsers interactive with the scripts.

We firstly introduce the windows and documents of the browser model.

Window. A window w is a term of the form $w = \langle nonce, documents, opener \rangle$, representing the the concrete browser window in the system. The *nonce* is the window reference to identify each windows. The *documents* is the set of documents (defined below) including the current document and cached documents (for example, the documents can be viewed via the "forward" and "back" buttons in the browser). The *opener* represents the widow is created in which document, for instance, while a user clicks the href in document d and it creates a new window w , there is $w.opener \equiv d.nonce$.

Document. A document d is a term of the form

$$\langle nonce, location, referrer, script, scriptstate, scriptinputs, subwindows, active \rangle$$

where document is the HTML content in the window. The *nonce* is to locate the document. *Location* is the URL where the document is loaded. *Referrer* is same as the Referer header defined in HTTP standard. *script* is the scripting process downloaded from each servers. *scriptstate* is define by the script, different in each scripts. *scriptinputs* is the message transmitted into the scripting process. *subwindows* is the set of *nonce* of document's created windows. *active* represents whether this document is active or not.

A scripting process is the dependent process relying on the browser, which can be considered as a relation R mapping a message input and a message output. And finally the browser will conduct the command in the output message. Here we give the description of the form of input and output.

- **Scripting Message Input.** The input is the term in the form

$$\langle tree, docnonce, scriptstate, stateinputs, cookies, localStorage, sessionStorage, ids, secret \rangle$$

- **Scripting Message Output.** The output is the term in the form

$$\langle scriptstate, cookies, localStorage, sessionStorage, command \rangle$$

The *tree* is the relations of the opened windows and documents, which are visible to this script. *Docnonce* is the document nonce. The *Scriptstate* is a term of the form defined by each script. *Scriptinputs* is the message transmitted to script. However, the *scriptinputs* are defined as standardized forms, for example `postMessage` is one of the forms of *scriptinputs*. *Cookies* is the set of cookies belong to the document's origin. *LocalStorage* is the storage space for browser and *sessionStorage* is the space for each HTTP sessions. *Ids* is the set of user IDs while *secret* is the password to corresponding user ID. The *command* is the operation which is to be conducted by the browser. Here we only introduce the form of commands used in UPPRESSO system. We have defined the `postMessage` and `XMLHttpRequest` (for HTTP request) message which are the *commands*. Moreover, a term in the form $\langle IFRAME, URL, WindowNonce \rangle$ asks the browser to create this document's subwindow and it visits the server with the URL.

C. Model Of UPPRESSO

In this section, we will introduce the model of processes in UPPRESSO system, containing IdP server process, RP server process, IdP scripting process and RP scripting process. We will focus on the state form and relation R . They can describe that what kind of event can be accepted by the process in each states, and the content of new output events and states.

D. IdP Server Process

The state of IdP server process is a term in the form $\langle ID, p, SignKey, sessions, users, RPs, Validity, Tokens \rangle$. Other data stored at IdP but not used during SSO authentication are not mentioned here.

- *ID* is the identifier of IdP.
- *p* is the large prime mentioned before.
- *SignKey* is the private key used by IdP to generate signatures.
- *sessions* is the term in the form of $\langle \langle Cookie, session \rangle \rangle$, the Cookie uniquely identify the session and sessions store the browser uploaded message.
- *users* is the set of user information. And each user informations contains the *username*, *password*, *wid* and other user attributes.
- *RPs* is the set of RP information which consists of ID of RP (PID_{RP}), *Endpoints* the set of RP's validity endpoints and *Validity*.

- *Validity* is the validity for IdP generated signatures.
- *Tokens* is the set of IdP generated Identity proofs.

To make the description clearer, we also provide the *functions* to define the complicated procedure.

- *SecretOfID(u)* is used to search the user *u*'s password.
- *UIDOfUser(u)* is used to search the user *u*'s *uid*.
- *ListOfPID()* is the set of IDs of registered RP.
- *EndpointsOfRP(r)* is the set of endpoints registered by the RP with ID *r*.
- *ModPow(a, b, c)* is the result of $a^b \bmod c$.
- *CurrentTime()* is the system current time.

The relation of IdP process R^i is shown as Algorithm 1.

Algorithm 1 R^i

Input: $\langle a, f, m \rangle, s$

```

1: let  $s := s'$ 
2: let  $n, method, path, parameters, headers, body$  such that
    $\langle \text{HTTPReq}, n, method, path, parameters, headers, body \rangle \equiv m$ 
   if possible; otherwise stop  $\langle \rangle, s'$ 
3: if  $path \equiv /script$  then
4:   let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{IdPScript} \rangle$ 
5:   stop  $\langle f, a, m' \rangle, s'$ 
6: else if  $path \equiv /login$  then
7:   let  $cookie := headers[Cookie]$ 
8:   let  $session := s'.sessions[cookie]$ 
9:   let  $username := body[username]$ 
10:  let  $password := body[password]$ 
11:  if  $password \neq \text{SecretOfID}(username)$  then
12:    let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{LoginFailure} \rangle$ 
13:    stop  $\langle f, a, m' \rangle, s'$ 
14:  end if
15:  let  $session[uid] := \text{UIDOfUser}(username)$ 
16:  let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{LoginSuccess} \rangle$ 
17:  stop  $\langle f, a, m' \rangle, s'$ 
18: else if  $path \equiv /loginInfo$  then
19:   let  $cookie := headers[Cookie]$ 
20:   let  $session := s'.sessions[cookie]$ 
21:   let  $username := session[username]$ 
22:   if  $username \neq \text{null}$  then
23:     let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{Logged} \rangle$ 
24:     stop  $\langle f, a, m' \rangle, s'$ 
25:   end if
26:   let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{Unlogged} \rangle$ 
27:   stop  $\langle f, a, m' \rangle, s'$ 
28: else if  $path \equiv /dynamicRegistration$  then
29:   let  $PID_{RP} := body[PID_{RP}]$ 
30:   let  $Endpoint := body[Endpoint]$ 
31:   let  $Nonce := body[Nonce]$ 
32:   if  $PID_{RP} \in \text{ListOfPID}()$  then
33:     let  $Content := \langle \text{Fail}, PID_{RP}, Nonce \rangle$ 
34:     let  $Sig := \text{Sig}(Content, s'.SignKey)$ 
35:     let  $RegistrationResult := \langle Content, Sig \rangle$ 
36:     let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, RegistrationResult \rangle$ 
37:     stop  $\langle f, a, m' \rangle, s'$ 
38:   end if
39:   let  $Validity := \text{CurrentTime}() + s'.Validity$ 
40:   let  $s'.RPs := s'.RPs + \langle \rangle \langle PID_{RP}, Endpoint, Validity \rangle$ 
41:   let  $Content := \langle \text{OK}, PID_{RP}, Nonce, Validity \rangle$ 

