

PRIOIDC: A CLIENT-ACCESS-HIDDEN EXTENSION FOR OPENID-CONNECT

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I. INTRODUCTION

To maintain each user's profile and provide individual services, each service provider needs to identify each user, which requires the users to be authenticated at multiple online services repeatedly. Single Sign-On (SSO) systems enable users to access multiple services (called relying parties, RP) with the single authentication performed at the Identity Provider (IdP). With SSO system deployed, a user only needs to maintain the credential of the IdP, who offers user's attributes (i.e., identity proof) for each RP to accomplish the user's identification. SSO system also brings the convenience to RPs, as the risks in the users' authentication are shifted to the IdP, for example, RPs don't need to consider to leakage of users' credentials. Therefore, SSO systems are widely deployed and integrated. The survey on the top 100 websites demonstrates that 24 websites (e.g., Google, Facebook and Twitter) serve as the IdP while 63 websites integrate the SSO service.

One basic requirement of SSO systems is the security, which includes two aspects: 1) the attacker should not be able to access the honest RP with the honest users' identity; 2) the identity injection will never succeed, that is, the attacker should not be able to make the honest user access the RP with an incorrect identity. Plenty of works are proposed for the security of SSO systems. Firstly, various standards, e.g., OAuth 2.0 [1], SAML [2] and OpenID Connect (OIDC) [3], are proposed to formalize the handling at each entity (i.e., the user, RP and IdP) and the information exchanges between the entities. Secondly, the standards, SAML, OAuth and OIDC, are formally analyzed, for example, a general Dolev-Yao style web model is proposed for the web infrastructure [4] and adopted to analyze the security of SAML, OAuth and OIDC [5]. Moreover, the typical implementations of SSO systems, e.g. Google, Facebook, Twitter and the corresponding RPs, are systematically analyzed [6] [7] [8], which makes the security of SSO systems improved significantly.

The other important requirement of SSO systems is the privacy. As suggested in NIST SP800-63C [9], in SSO systems, 1) the user should be able to control the range of the attributes exposed to the RP, 2) multiple RPs should fail to link the user through collusion, 3) IdP should fail to obtain

the trace of RPs accessed by a user. The first two properties are satisfied in the popular SSO systems. For example, in OAuth and OIDC, IdP exhibits the attributes requested by the RP and sends the attributes to the RP only when the user has provided a clear consent, which may also minimize the exposed attributes as the user may disagree to provide partial attributes. To prevent a possible correlation among users from multiple RPs, a Pairwise Pseudonymous Identifier (PPID) is suggested to be generated by the IdP for the user in each RP, which requires that the user's identifier in one RP should never be the same with or derivable from the ones of other RPs.

However, in widely deployed SSO systems, IdP knows which RP the user logs in, which reflects the service that user accesses and may be analyzed for various purposes, e.g., profiling and targeted advertising. In addition to the potential commercial purpose, exposing the identifier of accessed RP to the IdP, is required for security consideration in existing SSO systems [10]. Firstly, the identity proof should only be sent to the correct RP, which prevents the adversary from performing the impersonation attack with the leaked identity proof. Secondly, the identity proof should be bound with a specific RP and user, which ensures the identity proof is only valid in the certain RP, and avoids the misuse of identity proof, for example, the adversary fails to use the identity proof for a corrupted RP to access another RP on behalf of the victim user.

Two SSO systems (BrowserID [11] and SPRESSO [12]) are proposed to hide the user's accessed RPs from IdP, while ensuring the security of SSO systems simultaneously. In BrowserID, the user is responsible for sending the identity proof correctly and binding the proof with the correct RP using a newly generated private key, while the corresponding public key is bound with the email address by the IdP who fails to obtain the information of accessed RP. In SPRESSO, the identity proof is bound with an encryption of the RP's domain name by the IdP who knows the user's identity but not the plaintext of the RP's information, and sent to the exact RP by a newly introduced trusted entity (called FWD) who obtains the RP's domain name but not the identity of the user.

BrowserID and SPRESSO are both redesigns of SSO

systems, and therefore incompatible with existing widely deployed SSO systems (e.g., OAuth, OIDC and SAML). Moreover, the new SSO systems require a complicated, formal and thorough security analysis of both the designs and various implementations. As shown in [], vulnerabilities have been found in the implementation of BrowserID. More importantly, in order to provide the same identity to the RP in the multiple logins of a user, both BrowserID and SPRESSO use the email address as the identity, which makes the user linkage (from multiple RPs) possible.

In this paper, we propose an extension (named PriOIDC) of existing widely adopted SSO system (i.e., OIDC), which preserves the systematically and thoroughly analyzed security, and achieves the fully privacy. That is, (1) the security design in OIDC is inherited to prevent the impersonation attack and identity injection attack, (2) the privacy enhance mechanisms (e.g., the clear consent from the user and the PPID) are retained, (3) a new mechanism is introduced to hide the user's accessed RP from IdP. Unlike designing and deploying a newly designed SSO systems, we only need to analyze the compliance of the new function (i.e., hiding the user's accessed RP) and the influence to the security introduced by the new mechanism. And, the deployment of PriOIDC only requires: (1) IdP provides a set of public parameters and generates the PPID with a newly provided algorithm, (2) RP integrates the SSO service with a new version software development kit (SDK) whose interface remains unchanged, (3) the user installs an extension to access RP with full privacy anywhere as no storage is required in the user side.

