On the security of modern Single Sign-On Protocols –
Second-Order Vulnerabilities in OpenID Connect

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Abstract

OAuth is the new de facto standard for delegating authorization in the web. An important limitation of OAuth is the fact that it was designed for authorization and not for authentication. The usage of OAuth for authentication thus leads to serious vulnerabilities as shown by Zhou et. al in [44] and Chen et. al. in [9]. OpenID Connect was created on top of OAuth to fill this gap by providing federated identity management and user authentication. OpenID Connect was standardized in February 2014, but leading companies like Google, Microsoft, AOL and PayPal are already using it in their web applications [1], [2], [3], [30].

In this paper we describe the OpenID Connect protocol and provide the first in-depth analysis of one of the key features of OpenID Connect: the Discovery and the Dynamic Registration extensions. We present a new class of attacks on OpenID Connect that belong to the category of second-order vulnerabilities. These attacks consist of two phases: First, the injection payload is stored by the legitimate application. Later on, this payload is used in a security-critical operation.

Our new class of attacks – called Malicious Endpoints attacks – exploits the OpenID Connect extensions Discovery and Dynamic Registration. These attacks break user authentication, compromise user privacy, and enable Server Side Request Forgery (SSRF), client-side code injection, and Denial-of-Service (DoS). As a result, the security of the OpenID Connect protocol cannot be guaranteed when these extensions are enabled in their present form.

We contacted the authors of the OpenID Connect and OAuth specifications. They acknowledged our Malicious Endpoint attacks and recognized the need to improve the specification [29]. We are currently involved in the discussion regarding the mitigation of the existing issues and an extension to the OAuth specification.

1. Introduction

Single Sign-On (SSO). SSO protocols like SAML, OpenID or OpenID Connect replace multiple manual authentications at different Service Providers (SPs) with a single manual authentication at an Identity Provider (IdP), and multiple REST-based messages invisible to the End-User. An IdP manages identities of multiple End-Users, provides specific authentication mechanisms (e.g., username/password or 2-factor), and creates authentication tokens about authenticated End-Users. These authentication tokens are consumed by an SP granting or denying access to the End-User in dependence of the token verification.

Security of SSO. Many known attacks on SSO systems only tamper with one protocol step and achieve the desired results in the following step. For example, replay-attacks, or attacks manipulating the token directly or sending it to a different SP [17], [20], [32], [41] – they all achieve their attack goals in a single protocol request/response pair. We thus classify these vulnerabilities as first-order vulnerabilities, since they can be detected by only checking a single control flow. Modern analyzing tools like SSOScan [44], AuthScan [5] and InteGuard [43] are able to detect such first-order vulnerabilities but are limited to one protocol or cover only a small subset of existing attacks.

A more general approach is the automated analysis of SSO protocols, which remains a future challenge: Only the relatively simple flows of the SAML SSO protocol have been analyzed with protocol analyzers [17]. Sun et al. in 2012 [35] and Fett et al. in 2014 [15] proposed a formal model for analyzing OpenID and Browser ID, but admit that the protocols are far too complex to be analyzed automatically.

Summarized, previous work concentrated on first-order vulnerabilities in SAML [17], [20], [32], OpenID [24], [40], [35], OAuth [9], [34] and Facebook Connect [21], [44], but the OpenID Connect protocol and especially its extensions have not been investigated so far.

OpenID Connect. OpenID Connect is a new SSO protocol released in February 2014. It is the successor of OpenID and it is based on OAuth, but uses several ideas from OpenID.

The key feature of OpenID — the dynamic and fully automatic open trust establishment between IdP and SP — is also present in the OpenID Connect protocol by means of the Discovery and Dynamic Registration extensions. Open in the context of SSO means that users can be logged into an SP even if the user’s IdP is not known to the SP beforehand. A user can simply submit its identity on the SP,
which is usually a URL (e.g., https://IdP.com/alice) or an email address (e.g., alice@ldp.com). Based on this identity the SP discovers the responsible IdP (e.g., https://IdP.com/) and retrieves all information needed for the authentication. Afterwards, the SP dynamically registers on the discovered IdP and establishes a trust relationship to be able to (retrieve and) verify the authentication tokens used later on in the SSO protocol flow.