```

```

42: let  $Sig := \text{Sig}(\text{Content}, s'.\text{SignKey})$ 
43: let  $\text{RegistrationResult} := \langle \text{Content}, Sig \rangle$ 
44: let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{RegistrationResult} \rangle$ 
45: stop  $\langle f, a, m' \rangle, s'$ 
46: else if  $\text{path} \equiv /authorize$  then
47:   let  $\text{cookie} := \text{headers}[\text{Cookie}]$ 
48:   let  $\text{session} := s'.\text{sessions}[\text{cookie}]$ 
49:   let  $\text{username} := \text{session}[\text{username}]$ 
50:   if  $\text{username} \equiv \text{null}$  then
51:     let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{Fail} \rangle$ 
52:     stop  $\langle f, a, m' \rangle, s'$ 
53:   end if
54:   let  $PID_{RP} := \text{parameters}[PID_{RP}]$ 
55:   let  $\text{Endpoint} := \text{parameters}[\text{Endpoint}]$ 
56:   if  $PID_{RP} \notin \text{ListOfPID}() \vee \text{Endpoint} \notin \text{EndpointsOfRP}(PID)$  then
57:     let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{Fail} \rangle$ 
58:     stop  $\langle f, a, m' \rangle, s'$ 
59:   end if
60:   let  $UID := \text{session}[\text{uid}]$ 
61:   let  $PID_U := \text{ModPow}(PID_{RP}, UID, s'.p)$ 
62:   let  $\text{Validity} := \text{CurrentTime}() + s'.\text{Validity}$ 
63:   let  $\text{Content} := \langle PID_{RP}, PID_U, s'.ID, \text{Validity} \rangle$ 
64:   let  $Sig := \text{Sig}(\text{Content}, s'.\text{SignKey})$ 
65:   let  $\text{Token} := \langle \text{Content}, Sig \rangle$ 
66:   let  $s'.\text{Tokens} := s'.\text{Tokens} + \langle \rangle \text{Token}$ 
67:   let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \langle \text{Token}, \text{Token} \rangle \rangle$ 
68:   stop  $\langle f, a, m' \rangle, s'$ 
69: end if
70: stop  $\langle \rangle, s'$ 

```

E. RP process

The state of RP server process is a term in the form $\langle ID_{RP}, \text{Endpoints}, IdP, \text{Cert}, \text{sessions}, \text{users} \rangle$. Other attributes are not mentioned here.

- ID_{RP} and Endpoints are RP's registered information at IdP.
- Cert is the IdP signed RP information containing $ID_{RP}, \text{Endpoints}$ and other attributes.
- IdP is the term of the for $\langle \text{ScriptUrl}, p, q, \text{PubKey} \rangle$, where ScriptUrl is the site to download IdP script, p and q are large prime defined before, and PubKey is used to verify the IdP signed content.
- sessions is same as it in RP process.
- users is the set of RP registered user which is uniquely identified by the Account .

The new *functions* are defined as follows

- $\text{ExEU}(a, q)$ is the Extended Euclidean algorithm, of which the result in RP process the $a^{-1} \bmod q$.
- $\text{Random}()$ is a newly generated random number.
- $\text{RegisterUser}(\text{Account})$ add the new user with Account into RP's user list.

The relation of RP process R^r is shown as Algorithm 2.

Algorithm 2 R^r

Input: $\langle a, f, m \rangle, s$

```

1: let  $s := s'$ 
2: let  $n, \text{method}, \text{path}, \text{parameters}, \text{headers}, \text{body}$  such that
    $\langle \text{HTTPReq}, n, \text{method}, \text{path}, \text{parameters}, \text{headers}, \text{body} \rangle \equiv m$ 
   if possible; otherwise stop  $\langle \rangle, s'$ 
3: if  $\text{path} \equiv /script$  then
4:   let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{RPScript} \rangle$ 
5:   stop  $\langle f, a, m' \rangle, s'$ 