To hide the user's accessed RP from IdP, PriOIDC avoids the potential leakage in the identity proof (i.e., id token in OIDC) and the corresponding message transmission. Moreover, PriOIDC enables only the RP (and the user) to derive the user's unique identifier in this RP from different PPIDs, which avoids the user linkage and allows the RP to provide the individual service with the user's identifier. PriOIDC achieves these as follows:

- A new algorithm is proposed to negotiate the RP's identifier between the user and RP for each login. Therefore, the RP's identifier in multiple id tokens are different, and IdP fails to infer RP's information in the generation of one or multiple id tokens. Moreover, neither RP nor the user may control the generated identifier, which avoids the misuse of the id token. The detailed analysis is provided in Section *.
- A browser extension is introduced to transmit the messages (i.e., request and response) related with the id token. IdP fails to infer the RP's information through the network traffic, and the extension ensures only the correct RP receives the id token.
- A new generation algorithm of PPID is provided, which makes the PPIDs for one user in one RP indistinguishable from others (e.g., different users in different RPs),

while only the RP (and the user) has the trapdoor to derive the unique identifier from different PPIDs for one user in one RP.

The main contributions of PriOIDC are as follows:

- We propose a practical extension for OIDC, which inherits the systematically and thoroughly analyzed security and privacy mechanisms of OIDC, and achieves the full privacy for users by hiding the accessed RPs from IdP.
- We developed the prototype of PriOIDC. The evaluation demonstrates the effectiveness and efficiency of PriOIDC. We also provide a systematical analysis of PriOIDC to prove that PriOIDC introduces no degradation in the security of OIDC.

The rest of this paper is organized as follows. We introduce the background and the threat model in Sections II and III. Section IV describes the design and details of PriOIDC. A systematical analysis is presented in Section V. We provide the implementation specifics and evaluation in Section VI, then introduce the related works in Section VII, and finally draw the conclusion.

II. BACKGROUND

PriOIDC is an extension of OIDC to prevent the IdP from inferring the user's accessed RP, with the security of SSO systems under consideration. This section provides the necessary background information about OIDC and adopts OIDC as the example to present the security consideration of SSO systems.

II-A. OpenID Connect

OpenID Connect (current version 1.0) is an extension of OAuth (current version 2.0). OAuth is originally designed for authorizing the RP to obtain the user's personal protected resources stored at the resource holder. That is, the RP obtains an access token generated by the resource holder after a clear consent from the user, and uses the access token to obtain the specified resources of the user from the resource holder. However, plenty of RPs adopt OAuth 2.0 in the user authentication, which makes impersonation attack and identity injection possible. For example, the access token isn't bound with the RP, the adversary may act as a RP to obtain the access token and use it to impersonate as the victim user in another RP.

OIDC is designed to extend OAuth for user authentication by binding the identity proof for authentication with the information of RP. OIDC provides three protocol flows: authorization code flow, implicit flow and hybrid flow (i.e., a mix-up of the previous two flows). In the authorization code flow, the identity proof is the authorization code sent by the IdP, which is bound with the RP, as only the target RP is able to obtain the user's attributes with this authorization code and the corresponding secret.

The implicit flow of OIDC achieves the binding between the identity proof and the RP, by introducing a new token

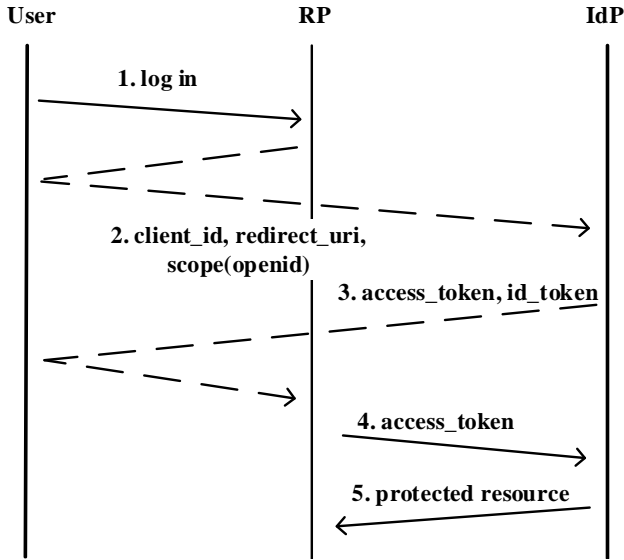


Fig. 1: The implicit protocol flow of OIDC.