During Discovery and Dynamic Registration, SP and IdP communicate directly with each other (server-to-server communication), so these protocol messages cannot be monitored by the End-User.

Second-Order Vulnerabilities in OpenID Connect. Second-order vulnerabilities have been described and detected in the context of web applications [7], [11], [27]. Speaking of second-order vulnerabilities in SSO protocols in general we have the same execution scheme: (1.) The injection of the attack vectors is allowed by the specification and protocol flow. Thus, no implementation or configuration flaws are required. (2.) The execution of the protocol can proceed as usual without any incidents. (3.) The attack vectors are loaded and lead to successful execution of the attack.

Analyzing and detecting second-order vulnerabilities in distributed systems like SSO is more complex than in web applications, because they are including multiple phases, plethora messages, parameters and participants. This makes detection significantly more complex. We are not aware of any previous work and any automated security tools capable to detect such vulnerabilities.

Malicious Endpoint Attacks. The concept of our Malicious Endpoint attacks abuses a weakness in the Discovery and Dynamic Registration extensions of the OpenID Connect protocol to initially store the payload on the SP and execute it in another step. The main reason for this is that an SP can be forced to start a Discovery on an attacker-controlled webservice, which returns attacker-chosen information. This information contains URL parameters that can be used for different threats. For instance we could use them to start Server Side Request Forgery (SSRF) targeting the internal network behind the SP, execute Denial-of-Service (DoS) attacks by forcing the SP to download huge data files, start code injection attacks, and even broke the user authentication on the SP — we were able to steal the user’s SSO token.

Our Contribution.

- We are the first providing an in-depth security analysis of the OpenID Connect features Discovery and Dynamic Registration.
- We identified serious second-order vulnerabilities and developed a new class of attacks called Malicious Endpoints attacks, which exploit a lack in the OpenID Connect specification resulting in SSRF, DoS, and authentication flaws.
- We propose countermeasures to prevent our attacks, and discuss their respective advantages and disadvantages. The integration of our countermeasures are currently discussed with the authors of the specification.
- We provide a public available online website that can be used by SPs for verifying the security against our Malicious Endpoint attacks.1

Our results show that protocol extensions must be designed with extreme care, and their security implications have to be discussed thoroughly. Otherwise, they can lead to serious attacks with critical impact, even in secure standards.

The Discovery and Dynamic Registration are optional extensions. Four libraries are officially certified to specific conformance profiles and interoperability [16]. We successfully verified our attacks against two of them: MITREidConnect and phpOIDC. However, it must be considered that our Malicious Endpoints attack targets on the OpenID Connect specification itself and not on a specific implementation. Thus, any implementation using the Discovery and Dynamic Registration extensions is vulnerable against the class of Malicious Endpoints attacks.

2. Modern SSO Protocols

Since their establishment in the early 1980s, protocols like Kerberos (first officially published in 1987 as Version 4 [22]) and the corresponding concepts of delegated authentication and authorization using Trusted Third Parties (TTPs) have been constantly developed and refined into modern SSO protocols. These protocols aim at being compliant with the requirements of the modern and flexible Internet infrastructure. Mainly, modern SSO protocols strive to achieve the following goals:

- (1) Decentralization – SSO appears to be centralized embracing only a very small set of fixed TTPs. The most widely known of these TTPs are Facebook and Google. However, exporting data and outsourcing infrastructure to companies like Facebook and Google can include certain security risks and trust issues.

  Luckily, modern protocols like OAuth, SAML, BrowserID, OpenID and OpenID Connect are designed and specified to set up custom TTPs, which act independently from each other. This enables companies to set up their own TTPs and use these for authentication purposes instead of having to rely on external providers.

- (2) Trust Establishment – Every SP has to establish a trust relationship with the TTP. In order to do this, key material has to be exchanged. An important requirement for modern SSO protocols is that this process occurs with minimal configuration, implementation, and installation effort. In the best case, the trust establishment should work automatically.