```

```

6: else if  $path \equiv /login$  then
7:   let  $m' := \langle \text{HTTPResp}, n, 302, \langle \langle Location, s'.IdP.ScriptUrl \rangle, \langle \rangle \rangle \rangle$ 
8:   stop  $\langle f, a, m' \rangle, s'$ 
9: else if  $path \equiv /startNegotiation$  then
10:  let  $cookie := headers[Cookie]$ 
11:  let  $session := s'.sessions[cookie]$ 
12:  let  $N_U := parameters[N_U]$ 
13:  let  $PID_{RP} := \text{ModPow}(s'.ID_{RP}, N_U, s'.IdP.p)$ 
14:  let  $t := \text{ExEU}(N_U, s'.IdP.q)$ 
15:  let  $session[N_U] := N_U$ 
16:  let  $session[PID_{RP}] := PID_{RP}$ 
17:  let  $session[t] := t$ 
18:  let  $session[state] := expectRegistration$ 
19:  let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \langle Cert, s'.Cert \rangle \rangle$ 
20:  stop  $\langle f, a, m' \rangle, s'$ 
21: else if  $path \equiv /registrationResult$  then
22:  let  $cookie := headers[Cookie]$ 
23:  let  $session := s'.sessions[cookie]$ 
24:  if  $session[state] \neq expectRegistration$  then
25:    let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{Fail} \rangle$ 
26:    stop  $\langle f, a, m' \rangle, s'$ 
27:  end if
28:  let  $RegistrationResult := body[RegistrationResult]$ 
29:  let  $Content := RegistrationResult.Content$ 
30:  if  $\text{checksig}(Content, RegistrationResult.Sig, s'.IdP.PubKey) \equiv \text{FALSE}$  then
31:    let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{Fail} \rangle$ 
32:    let  $session := \text{null}$ 
33:    stop  $\langle f, a, m' \rangle, s'$ 
34:  end if
35:  if  $Content.Result \neq OK$  then
36:    let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{Fail} \rangle$ 
37:    let  $session := \text{null}$ 
38:    stop  $\langle f, a, m' \rangle, s'$ 
39:  end if
40:  let  $PID_{RP} := session[PID_{RP}]$ 
41:  let  $N_U := session[N_U]$ 
42:  let  $Nonce := \text{Hash}(N_U)$ 
43:  let  $Time := \text{CurrentTime}()$ 
44:  if  $PID_{RP} \neq Content.PID_{RP} \vee Nonce \neq Content.Nonce \vee Time > Content.Validity$  then
45:    let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{Fail} \rangle$ 
46:    let  $session := \text{null}$ 
47:    stop  $\langle f, a, m' \rangle, s'$ 
48:  end if
49:  let  $session[PIDValidity] := Content.Validity$ 
50:  let  $Endpoint \in s'.Endpoints$ 
51:  let  $session[state] := expectToken$ 
52:  let  $Nonce' := \text{Random}()$ 
53:  let  $session[Nonce] := Nonce'$ 
54:  let  $Body := \langle PID_{RP}, Endpoint, Nonce' \rangle$ 
55:  let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, Body \rangle$ 
56:  stop  $\langle f, a, m' \rangle, s'$ 
57: else if  $path \equiv /uploadToken$  then
58:  let  $cookie := headers[Cookie]$ 
59:  let  $session := s'.sessions[cookie]$ 
60:  if  $session[state] \neq expectToken$  then
61:    let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{Fail} \rangle$ 
62:    stop  $\langle f, a, m' \rangle, s'$ 
63:  end if
64:  let  $Token := body[Token]$ 
65:  if  $\text{checksig}(Token.Content, Token.Sig, s'.IdP.PubKey) \equiv \text{FALSE}$  then
66:    let  $m' := \langle \text{HTTPResp}, n, 200, \langle \rangle, \text{Fail} \rangle$ 
67:    stop  $\langle f, a, m' \rangle, s'$ 

```

```

68: end if
69: let  $PID_{RP} := session[PID_{RP}]$ 
70: let  $Time := CurrentTime()$ 
71: let  $PIDValidity := session[PIDValidity]$ 
72: let  $Content := Token.Content$ 
73: if  $PID_{RP} \neq Content.PID_{RP} \vee Time > Content.Validity \vee Time > PIDValidity$  then
74:   let  $m' := \langle HTTPResp, n, 200, \langle \rangle, Fail \rangle$ 
75:   stop  $\langle f, a, m' \rangle, s'$ 
76: end if
77: let  $PID_U := Content.PID_U$ 
78: let  $t := session[t]$ 
79: let  $Account := ModPow(PID_U, t, s'.IdP.p)$ 
80: if  $Account \in ListOfUser()$  then
81:   let  $RegisterUser(Account)$ 
82: end if
83: let  $session[user] := Account$ 
84: let  $m' := \langle HTTPResp, n, 200, \langle \rangle, LoginSuccess \rangle$ 
85: stop  $\langle f, a, m' \rangle, s'$ 
86: end if
87: stop  $\langle \rangle, s'$ 

```

F. IdP scripting process

The state of IdP scripting process *scriptstate* is a term in the form $\langle IdPDomain, Parameters, p, q, refXHR \rangle$, where

- *IdPDomain* is the IdP's host.
- *Parameters* is used to store the parameters received from other process.
- *p* is the large prime defined before.
- *q* is used to label the procedure point in the login.
- *refXHR* is the nonce to mapping HTTP request and response.

The new *functions* are defined as follows

- $PARENTWINDOW(tree, docnonce)$. The first parameter is the input relation tree defined before, and the second parameter is the nonce of a document. The output returned by the function is the current window's opener's nonce if it exists and is visible to this document.
- $CHOOSEINPUT(inputs, pattern)$. The first parameter is a set of messages, and the second parameter is a pattern. The result returned by the function is the message in *inputs* matching the *pattern*.
- $RandomUrl()$ returns a newly generated host string.

The relation of IdP scripting process *script_idp* is shown as Algorithm 3.

Algorithm 3 *script_idp*

Input: $\langle tree, docnonce, scriptstate, scriptinputs, cookies, localStorage, sessionStorage, ids, secret \rangle$

```

1: let  $s' := scriptstate$ 
2: let  $command := \langle \rangle$ 
3: let  $target := PARENTWINDOW(tree, docnonce)$ 
4: let  $IdPDomain := s'.IdPDomain$ 
5: switch  $s'.q$  do
6:   case start:
7:     let  $N_U := Random()$ 
8:     let  $command := \langle POSTMESSAGE, target, \langle \langle N_U, N_U \rangle \rangle, null \rangle$ 
9:     let  $s'.Parameters[N_U] := N_U$ 
10:    let  $s'.q := expectCert$ 
11:  case expectCert:
12:    let  $pattern := \langle POSTMESSAGE, *, Content, * \rangle$ 
13:    let  $input := CHOOSEINPUT(scriptinputs, pattern)$ 
14:    if  $input \neq null$  then
15:      let  $Cert := input.Content[Cert]$ 