(i.e., id token). In details, id token includes the user's PPID (i.e., sub), the RP's identifier (i.e., aud), the valid period and the other requested attributes. The IdP completes the construction of the id token by generating the signature of these elements with its private key, and sends it to the correct RP through the redirect URL registered previously. The RP validates the id token, by verifying the signature with the IdP's public key, checking the correctness of the valid period and the consistency of aud with the identifier stored locally. Figure 1 provides the details in the implicit flow of OIDC, where the dashed lines represent the message transmission in the browser while the solid lines denote the network traffic. The detailed processes are as follows:

- Step 1: User attempts to login at one RP.
- Step 2: The RP redirects the user to the corresponding IdP with a newly constructed request of id token. The request contains RP's identifier (i.e., `client_id`), the endpoint (i.e., `redirect_uri`) to receive the id token, and the set of requested attributes (i.e., `scope`). Here, the `openid` should be included in `scope` to request the id token.
- Step 3: The IdP generates the id token and the access token for the user who has been authenticated already, and constructs the response with registered `redirect URL`. If the user hasn't been authenticated, an extra authentication process is performed.
- Step 4, 5: The RP verifies the id token, identifies the user with `sub` in the id token, and requests the other attributes from IdP with the access token.

Dynamic Registration. The id token (also, the authorization code) is bound with the RP's identifier. OIDC provides the dynamic registration [13] mechanism to register the

RP dynamically. After the first successful registration, RP obtains a registration token from the IdP, and is able to update its information (e.g., the `redirect URI` and the response type) by a dynamic registration process with the registration token. One success full dynamic registration process will make the IdP assign a new unique client id for this RP.

II-B. Security Consideration

OIDC is designed with the following security considerations, and various implementations of IdP and RP are also analyzed with the same security principles under the assumption that IdP is trusted. Here, we use the implicit flow of OIDC as an example to list the security considerations:

- The contents in the id token is determined by the user through a clear consent. The contents include the RP's information and the range of exposed attributes.
- The confidentiality of the id token is ensured, that is, only the target RP obtains the id token which will never be leaked by the honest RP. The HTTPS connection is used to protect the id token between the IdP and the user, while the trusted user proxy (e.g., the browser) ensures the id token only sent to the correct URL (of RP) which is confirmed by both the user and the IdP.
- No one except the IdP is able to construct a valid id token, as only the IdP has the private key to generate a valid signature for the id token. Any modification in the id token makes the signature (then the id token) invalid.
- The identity proof is only valid for the target RP, as the id token is bound with the identifier of the target RP, and the honest RP checks the consistency of the identifier in the id token with the one stored locally.

III. SYSTEM OVERVIEW

PriOIDC allows user to conduct single sign on with out leaking login information to IdP. And even multi RPs' collusion can not trace the user. In this section, we are going to make an overview of our user privacy respecting protocol based on OpenID Connect 1.0.

III-A. Anonymity in OpenID Connect System

In OpenID Connect systems IdP gets RP's identity by `client_id` or `redirect_uri` in request (Figure 1 step 2) and gets user's identity when authenticating the user (Figure 1 step 3). As IdP has to provide RP a user's authenticator bound with user's identity, it's not possible to keep user anonymous in IdP without modifying the structure of current SSO system. So it is only feasible to protect user's privacy by keeping RP anonymous in IdP. But it introduces new challenges.

III-A1. Challenges

The simplest way to make RP anonymous in IdP is using random `client_id` and `redirect_uri` in each authentication. But the simple method will introduce some problems in two fields.

Using random `client_id` and `redirect_uri` results in the failure of authentication. In OpneID Connect system, IdP only accepts a request when the `client_id` and `redirect_uri` have been registered at IdP. So IdP will drop the request with random `client_id` and `redirect_uri`, in another word unregistered parameters, as the invalid request. Additionally to protect user's privacy from RPs' collusion attack, it's required that IdP should provide different `user_ids` for different RPs [3]. It means that `user_id` is bound to `client_id`, so random `client_id` means the `user_id` is random too. As RP wants to provide a user personalize service it must identify a user with a constant identity. So randomness of `client_id` is not appropriate for widely used SSO systems.

In the other field, anonymous RP with random `client_id` and `redirect_uri` causes secure problems. To avoid the misuse of `id_token` among different RPs, RP checks the validation of `id_token`. An `client_id` represents a specific RP's identity, a `id_token` with this `client_id` is only valid in this specific RP. But when using a random `client_id`, different RPs may share the same `client_id`. When a user log in a malicious RP, this RP possibly logs in other RPs with the user's `id_token` if they have the same `client_id`. Additionally `redirect_uri` is the address where RP waits for the `id_token`. Before issuing a `id_token`, IdP will check the validation of `redirect_uri` to avoid attacker getting the `id_token`. If the `redirect_uri` is random, IdP can no more protect user from sending `id_token` to an attacker.

III-A2. Solutions against the problems

With dynamic registration, a RP can register new random `client_id` and `redirect_uri` before sending a request to IdP for `id_token`. And to avoid IdP finding out RP's identity through dynamic registration, the requirement of registration token is omitted. IdP will delete the expired registration to reduce storage stress.

To identify a user in different logins, RP must have the ability to transform the `user_id` provided by IdP into a constant user identity for each user. Most of current SSO system generate `user_id` as a random character string. So a new user-id-generating algorithm has to be created for user authentication. As `user_id` is required to be bound to random `client_id` to protect from RPs' collusion, `client_id` should be the primary input parameter to user-id-generating algorithm. To make `user_id` able to be transformed into a constant user identity, it is a feasible way that generating `client_id` through a client-id-generating algorithm. The user-id-generating algorithm and client-id-generating algorithm will be described detailedly in Section IV.