1. The website does not provide any tests against DoS and SSRF attacks in order to avoid misuse.


### 2.1. OpenID Connect

The OpenID Connect protocol efficiently addresses the goals stated above – it is decentralized and allows automated trust establishment without any configuration effort or user interaction.

OpenID Connect was designed on basis of the OAuth framework [31] in order to enable the authentication of End-Users without changing the OAuth protocol flow. Thus, OAuth capabilities are integrated with the protocol itself [36], providing OpenID Connect with the capability of delegated authorization.

Additionally, OpenID Connect also incorporates concepts utilized by another SSO protocol – OpenID [39]. Such concepts are the Discovery and Dynamic Registration of OpenID Providers (OPs). The Discovery process allows an SP to automatically discover new OPs without any configuration and user interaction. The Dynamic Registration enables the on-the-fly registration and trust establishment between a Client and OP, also without any user interaction.

A major advantage of OpenID Connect is its integration into existing applications: OpenID Connect was designed to be easily integrated into current OAuth compliant systems, with only minimal extensions to the already available OAuth APIs.

### 2.2. Roles

Within the OpenID Connect protocol, three different parties each assuming a different role can be found. The relationship between the different roles can be seen in Figure 1.

![Figure 1: Role Relationship within the OpenID Connect protocol](image)

**The End-User**, represented by his user agent (UA), wants to access selected services of a Client. Therefore, he needs to prove his identity to the Client. Additionally, the End-User has the possibility to authorize the Client to access a specific set of his resources stored on the OP.

**The Client** is an application providing a certain service, which requires authentication of an End-User. This authentication process is delegated to the corresponding OP. Therefore, the Client requests an authentication token signed by OP, which proves the identity of the End-User. Optionally, the Client can also request authorization to access certain protected resources of the End-User stored on OP, for example, photos.

Please note that the term “Client” according to OpenID Connect terminology denotes an SP according to the common SSO terminology – a service, which can be accessed by the End-User. In order to be compliant to the terminology within the OAuth and OpenID Connect specification, we will use the term “Client” from now on.

**The OpenID Provider (OP)** acts as a TTP/IdP towards Client and End-User, handles End-User authentication and issues an authentication token containing a specific set of claims proving the identity of the End-User. Additionally, an authorization token can be issued, in order to authorize the Client to access End-User’s resources.

### 2.3. OP Endpoints

Within the OpenID Connect Core specification [36] the following endpoints on the OP are defined and their relation to the according SSO phases is depicted in Figure 2:

1. **Registration Endpoint (regEndp):** In order to use OpenID Connect services for authentication, a Client has to register on the OP. For this registration, the Client accesses this URL `regEndp`, e.g., `https://google.com/register`.
2. **Authorization Endpoint (authEndp):** In order to execute the Authentication Request of the Client, the End-User has to be redirected to the `authEndp` of the OP, e.g., `https://login.google.com/`. Here, the End-User has to authenticate to the OP via a corresponding authentication process and authorize the Client to access the requested resources.
3. **Token Endpoint (tokenEndp):** The Client communicates with the `tokenEndp`, e.g., `https://google.com/consume-token`, in order to obtain the `id_token` described in Section 2.5 and authenticate the End-User. In addition, an `access_token` can be sent to the Client in order to authorize the access to restricted resources. This communication is done directly between Client and OP (without involving the End-User).
4. **UserInfo Endpoint (userinfoEndp):** returns information about the authenticated End-User like email, address, phone, gender etc. In order to access the resources the Client uses an Access Token obtained through the OpenID Connect authentication.

### 2.4. Information Flow

OpenID Connect contains three phases, as shown in Figure 2. In this section we explain the information flow during the different phases.

**Phase 1: Client Registration.** The Client initially communicates with the OP’s registration endpoint (regEndp). It submits the `domain(s)`, where the Client is deployed,
for example https://clientA.com. The OP then generates a random client_id/client_secret pair, stores them both together with the domain as a triplet, and sends the credentials to the Client. The Client stores the same information in order to use it during phases 2 and 3.