```



```

16:   if  $\text{checksig}(Cert.Content, Cert.Sig, s'.PubKey) \equiv \text{null}$  then
17:     let stop  $\langle \rangle$ 
18:   end if
19:   let  $s'.Parameters[Cert] := Cert$ 
20:   let  $N_U := s'.Parameters[N_U]$ 
21:   let  $PID_{RP} := \text{ModPow}(Cert.Content.ID_{RP}, N_U, s'.p)$ 
22:   let  $s'.Parameters[PID_{RP}] := PID_{RP}$ 
23:   let  $Endpoint := \text{RandomUrl}()$ 
24:   let  $s'.Parameters[Endpoint] := Endpoint$ 
25:   let  $Nonce := \text{Hash}(N_U)$ 
26:   let  $Url := \langle \text{URL}, S, IdPDomain, /dynamicRegistration, \langle \rangle \rangle$ 
27:   let  $s'.refXHR := \text{Random}()$ 
28:   let  $command := \langle \text{XMLHTTPREQUEST}, Url, \text{POST},$ 
     $\langle \langle PID_{RP}, PID_{RP} \rangle, \langle Nonce, Nonce \rangle, \langle Endpoint, Endpoint \rangle \rangle, s'.refXHR \rangle$ 
29:   let  $s'.q := \text{expectRegistrationResult}$ 
30: end if
31: case expectRegistrationResult:
32:   let  $pattern := \langle \text{XMLHTTPREQUEST}, Body, s'.refXHR \rangle$ 
33:   let  $input := \text{CHOOSEINPUT}(\text{scriptinputs}, pattern)$ 
34:   if  $input \neq \text{null} \wedge input.Content[RegistrationResult].type \equiv OK$  then
35:     let  $RegistrationResult := input.Body[RegistrationResult]$ 
36:     if  $RegistrationResult.Content.Result \neq OK$  then
37:       let  $s'.q := \text{stop}$ 
38:       let stop  $\langle \rangle$ 
39:     end if
40:     let  $command := \langle \text{POSTMESSAGE}, target, \langle \langle RegistrationResult, RegistrationResult \rangle \rangle, \text{null} \rangle$ 
41:     let  $s'.q := \text{expectProofRequest}$ 
42:   end if
43: case expectProofRequest:
44:   let  $pattern := \langle \text{POSTMESSAGE}, *, Content, * \rangle$ 
45:   let  $input := \text{CHOOSEINPUT}(\text{scriptinputs}, pattern)$ 
46:   if  $input \neq \text{null}$  then
47:     let  $PID_{RP} := input.Content[PID_{RP}]$ 
48:     let  $Endpoint_{RP} := input.Content[Endpoint]$ 
49:     let  $s'.Parameters[Nonce] := input.Content[Nonce]$ 
50:     let  $Cert := s'.Parameters[Cert]$ 
51:     if  $Endpoint_{RP} \notin Cert.Content.Endpoints \vee PID_{RP} \neq s'.Parameters[PID_{RP}]$  then
52:       let  $s'.q := \text{stop}$ 
53:       let stop  $\langle \rangle$ 
54:     end if
55:     let  $s'.Parameters[Endpoint_{RP}] := Endpoint_{RP}$ 
56:     let  $Url := \langle \text{URL}, S, IdPDomain, /loginInfo, \langle \rangle \rangle$ 
57:     let  $s'.refXHR := \text{Random}()$ 
58:     let  $command := \langle \text{XMLHTTPREQUEST}, Url, \text{GET}, \langle \rangle, s'.refXHR \rangle$ 
59:     let  $s'.q := \text{expectLoginState}$ 
60:   end if
61: case expectLoginState:
62:   let  $pattern := \langle \text{XMLHTTPREQUEST}, Body, s'.refXHR \rangle$ 
63:   let  $input := \text{CHOOSEINPUT}(\text{scriptinputs}, pattern)$ 
64:   if  $input \neq \text{null}$  then
65:     if  $input.Body \equiv \text{Logged}$  then
66:       let  $username \in ids$ 
67:       let  $Url := \langle \text{URL}, S, IdPDomain, /login, \langle \rangle \rangle$   $mystates'.refXHR := \text{Random}()$ 
68:       let  $command := \langle \text{XMLHTTPREQUEST}, Url, \text{POST}, \langle \langle username, username \rangle, \langle password, secret \rangle \rangle, s'.refXHR \rangle$ 
69:       let  $s'.q := \text{expectLoginResult}$ 
70:     else if  $input.Body \equiv \text{Unlogged}$  then
71:       let  $PID_{RP} := s'.Parameters[PID_{RP}]$ 
72:       let  $Endpoint := s'.Parameters[Endpoint]$ 
73:       let  $Nonce := s'.Parameters[Nonce]$ 
74:       let  $Url := \langle \text{URL}, S, IdPDomain, /authorize,$ 
     $\langle \langle PID_{RP}, PID_{RP} \rangle, \langle Endpoint, Endpoint \rangle, \langle Nonce, Nonce \rangle \rangle \rangle$ 
75:       let  $s'.refXHR := \text{Random}()$ 

```

```

76:     let command := ⟨XMLHTTPREQUEST, Url, GET, ⟨⟩, s'.refXHR⟩
77:     let s'.q := expectToken
78:   end if
79: end if
80: case expectLoginResult:
81:   let pattern := ⟨XMLHTTPREQUEST, Body, s'.refXHR⟩
82:   let input := CHOOSEINPUT(scriptinputs, pattern)
83:   if input ≠ null then
84:     if input.Body ≠ LoginSuccess then
85:       let stop ⟨⟩
86:     end if
87:     let PIDRP := s'.Parameters[PIDRP]
88:     let Endpoint := s'.Parameters[Endpoint]
89:     let Nonce := s'.Parameters[Nonce]
90:     let Url := ⟨URL, S, IdPDomain, /authorize,
      ⟨⟨PIDRP, PIDRP⟩, ⟨Endpoint, Endpoint⟩, ⟨Nonce, Nonce⟩⟩⟩
91:     let s'.refXHR := Random()
92:     let command := ⟨XMLHTTPREQUEST, Url, GET, ⟨⟩, s'.refXHR⟩
93:     let s'.q := expectToken
94:   end if
95: case expectToken:
96:   let pattern := ⟨XMLHTTPREQUEST, Body, s'.refXHR⟩
97:   let input := CHOOSEINPUT(scriptinputs, pattern)
98:   if input ≠ null then
99:     let Token := input.Body[Token]
100:    let RPOrigin := ⟨s'.Parameters[EndpointRP], S⟩
101:    let command := ⟨POSTMESSAGE, target, ⟨Token, Token⟩, RPOrigin⟩
102:    let s.q := stop
103:  end if
104: end switch
105: let stop ⟨s', cookies, localStorage, sessionStorage, command⟩