Misuse of `id_token` only happens when different RPs use the same `client_id`. Although IdP will keep the registered `client_id` unique, an attacker is possible to be the executor of registration (RP or user) and tamper with the failed registration result. So victim will regard the repetitive `client_id` as a validate one. To prevent misuse of `id_token`, client-id-generating algorithm should require two random parameters

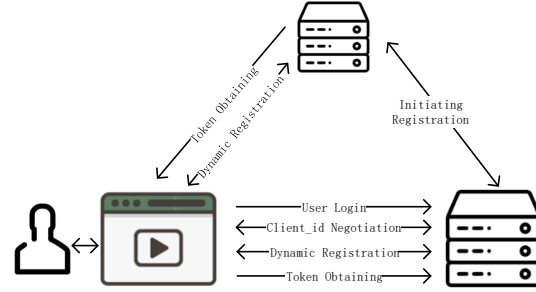


Fig. 2: Overview of System

respectively generated by RP and user. So even if an attacker possesses a user's `id_token` (or negotiates a `client_id` with RP), he is unable to negotiate the same `client_id` with a RP (or get the `id_token` with same `client_id` from user).

As `redirect_uri` is random, IdP is going to send `id_token` to the invalidate address. User agent must intercept the `id_token` redirection from IdP and send `id_token` to RP. In PRISSO system IdP issues RP certification for each RP. A RP certification contains RP's identity and its address for token acceptance. User gets the real acceptance address of RP from certification and makes sure that the `id_token` is going to be sent to the RP. RP certification is also useful in defending phishing attack.

III-B. Overview of proposed scheme

The procedure of PRIODC can be divided into two parts: Initiating registration and Login procedure. Login procedure contains user login, `client_id` negotiation, dynamic registration and token obtaining. The overview is shown in Figure 2

- Initiating Registration: RPs and users register at IdP. IdP generates unique basic `client_id` for each RP and unique user id for each user.
- User Login: User starts log in an RP. If user is labeled as logged in, RP is going to offer service to user. Otherwise RP requires user to start SSO procedure.
- Client_id Negotiation: For each SSO procedure, RP is going to start `client_id` negotiation with user. `Client_id` is a random number generated by client-id-generating algorithm unrelated with any RP. A `client_id` represents login from a user to an RP.
- Dynamic Registration: To make the `client_id` generated by negotiation between user and RP, user is going to register `client_id` at IdP by the dynamic registration API provided by IdP. IdP is going to check whether `client_id` is unique and ask RP to restart `client_id` negotiation for another `client_id`.
- Token Obtaining: After dynamic registration success, RP is going to redirect token request to IdP. IdP firstly authenticates user and then generates `id_token` for RP. `Id_token` contains RP's `client_id` and user id. `Client_id` is

provided by RP and user id is generated through sser-id-generating algorithm by IdP. RP is able to get the constant user identity from user id.

III-C. Roles in PriOIDC

To achieve the goals outlined in Section I, the requirements and restrictions of abilities owned by each roles in single-sign-on system is defined as following:

- **User** is able to generate RP's client_id with RP by key data exchanging. User is able to register client_id in IdP. User is able to modify redirect_uri in token request and redirect token response to the correct RP's redirect_uri. User need not to store any data in its computer so that user is able to conduct single sign on in any computer.
- **RP** is able to generate client_id with user by key data exchanging. RP is able to check the client_id registration result. RP is able to get a constant user identity from id_token generated by IdP. RP is unable to find out its user's identity in other RPs even through RPs' collusion.
- **IdP** is able to generate user's id for specific login by client_id and user's unique id in IdP. IdP is unable to find out RP's identity by client_id. IdP is unable to find out the relevance between an RP's different client_ids.
- **User agent** is the software used by the user, such as browser and the application on the mobile device.

More detailedly, the enhanced protocol is going to provide new client-id-generating and user-id-generating algorithm: Client_id is random in each logins to make RP anonymous in IdP. There is a one-to-one correspondence between client_id and user_id provided by IdP so that user id is random. So RP is able to transform user_id IdP into constant user identity and RPs are unable to find the relationship between one user's user_ids for different RPs.

III-D. Threat Model

Considered different attack scenarios, malicious opponent can be divided into following situations: malicious IdP, malicious RP, malicious user and external attacker. In different situations malicious owns different abilities.

Curious IdP As IdP service is usually provided by a leading internet company. In consideration of in consideration of, Idp is considered secure but curious. Phishing attack on IdP is not considered. It means IdP would not try to do the impersonation attack or abduction attack. But an IdP is probably interested in user's login trace in RPs so that it is able to deduce user's interests and behavioral traits. During SSO login, as IdP need authenticate the user, so IdP has the ability to collect the user's information. And IdP is able to get client_id and redirect_uri from token request. IdP is also able to store each user's login history and analyze each client_id and redirect_uri to find out the relevance among each login.

Malicious RP There are two kinds of malicious RPs. The first is the legal RP owned by malicious opponent and the other is phishing site. Because everyone is able to register as an RP at IdP, it is considered that RP can be fully controlled by malicious. A malicious RP is going to conduct impersonation attack and privacy undermining attack on user. As some attack methods require attacker act as both RP and user, to avoid the repetitive description malicious RP and malicious user is defined: If attacker acts as an RP in attack, attacker is considered as malicious RP. If attacker only acts as a user, it's malicious user. A malicious RP's goals include: 1) Getting id_token from user which is validate in other RPs. 2) Deducing user's login trace by colluding with other RPs. Malicious RP is able to make fake basic_rp_id and conduct client_id negotiation with user. Malicious RP is also able to construct the id_token request to IdP and receive id_token from IdP. In phishing attack, it is considered that user trusts attacker completely.

Malicious User A malicious user is only going to conduct impersonation attack. In the attack malicious opponent acts as both user and RP, user is able to conduct client_id negotiation, construct dynamic registration request. User is also able to temper all the data transformed through itself. It is considered that the user agent is trustful, but there are external attacker trying to exploit the flaw of user agent.

IV. DESIGN OF PROTOCOL

IV-A. Client-id-generating and User-id-generating algorithm

Client-id-generating and User-id-generating algorithm are created based on Discrete Logarithm problem [14]. IdP carefully chooses a big prime p [15] for system. When a RP initialize registration at IdP, IdP will provide RP a unique primitive element module p . It's used in RP as the basic_rp_id and RP will generate another primitive g from basic_rp_id for further client_id negotiation. As p is a prime and a is a primitive element module p , if α is a relatively prime of $p-1$, $a^\alpha \bmod p$ is another prime element module p .

For each login process, the user and RP negotiate the temporary $client_{id}$ for the RP registration at the IdP. While starting a login procedure, there is **Diffie-Hellman key Exchange** [16] between RP and user. Firstly RP sends $pk_{rp} = g^x \bmod p$ to user, and x is a random number. After receiving the pk_{rp} , user continue generating the random number y until $r = pk_{rp}^y \bmod p$ is a relative prime of $p-1$. Then user sends $pk_{user} = g^y \bmod p$ to RP so that both user and RP can get $r = g^{xy} \bmod p$. So the client_id is generated as:

$$client_{id} = basic_rp_id^r \bmod p$$

such that client_id is another primitive element module p .

To identify users, IdP keeps a unique id for each user. After receiving a client_id, IdP will generate the one-to-one correspondence user_id

$$user_id = client_id^{id} \bmod p$$

so

$$user_id = basic_rp_id^{r-id} \bmod p$$

As r is a relative prime of $p-1$, according to **Extended Euclidean** algorithm RP can get r^{-1} and let $1 = r \cdot r^{-1} \bmod (p-1)$. While receiving user_id from IdP, RP can get a user identity

$$user_rp_id = user_id^{r^{-1}} \bmod p$$

so

$$user_rp_id = basic_rp_id^{id} \bmod p$$

For one user in a RP, user_rp_id is constant. But user_rp_ids are disparate in RPs because basic_rp_ids are different in each RP.

IV-B. Login flow

User firstly logs in an RP. If RP find that user is unauthenticated, RP is going to negotiate a new client_id with user. Then user starts dynamic registration and forward the registration result from IdP to RP. If registration succeeds RP will construct a token request and redirect user to IdP. IdP authenticates user and generates an id_token of user for RP. Id_token is sent to RP and RP gets user_rp_id from id_token. RP is going to identify the user through user_rp_id.

IV-B1. Initiating Registration

If an RP wants to join the SSO system, it must do the initialization registration at IdP. As well as traditional SSO system, IdP is going to inspect the real identity of RP and store RP's information on IdP's server. During registration procedure RP sends its URL for id_token acceptance to IdP. IdP generates a unique primitive element module p for RP as basic_rp_id. Then IdP puts basic_rp_id, URL and the prime p together and encodes them to Json Web Token. This token is called rp_certificate. A typical rp_token carries the following information: [language=[ANSI]C,basicstyle=] "alg": "RSA", "type": "certificate" . "iss": IdP URL, "sub": basic_rp_id, "name" : RPname, "redirect_uri" : URL

Same as RP, user need to register at IdP. IdP is going to generate unique user id for each user during registration.

IV-B2. Client_id Negotiation

An attacker is able to be the man in the middle between RP and user in client_id negotiation using phishing attack. When a user logs in attacker's website, attacker logs in another RP as a user. In client_id negotiation, attacker just transmits user and RP's requests and responses to each other. As a result, attacker shares the same client_id with user and RP and gets a id_token valid in RP from user. So besides of generating client_id, RP has to send its rp_certificate to user in this

phase. It protects user from sending id_token to malicious opponent. As rp_certificate contains RP's name, it allows user can identify the real RP's identity when doing login.