```

G. RP scripting process

The state of RP scripting process *scriptstate* is a term in the form $\langle IdPDomain, RPDomain, Parameters, q, refXHR \rangle$. The *RPDomain* is the host string of the corresponding RP server, and other terms are defined same as them in IdP scripting process.

Here we define another new function *SUBWINDOW(tree, docnonce)*. This function takes the *tree* define above and the current document's *nonce* as the input. And it selects the *nonce* of the first window opened by this document as the output. However, if there is not the opened windows, it will return the null.

The relation of RP scripting process *script_rp* is shown as Algorithm 4.

Algorithm 4 *script_rp*

Input: $\langle tree, docnonce, scriptstate, scriptinputs, cookies, localStorage, sessionStorage, ids, secret \rangle$

```

1: let s' := scriptstate
2: let command := ⟨⟩
3: let IdPWindow := SUBWINDOW(tree, docnonce).nonce
4: let RPDomain := s'.RPDomain
5: let IdPOrigin := ⟨s'.IdPDomain, S⟩
6: switch s'.q do
7:   case start:
8:     let Url := ⟨URL, S, RPDomain, /login, ⟨⟩⟩
9:     let command := ⟨IFRAME, Url, _SELF⟩
10:    let s'.q := expectNU
11:   case expectNU:
12:     let pattern := ⟨POSTMESSAGE, *, Content, *⟩
13:     let input := CHOOSEINPUT(scriptinputs, pattern)
14:     if input ≠ null then
15:       let NU := input.Content[NU]
16:       let Url := ⟨URL, S, RPDomain, /startNegotiation, ⟨⟩⟩

```

```

17:   let  $s'.refXHR := Random()$ 
18:   let  $command := \langle XMLHTTPREQUEST, Url, POST, \langle \langle N_U, N_U \rangle \rangle, s'.refXHR \rangle$ 
19:   let  $s'.q := expectCert$ 
20:   end if
21: case  $expectCert$ :
22:   let  $pattern := \langle XMLHTTPREQUEST, Body, s'.refXHR \rangle$ 
23:   let  $input := CHOOSEINPUT(scriptinputs, pattern)$ 
24:   if  $input \neq null$  then
25:     let  $Cert := input.Content[Cert]$ 
26:     let  $command := \langle POSTMESSAGE, IdPWindow, \langle \langle Cert, Cert \rangle \rangle, IdPOringin \rangle$ 
27:     let  $s'.q := expectRegistrationResult$ 
28:   end if
29: case  $expectRegistrationResult$ :
30:   let  $pattern := \langle POSTMESSAGE, *, Content, * \rangle$ 
31:   let  $input := CHOOSEINPUT(scriptinputs, pattern)$ 
32:   if  $input \neq null$  then
33:     let  $RegistrationResult := input.Content[RegistrationResult]$ 
34:     let  $Url := \langle URL, S, RPDomain, /registrationResult, \rangle \rangle$ 
35:     let  $s'.refXHR := Random()$ 
36:     let  $command := \langle XMLHTTPREQUEST, Url, POST, \langle \langle RegistrationResult, RegistrationResult \rangle \rangle, s'.refXHR \rangle$ 
37:     let  $s'.q := expectTokenRequest$ 
38:   end if
39: case  $expectTokenRequest$ :
40:   let  $pattern := \langle XMLHTTPREQUEST, Body, s'.refXHR \rangle$ 
41:   let  $input := CHOOSEINPUT(scriptinputs, pattern)$ 
42:   if  $input \neq null$  then
43:     let  $PID_{RP} := input.Content.Body[PID_{RP}]$ 
44:     let  $Endpoint := input.Content.Body[Endpoint]$ 
45:     let  $Nonce := input.Content.Body[Nonce]$ 
46:     let  $command := \langle POSTMESSAGE, IdPWindow, \langle \langle PID_{RP}, PID_{RP} \rangle, \langle Endpoint, Endpoint \rangle, \langle Nonce, Nonce \rangle \rangle, IdPOringin \rangle$ 
47:     let  $s'.q := expectToken$ 
48:   end if
49: case  $expectToken$ :
50:   let  $pattern := \langle POSTMESSAGE, *, Content, * \rangle$ 
51:   let  $input := CHOOSEINPUT(scriptinputs, pattern)$ 
52:   if  $input \neq null$  then
53:     let  $Token := input.Content[Token]$ 
54:     let  $Url := \langle URL, S, RPDomain, /uploadToken, \rangle \rangle$ 
55:     let  $s'.refXHR := Random()$ 
56:     let  $command := \langle XMLHTTPREQUEST, Url, POST, \langle \langle Token, Token \rangle \rangle, s'.refXHR \rangle$ 
57:     let  $s'.q := expectLoginResult$ 
58:   end if
59: case  $expectLoginResult$ :
60:   let  $pattern := \langle XMLHTTPREQUEST, Body, s'.refXHR \rangle$ 
61:   let  $input := CHOOSEINPUT(scriptinputs, pattern)$ 
62:   if  $input \neq null$  then
63:     if  $input.Body \equiv LoginSuccess$  then
64:       let  $LoadHomepage$ 
65:     end if
66:   end if
67: end switch

```

H. Proof of Theorem 1

We assume that all the network messages are protected by HTTPS and postMessage messages are protected by the browser, and the browsers are all honest, such that web attackers listening the network flow are not considered.