IV-B3. Dynamic Registration

User generates IdP's registration URL by iss from rp_certificate. The client_id negotiation is described in client-id-generating algorithm. Dynamic registration starts after client_id negotiation. User generates a random redirect_uri and sends it to IdP as well as client_id. IdP checks the uniqueness of client_id and sends the result success or fail back. If registration fails, user is going to restart client_id negotiation. Otherwise user will forward the registration response to RP.

IV-B4. Obtaining Token

RP firstly redirects user to IdP with its token request. User generates IdP's authenticate URL by iss from rp_certificate and compared it with RP's redirect location. If they point the same address, user is going to continue the login. To keep the advanced protocol same as OpenID Connect 1.0, after authenticating a user IdP is going to redirect the user to the redirect_uri of RP with id_token as parameter. As redirect_uri is random, user stops the redirection. User then sends id_token to the URL received from client_token negotiation to defend man-in-the-middle attack. RP gets user_id from id_token and gets user_rp_id computed from user_id. If it's the first time user logs in RP, RP is going to finish the registration. Otherwise RP searches user profile through user_rp_id.

V. SECURITY ANALYSIS

In SSO system, malicious opponent's attacks can be concluded into 3 goals:

- 1) Privacy undermining attack: Malicious opponent tries to get user's login trace on different RPs.
- 2) Impersonation attack: Attacker tries to log in RP as a victim's identity. In this way, attacker can get the full control of victim's account in RP.
- 3) Abduction attack: Attacker also tries to lead user to upload users personal information to it. To achieve this goal, there are two ways. The first is letting a victim log in an RP as attacker's identity. In this way, if the RP is online storage system, victim may upload its privacy data to attacker's account. The other way is phishing attack. A malicious RP disguises it as another RP and abducts user to upload some information.

V-A. Privacy undermining attack

PRIOIDC tries to protect user's privacy by keeping RP anonymous to IdP. IdP is able to get client_id and redirect_uri. As redirect_uri is generated by user, it will show nothing about RP. IdP can only undermine user's privacy by get RP's identity from client_id. It's described in Client-id-generating algorithm: $client_id = basic_rp_id^r \bmod p$. p is a large prime and basic_rp_id is a primitive element module

p . And r is the random number generated by user and RP. IdP can only find out RP's real identity by finding out r^{-1} and let $1 = r \cdot r^{-1} \bmod (p - 1)$, so that

$$basic_rp_id = client_id^{r^{-1}} \bmod p$$

But r is secret shared by user and RP, and according to **Discrete Logarithm** problem calculating r from $client_id$ is difficult. So $basic_rp_id$ is invisible to IdP. In other way if IdP gets a user's repeatedly login, it is going to find out whether they are about the same RP. If there are two $client_ids$ from the same RP marked as $client_id_1 = basic_rp_id^{r_1} \bmod p$ and $client_id_2 = basic_rp_id^{r_2} \bmod p$. $Client_id_1$ and $client_id_2$ meet the following formula

$$client_id_1 = client_id_2^{r_2/r_1} \bmod p$$

So that only when knowing r_1 and r_2 IdP can find out the relevance between $Client_id_1$ and $client_id_2$. But r_1 and r_2 are invisible to IdP. So IdP is never able to undermine user's privacy.

RPs try to find out user's login trace in three ways: 1) Getting the user's unique id in IdP. 2) Finding the relevance among $user_rp_ids$. 3) Deducing user's login trace from IP address. As user's id is used in generating $user_id$ in id_token , RP is able to obtain $user_id = client_id^{id} \bmod p$. $Client_id$ is primitive element module p . Although $client_id$, $user_id$ and p are known by RP, according to **Discrete Logarithm** problem calculating id from $user_id$ is difficult. For different RPs, they are able to get user's $user_rp_id$. $User_rp_ids$ from different RPs can be marked as $user_rp_id_1 = basic_rp_id_1^{id} \bmod p$ and $user_rp_id_2 = basic_rp_id_2^{id} \bmod p$. As $basic_rp_id_1$ and $basic_rp_id_2$ are primitive element module p , there is $0 < \alpha < p$ and $basic_rp_id_1 = basic_rp_id_2^\alpha \bmod p$. So $user_rp_id_1$ and $user_rp_id_2$ meet the following formula

$$user_rp_id_1 = user_rp_id_2^\alpha \bmod p$$

So RP is able to deduce the relevance between $user_rp_id_1$ and $user_rp_id_2$ only when knowing α . As $basic_rp_id$ is generated by IdP and calculating α from $basic_rp_ids$, RP is never able to find the relevance. If an RP does not use the $basic_rp_id$ from IdP, user is able to find it dishonest through $rp_certificate$ and stop the login. Most of current users use dynamic IPs so that it is impossible to get user's login trace from user's IP.

V-B. Impersonation attack

RP conducts impersonation attack by getting user's id_token which is valid in other RPs. OpenID Connect protocol protect id_token from malicious RP by keep RP owns unique $client_id$ and check RP's $redirect_uri$ during login. Unique $client_id$ makes one RP's id_token invalid in other RPs. And IdP only redirects id_token to it's relevant RP's $redirect_uri$ registered in IdP so that attacker is never able get RP's id_token . There are three conditions for a

malicious to try getting a validate id_token . 1) Malicious RP has already finished $client_id$ negotiation with an RP as a user. As $client_id$ is generated by both RP and user, malicious RP is unable to get the id_token with the same $client_id$. 2) Malicious RP has got a user's id_token , same as condition 1 malicious RP is unable to negotiate the same $client_id$ with another RP. 3) Malicious RP acts as the man in the middle between RP and user. As RP sends its URL in $rp_certificate$ user only sends its id_token to this URL so that attacker can never achieve id_token . As a summary, malicious is unable to conduct impersonation attack.