In this section, we will give a full version of proof about UPPRESSO security. Firstly, we recall the security requirements of UPPRESSO. That is, the system must ensure that only a legitimate user can log into an honest RP under her unique account. We consider the visits to RP's resource paths are controlled by the visitors' cookie, so that the attacker can break the security only when he own the cookie bound to the honest user. Therefore, we can propose the definition 1 about the secure UPPRESSO system.

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

Therefore, the proof of Theorem 1 is converted into whether the UPPRESSO system meet the requirement in definition 1. However, as we consider the attacker initially knows any honest users' cookies, the requirement of definition 1 can be separated as following requirements. Before describe the requirements, we firstly define the user u 's authenticated cookie for RP r as $c(u, r)$.

Requirement 1. If $c(u, r)$ is the authenticated cookie owned by u , $c(u, r)$ cannot be obtained by a .

Requirement 2. If c is an unauthenticated cookie owned by a , c cannot be set as $c(u, r)$.

Requirement 3. The user u does not use the attacker's cookie (defined as $c(a, r)$).

To prove that UPPRESSO meets the requirements, we now show some lemmas. The first lemma here can prove that the UPPRESSO system meets requirement 1.

Lemma 1. Attacker does not learn users' cookies.

Proof: As the Brute-force attacks, such as exhausting the possible users' cookies, are not considered, the attackers can only try to obtain the cookies from honest processes in the system. For an honest user u and the honest RP r , the valid cookie $c(u, r)$ can only be obtained by u 's browser b_u , the r 's script $script_{rp}$ and RP's server P^r . Here we only need to prove that attacker cannot receive the event from these processes carrying $c(u, r)$.

- b_u . The browsers used by users are considered honest and well implemented. Therefore, based on the same-origin policy, b_u only sends r 's cookie to RP's domain, so that attackers cannot receive the cookie.
- $script_{rp}$. According to Algorithm 4, the $script_{rp}$ does not send any cookie.
- P^r . According to Algorithm 2, the P^r does not send any cookie.

Therefore, lemma 1 is proved. ■

To prove UPPRESSO system meets the requirement 2, firstly we need to know how the cookie can be set as $c(u, r)$. Based on the algorithm 2, we propose the new definition.

Definition 2. In UWS , the cookie c is to be set $asc(u, r)$ only when RP r receives a valid u 's identity proof, here we defined as $t(u, r)$, from the owner of c .

To prove that $t(u, r)$ cannot be obtained by attackers, we firstly show some lemmas.

Lemma 2. Attacker does not learn users' passwords.

Proof: Same as the proof to lemmas 1, we only need to prove that attackers cannot receive the message form honest processes carrying password. The honest IdP server is defined as P^i and the IdP script is defined as $script_{idp}$. Here we give the proof about each processes.

- $script_{rp}$. According to algorithm 4, we can prove that RP script does not send any stored passwords.
- P^r . According to algorithm 2, it is easy to find out that RP server does not receive or send any stored passwords.
- $script_{rp}$. Based on algorithm 3, we can find that IdP script sends the user's password at line 68. The target of this message is Url whose host is $IdPDoaim$ set at line 67. The $IdPDomain$ is set at line 4 and the value is defined by the script initially with no modification. Therefore the password can only be sent to IdP server. The IdP server obtain the password at algorithm 1 line 10 and does not send this parameter to any other processes.
- P^i . Based on algorithm 1, we can find that IdP server does not send any stored passwords.

Therefore, no attackers can obtain the password from honest processes, so that this lemma is proved. ■

Lemma 3. Attacker cannot forge or modify the IdP issued proofs.

Proof: Here we only consider the $Cert$ used in $script_{idp}$, the $RegistrationResult$ and $Token$ used in P^r . First of all, we can easily find that the IdP does not send the private key to any processes so that the attackers cannot obtain the private key.

- $Cert$ is used at algorithm 3 line 21, 52. At line 21, the $Cert$ has already been verified at line 16. At line 52, the $Cert$ is picked from the state parameters, and the cert parameter is set at line 19. At line 19, the $Cert$ has already been verified at line 16. At line 16 the $Cert$ is verified with the public key in the scriptstate, where the key is considered initially honest and the key is not modified at algorithm 3. Therefore, $Cert$ cannot be forged or modified.

- *RegistrationResult* is used at algorithm 2 from line 35 to 55 after line 30 where it is verified. The public key is initially set in the RP and never modified so that it is considered honest. Therefore, *RegistrationResult* cannot be forged or modified.
- *Token* is used at algorithm 2 from line 69 to 84 after line 65 where it is verified. And the public has been proved honest. Therefore, *Token* cannot be forged or modified.

Therefore, this lemma is proved. ■

Here we now show the lemma to prove that UPPRESSO meets the requirements in definition 2 .

Lemma 4. Attacker cannot learn users' valid identity proofs.

Proof: As the *Token* has been proved that it can not be gorged by the attackers, here we only need to prove attackers cannot receive *Token* from other honest processes.