Malicious user is only able to conduct impersonation attack by tempering id_token . If attacker has already get victim's $user_rp_id$, attacker is able to calculate $user_id = user_rp_id^r \bmod p$. r is shared by RP and attacker. However id_token is protected by the signature generated by IdP so that it is impossible for attacker to log in RP as victim.

V-C. Abduction attack

To lead user to login an RP as attacker, attacker needs to make sure that user receive a malicious token from IdP. As https is used to protect parameters transforming between user and IdP, it's impossible to temper user's token during transmission. The other way to conduct the attack is phishing attack on IdP. In traditional SSO protocol such as OAuth 2.0 and OpenID Connect, it is possible for malicious to conduct phishing attack on IdP. As it is shown in 1 step 2, the request from user to IdP is built by RP. If an malicious RP set the IdP's url as its phishing site, an unwary user may input its id and password on the phishing website so that attacker is able to get the full control of user's account. In PriOIDC as RP_Cert contains IdP's url, user agent is going to compare the IdP's url in request and RP_Cert . If they are not matched, the request is deemed invalid.

Phishing attack on RP in SSO system is quite different from it in normal website. In SSO system even an unwary user has visited a phishing RP's website, IdP is going to ask user to make sure RP's identity in 1 step 2. The identity is bound with RP's client id and client id is bound with its redirect uri. If malicious RP constructs the request in 1 step 2 to IdP with its personal client id, user is able to find out the true identity of RP and protect itself from phishing attack. In traditional SSO system if malicious uses a client id of another RP, IdP is going to redirect user to the corresponding redirect uri. In PriOIDC user agent is going to compare redirect uri from RP with the redirect uri in RP_Cert . If uris are not matched, the request is regarded invalid. A phishing RP can never achieve another RP's token and never lead user to log in its website.

V-D. Discussion

An external attacker is also taken into account in SSO system. External attacker is able to capture and temper all the network flow through user, RP and IdP. External attacker's

targets include impersonation attack, abduction attack and privacy undermining attack. If an attacker keeps its eye on a specific user, it is able to find that the user's login on different RPs. So it is easy for an external attacker to draw a user's login trace. Privacy protection is not effective for external attacker. To protect user from privacy leaking a proxy is probably a appropriate scheme. Proxy is able to mix multi-user's request and keep user's login trace invisible to attacker. User's dynamic IP makes proxy impossible to get user's login trace from user's IP. External attacker is going to steal user's id_token from network flow to make the attack and it is also going to make the attack by temper user's id_token into attacker's id_token when id_token is transformed on the network. As all the network flows are protected by https, external attacker is unable to conduct the attacks.

VI. EVALUATION

The prototype system runs on Thinkcentre M8600t with an Intel Core i7-6700 CPU, 500GB SSD and 8GB of RAM running Windows 10.

VI-A. Implementation

Implementation of system contains modification of IdP as well as RP and creation of user agent. User agent runs on chrome 71.0.3578.98 as its extension.

System's parameters are carefully chosen in specification about **Diffe-Hellman** algorithm. p is one of primes provided by the specification and a is its generator. All the primitive elements module p is generated by a .

Compared with formal openid connect system, the work we do is shown as following:

- Modifying RP registration so that IdP is able to offer RP_cert to RP.
- Providing RP's client_id negotiation interface.
- Providing RP's dynamic registration acceptance interface.
- Implementing user-id-generating algorithm at IdP.
- Implementing the function of getting user_rp_id from user_id at RP.
- Realizing function of client_id negotiation, dynamic registration, id_token transmitting and so on at user agent.

VI-B. Storage

As the prime p is 2048-bit-length, storage of client_id, user_id and user_rp_id are no larger than 512 Bytes as hexadecimal. We consider they are all 512 Bytes in evaluation.

For IdP and RP's user Personally Identifiable Information (PII) storage, it changes from a short user id into a 512 Bytes id. It is assumed that an IdP owns 100 million users and an RP owns 10 million users. If a user's PII costs 500 Bytes extra storage so that IdP need to offer 50 billion Bytes (less than 50 GB) storage and RP need to offer 5 billion Bytes

Table I: Benchmark Result

phase	time (ms)
Client_id Negotiation (RP)	49
Client_id Negotiation (user)	2967
Dynamic registration (IdP)	16
Dynamic registration (user)	1001
Obtaining Token (IdP)	369
Obtaining Token (RP)	19
Network Cost	12
Total Time	4433

(less than 5 GB) storage. The extra cost of storage can be omitted.

For IdP's dynamic registration storage, the data contains RP's client_id and redirect_uri. We consider that each dynamic registration data cost no more than 550 Bytes storage. And for each client_id IdP can set the lifetime of validity. It is assumed that for each client_id its lifetime is 2 minutes and during 2 minutes there are 1 million requests for dynamic registration. So IdP need to offer 550 million Bytes (about 500 MB) storage for dynamic registration. The extra cost of storage can be omitted.

For user's login log stored in RP and IdP, RP and IdP are able to transform PII into a shorter hash characters. So it almost cost no more extra storage.

VI-C. Timings

Table I shows the result of the time cost in PRISSO's each phases. We log in the prototype 100 times and figure out the average time cost. It can be found that the most of time consumed in client_id negotiation phase, dynamic registration conducted by user and IdP providing id_token. They cost 4337ms in average which is more than 90% of total time. In client_id negotiation to confirm $r = pk_{rp}^y \bmod p$ is a relative prime of $p-1$ user has to continue generating y until r is validate which costs most of time. In dynamic registration user need check validation of basic_rp_id and IdP's URL by rp_certificate, calculate client_id by basic_rp_id, r and check the result of registration and forward it to RP. In SSO system if user firstly log in an RP it is necessary for user to confirm permission of login in the specific RP. It is showed as user has to press the confirm button in IdP's website. In PRISSO client_id is random so that every login for a user is first login. So every login requires user to press a button redundantly. Even the press action is conducted by chrome extension, it costs some time.

We also do login in traditional OpenID-Connect system 100 times and get a total time cost 44ms in average. Compared with traditional system, PRISSO's time cost is about 100 times.

VI-D. Optimizing

As the most time cost is in client_id negotiation and dynamic registration and these two phases are transparent to

user. To reduce time cost we move client_id negotiation and dynamic registration to website initiation. When user visit RP's login page user agent conducts client_id negotiation and dynamic registration during page loading. So for a user its login procedure starts at obtaining token and network time cost is halved. The total time cost is about 406ms and the system possesses practicability.

VII. RELATED WORKS

In 2014, Chen et al. [10] concludes the problems developers may face to in using sso protocol. It describes the requirements for authentication and authorization and different between them. They illustrate what kind of protocol is appropriate to authentication. And in this work the importance of secure base for token transmission is also pointed.

In 2016, Daniel et al. [6] conduct comprehensive formal security Analysis of OAuth 2.0. In this work, they illustrate attacks on OAuth 2.0 and OpenID Connect. Besides they also presents the analysis of OAuth 2.0 about authorization and authentication properties and so on.

Besides of OAuth 2.0 and OpenID Connect 1.0, Juraj et al. [17] find XSW vulnerabilities which allows attackers insert malicious elements in 11 SAML frameworks. It allows adversaries to compromise the integrity of SAML and causes different types of attack in each frameworks.

Other security analysis [5] [7] [8] [18] [19] on SSO system concludes the rules SSO protocol must obey with different manners.

In 2010, Han et al. [20] proposed a dynamic SSO system with digital signature to guarantee unforgeability. To protect user's privacy, it uses broadcast encryption to make sure only the designated service providers is able to check the validity of user's credential. User uses zero-knowledge proofs to show it is the owner of the valid credential. But in this system verifier is unable to find out the relevance of same user's different requests so that it cannot provide customization service to a user. So this system is not appropriate for current web applications.

In 2013, Wang et al. proposed anonymous single sign-on schemes transformed from group signatures. In an ASSO scheme, a user gets credential from a trusted third party (same as IdP) once. Then user is able to authenticate itself to different service providers (same as RP) by generating a user proof via using the same credential. SPs can confirm the validity of each user but should not be able to trace the users identity.

In 2018, Han et al. [21] proposed a novel SSO system which uses zero knowledge to keep user anonymous in the system. A user is able to obtain a ticket for a verifier (RP) from a ticket issuer (IdP) anonymously without informing ticket issuer anything about its identity. Ticket issuer is unable to find out whether two ticket is required by same user or not. The ticket is only validate in the designated verifier. Verifier cannot collude with other verifiers to link a

user's service requests. Same as the last work, system verifier is unable to find out the relevance of same user's different requests so that it cannot provide customization service to a user. So this system is not appropriate for current web applications.

BrowserID [22] [23] is a user privacy respecting SSO system proposed by Molliza. BrowserID allows user to generates asymmetric key pair and upload its public to IdP. IdP put user's email and public key together and generates its signature as user certificate (UC). User signs origin of the RP with its private key as identity assertion (IA). A pair containing a UC and a matching IA is called a certificate assertion pair (CAP) and RP authenticates a user by its CAP. But UC contains user's email so that RPs are able to link a user's logins in different RPs.

SPRESSO [12] allows RP to encrypt its identity and a random number with symmetric algorithm as a tag to present itself in each login. And token containing user's email and tag signed by IdP is also encrypted by a symmetric key provided by RP. During parameters transmission a third party credible website is required to forward important data. As token contains user's email, RPs are able to link a user's logins in different RPs.

All the SSO system protocols above are quite different from current popular SSO protocol. So it is difficult for IdPs and RPs to remould their system into new protocols.

VIII. CONCLUSION

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