- Attacker cannot obtain the *Token* from RP server. We check all the messages sent by the RP server at algorithm 2 line 4, 7, 19, 25, 31, 36, 45, 55, 61, 66, 74, 84. It is easy to proved that the RP server does not sent any *Token* to other processes.
- Attacker cannot obtain the *Token* from RP script. The messages sent by RP script can be classified into two classes. The messages at algorithm 4 line 18, 36, 56 are sent to the RPDomain set at line 4, so that attackers cannot receive these messages. However, the messages at line 26, 46 only carry the contents received from RP server. We have already that RP server does not send any *Token*. Therefore, attackers cannot receive the *Token* from RP script.
- Attacker cannot obtain the *Token* from IdP server. Considered the messages at algorithm 1 line 4, 12, 16, 23, 26, 36, 44, 51, 67, it can be found that only the message at line 67 carries the *Token*. This *Token* is generated at line 65, following the trace where the *Content* at line 63, the *PID_U* at line 61, the *UID* at line 60, the *session* at line 48, and finally the *cookie* at line 47. That is the *Token* receive must be the owner of the *cookie* the session of which save the parameter *UID* . The *UID* is set at line 15 after verifying the password and never modified. As we have already proved that the cookies and passwords cannot be known to attackers, so that attackers cannot obtain the *Token* from IdP server.
- Attacker cannot obtain the *Token* from IdP script. As the proof above, only IdP sends the *Token* with the message at algorithm 1 line 67, the IdP script can only receive the *Token* at algorithm 3 line 99. Here we are going to proof that the token $t(u, r)$ can be only sent to the corresponding RP server through IdP script. The receiver of $t(u, r)$ is restricted by the *RPOrigin* at line 100, which is set at line 55. The host in the *RPOrigin* is verified included in *Cert* at line 51. If the *Cert* belong to r , the attacker cannot obtain the $t(u, r)$. Now we give the proof that the *Cert* belong to r . Firstly we define the negotiated *PID_{RP}* in $t(u, r)$ as p . That is the *PID_{RP}* at algorithm 2 line 69 must equals with p and the *PID_{RP}* is verified at line 44 with the *RegistrationToken*. This verification cannot be passed due to the state check at line 60. At the same validity period, the IdP script need to send the registration request with same p and receive the successful registration result. As the IdP checks the uniqueness of *PID_{RP}* at algorithm 1 line 32. Therefore the r and IdP script must share the same *RegistrationToken*. As the *RegistrationToken* contains the $\text{Hash}(N_U)$, the IdP script and r must share the same *ID_{RP}*. Therefore, the the *Cert* saved as the IdP scriptstate parameter must belong to r .

Therefore, attackers cannot learn users' valid identity proofs. ■

Here we confirm that UPPRESSO meet the requirement 3. As the browser follows the same-origin policy, we consider that the attackers cannot set its cookie to user's browser at RP's origin. Therefore, due to definition 2, the user only sets her cookie as $c(a, r)$ when RP receives the *Token* containing the attacker's *PID_{RP}* and a valid *PID_{RP}* negotiated by u and r . It requires that the attackers must know a valid *PID_{RP}*. Here we give a lemma.

Lemma 5. Attacker does not know a valid *PID_{RP}* negotiated by user u and RP r .

Proof: Here we give the proof that attacker cannot obtain the *PID_{RP}* and N_U from each processes.

- P^i . We can find at algorithm 1 IdP only returns the message containing *PID_{RP}* to other processes when the *PID_{RP}* is included in the request message.
- P^r . Same as IdP server, RP server only send the message containing *PID_{RP}* at algorithm at line 55, and the *PID_{RP}* is contained in the *RegistrationResult* received at line 28 and werified at line 44. *script_rp*. We can find at algorithm 4, RP script only sends the messages to RP server and IdP script. The receivers' identities are ensured at line 3, 4. Therefore, attackers cannot obtains the *PID_{RP}* and N_U . *script_idp*. The HTTP requests sent by Idp script are forwarded to the domain set at algorithm 3 line 4. The HTTP requests are ensured sent to IdP server. The postMessages are sent to the target set at line 3, and we will prove the target cannot be attacker. According to algorithm 2 line 44, the *PID_{RP}* is valid at RP server only when server receives the registration result. The $\text{Hash}(N_U)$ in the result ensure the result must

issued for the correct ID_{RP} . As the registration result is PID_{RP} -unique due to algorithm 1 line 32, the registration result received by IdP script at algorithm 3 line 35 must be same as it in RP server. This HTTP response is related with the HTTP request at line 28, carrying PID_{RP} and $\text{Hash}(N_U)$ at line 21, 25. It ensure the $Cert$ obtained at line 15 must belong to RP not the attacker. As the target at line 3 is the window which opens the IdP script window and asks for user's login consent, user can easily find out the target site is not coincident with the consent requirement. Therefore, the target cannot be the attacker. ■

Here we have proved that UPPRESSO meets the requirements in definition 2. Therefore the requirement 2 is met, so that the theorem 1 is proved.

I. Proof of Theorem 2

In this section, we will give a full version of proof about UPPRESSO privacy. That is, if UPPRESSO is a privacy-preserving system, the system must be IdP-Privacy and RP-Privacy. Firstly we recall the requirements of IdP-Privacy and RP-Privacy system. Then we will give the proof that UPPRESSO system meets these requirements.

Requirement 4. IdP-Privacy. There are honest RPs r_1, r_2 , IdP i and the honest user u . We define the event sets containing each users' login procedure, for instance, the $events_{(u, r_1)}$ consists of all the events generated during the u logging in to r_1 in correct procedure. It requires that for every event $e_1 \in events_{(u, r_1)}$ received by IdP, there is always an event $e_2 \in events_{(u, r_2)}$, and e_1 and e_2 are equivalent.

Here we give the proof that UPPRESSO system meets the requirement 4.

Proof: Here we consider the IdP behave honestly, therefore, we only focus on all events sent to the IdP and prove the equivalence of these events. As the IdP only accepts the HTTP requests to the path $/script, /dynamicRegistration, /login, loginInfo$ and $/authorize$, we will examine each of these paths.

- $/script$. Based on algorithm 1, we can find that every requests to this path does not carry any parameters and bodies. Therefore, for event $e_1 \in events_{(u, r_1)}$ and $e_2 \in events_{(u, r_2)}$, the HTTPS messages in e_1 and e_2 meet the requirements in definition 5, such that e_1 and e_2 are equivalent.
- $/loginInfo$. As it defined in algorithm 1, no parameters and bodies are sent to this path. The proof is same as it in path $/script$.
- $/login$. According to algorithm 1, the requests carry the body including u 's username and password. For event $e_1 \in events_{(u, r_1)}$ and $e_2 \in events_{(u, r_2)}$, the usernames and passwords must be the same. Therefore, e_1 and e_2 are equivalent.
- $/dynamicRegistration$. As defined in algorithm 1, the requests should carry the body containing PID_{RP} , $Endpoint$ and $Nonce$. That is the PID_{RP} is the result of $ID_{RP}^{N_U} \bmod p$, where N_U is unknown to IdP, so that based on definition 4 the PID_{RP} in e_1 and e_2 are equivalent. The $Endpoints$ and $Nonces$ are all randomly generated unrelated, therefore, they are equivalent in each events. It is proved that e_1 and e_2 are equivalent.
- $/authorize$. Based on the algorithm 1, it is easy to find that the requests to this path carry the body including PID_{RP} and $Endpoint$ same as in path $/dynamicRegistration$. The proof of equivalence is also same as above.

Therefore, we prove that UPPRESSO meets the requirement 4. ■

Requirement 5. IRP-Privacy. There are honest RPs r_1, r_2 , IdP i and the honest users u_1, u_2 . It requires that for every event $e_1 \in events_{(u_1, r_2)}$ received by IdP. The following requirements are proposed even if r_1 and r_2 share their states.

- There is always an event $e_2 \in events_{(u_2, r_2)}$, and e_1 and e_2 are equivalent.
- For any user u , the event $e \in events_{(u_2, r_2)}$ can not linked with specific *Account*.

Here we give the proof that UPPRESSO system meets the requirement 5.

Proof: As the RPs are considered maybe malicious, at the beginning of the proof we only focus on the procedure with legal parameters. Then the RPs are considered able to use illegal parameters and conduct illegal processes.

The events known to the RPs contains the postMessages from IdP script to RP script, and the HTTPS messages from RP script to RP server. However, we can find at algorithm 2 that all the postMessages received by RP script are transmitted to RP server, so that we can only focus on the RPs paths for HTTPS requests. The proof when RPs behave honestly is described as follows.

- $/script$. As it is defined at algorithm 2, every requests to this path does not carry any parameters and bodies. The HTTPS messages in event $e_1 \in events_{(u_1, r_2)}$ and $e_2 \in events_{(u_2, r_2)}$ must be equivalent based on definition 5, such that e_1 and e_2 are equivalent.

- */login*. According to algorithm 2, the requests to this path do not carry any parameters and bodies. Therefore, same as it in path */script*, e_1 and e_2 must be equivalent.
- */startNegotiation*. Based on algorithm 2, we can find that the requests to this path only carry the body including N_U . As N_U is the new generated random constant number, the messages in e_1 and e_2 are equivalent, so that e_1 and e_2 are equivalent.
- */registrationResult*. According to algorithm 2, the requests to this path contains the *RegistrationResult* in the body. The *RegistrationResult*'s content contains PID_{RP} , *Endpoint*, *Nonce* and the *Validity*. However, the PID_{RP} is considered equal with N_U , and *Nonce* is the hash of N_U , so that PID_{RP} s and *Nonces* are equivalent. *Endpoint* is newly generated random string. *Validity* is generated based on the current time. Therefore, all the parameters in e_1 and e_2 are considered equivalent, such that e_1 and e_2 are equivalent.
- */uploadToken*. As it defined algorithm 2, the requests to this path carry the *Token*. *Token* consists of PID_{RP} , PID_U and *Validity*. As it is proved above, PID_{RP} s and *Validities* in each events are equivalent. PID_U is the result of $ID_{RP}^{ID_U} \bmod p$, so that PID_U s are equivalent to RP without knowing ID_U sue to definition 4. Therefore, e_1 and e_2 are equivalent.

Moreover, with the r_2 shared states, users' *Accounts* at r_2 are known to r_1 . However, as ID_{RP} s of r_1 and r_2 have the relation $ID_{RP_{r_1}} \equiv ID_{RP_{r_2}}^n \bmod p$. But n is unknown to RPs due to the discrete logarithm problem. Therefore, the *Account* at r_2 cannot be linked with the *Account* at r_1 .

Therefore, the UPPRESSO meets the requirement 5 while RPs behave honestly.

Then we prove that UPPRESSO meets the RP-Privacy requirements even though RPs behave maliciously. The malicious RPs will attempt to steal the data from other process or set the malicious parameters during the login procedure. That is, according to Definition 4, the PID_U s the *Accounts* must be equivalent to the attacker as long as the attacker does not know the ID_U . However, based on algorithm 1 we can find out that IdP does not send ID_U to any processes, so that PID_U s the *Accounts* must be equivalent in each events.

Moreover, another way is that RPs may attempt to treat the *Account* or PID_U to be generated incorrectly, but we are going to prove it is impossible.

- RP may lead the login using the forged ID_{RP} or PID_{RP} so that PID_U s and *Accounts* are no more equivalent. However, ID_{RP} are provided by the *Cert* which is verified at algorithm 3 line 17, by the IdP's public key set initially and not modified. PID_{RP} is generated by the ID_{RP} at line 21 using the honest user generated nonce at line 20. Therefore, it is impossible to lead the honest user to use the illegal ID_{RP} and PID_{RP} .
- RP may also lead the same user to upload the identity proof with same PID_U or *Account* so that the system is not RP-Privacy according to requirement 5. However, the PID_U is generated containing the user's generated nonce N_U so that it is not controlled by the RP. *Account* is generated as the form $ID_{RP}^{ID_U} \bmod p$, while RPs may lead the user to use the same ID_{RP} to generate identity proof. However, the ID_{RP} is bound with *Cert* which is verified by the user and it is easy for user to find out the login RP does not coincide the RP name shown on her browser.

In conclusion, we prove that UPPRESSO system meets the requirement 5. ■

As we have proved the UPPRESSO system meets the requirement 4 and 5, the theorem 2 is proved.