The Client’s registration is mostly processed only once and is usually done via the web interface of the OP, for example by the domain administrator or the developer of the Client. Thus, the registration needs user interaction, causes management overhead, and cannot be executed automatically.

**Phase 2: User Authentication on the OP.** In the context of delegated authentication the Client redirects unauthenticated End-Users to the Authorization service endpoint on the OP (authEndp). Subsequently, the End-User authenticates to the OP using his credentials. Then, the OP generates an authorization code and sends it to the End-User. The code is an intermediary between the End-User and the Client. By sending the code to the Client, the End-User authorizes the Client to access restricted resources.

Once received, the Client uses the code to retrieve the authentication token (id_token), containing user’s identity, and optionally the access_token granting access to restricted resources.

**Phase 3: User Authentication on the OP – ID and Access Token.** Once the Client receives the code, it sends it to the Token Service endpoint on the OP (tokenEndp). In the same message, the Client sends its credentials (client_id and client_secret, cf. Phase 1) and authenticates to the OP.

The OP responds with the id_token and possibly the (optional) access_token. Once the id_token is received, the Client verifies it and subsequently authenticates the End-User.

The optional access_token is part of the OAuth protocol flow and it authorizes the Client to access restricted resources of the End-User on the OP.

**2.5. ID Token**

The OpenID Connect protocol is basically an extension of OAuth by adding an id_token. The id_token is a security token containing claims about the identity of an End-User by an OP, proving the End-User’s identity to a Client. Its data structure is represented as a JSON Web Token (JWT) [19]. In order to provide authenticity as well as integrity of the token, the OP is responsible for signing it using JSON Web Signature (JWS) [18].

```json
Listing 1: An example of ID Token as JSON object.

A signed id_token consist of three parts: Header, containing information regarding the used cryptographic
```
algorithms, Body, including information needed for the authentication of an End-User, and Signature providing the authenticity and integrity of the id_token.

Identity of the End-User. The identity of the user consists of two parts: (1.) issuer and (2.) subject. The issuer (cf. Listing 1: iss, Line 3) is a mandatory identity claim identifying the originator (the OpenID Provider) of the id_token, for example https://www.myOpenIDProvider.com. The subject (sub, Line 4) is a mandatory identity claim that specifies the End-User’s identifier and is consumed by the Client. Issued by the OpenID Provider (issuer), it has to be locally unique and never reassigned (e.g., alice@myOpenIDProvider.com). It is essential to note that both values – issuer and subject – must be used to uniquely identify the End-User.

Timestamps and Freshness. The claims timestamp (iat, Line 6) and expired (exp, Line 5) define the creation and expiration times of the token. The nonce (Line 7) claim is a randomly chosen String value, sent by the Client within the Authentication Request and passed through unmodified to the id_token, used to mitigate replay attacks.

Audience Restrictions. The audience (aud, Line 8) is a mandatory claim specifying the audience(s) that this id_token is intended to be used for (e.g., https://clientA.com). It must, at least, contain the client_id of the Client which requests the token.

3. Security Model

This section will give a detailed description of the security model used in the analysis of the OpenID Connect protocol.

3.1. Assumptions

We make the following assumptions for the analyzed systems:

- **Secure TLS channels**: A huge proportion of the security of OpenID Connect is based on the assumption that Transport Layer Security (TLS) is used to secure the communication between the involved parties. Naturally, we follow this approach and assume the corresponding TLS channels to be secure.

- **Uncompromised software**: All software used by the End-User is assumed to be uncompromised. This especially holds for the user agent and the operating system – we assume that no malicious web browser plugins and that no keyloggers etc., are active on the End-User’s system. We additionally assume that the Client and the OP can also not be compromised. For example, we assume that we do not have any other access except for their publicly available website (e.g., we do not have shell access).

- **No impersonation towards the End-User**: The attacker controls his own webservers and services, but we assume that he does not impersonate legitimate web applications. We thus assume that the End-User can neither be tricked into accepting attacker generated TLS certificates as valid certificates for genuine Clients, nor will the End-User react to Phishing mails claiming to originate from the legitimate Client. In short, we assume the attacker must not able to impersonate a legitimate Client towards the End-User in any meaningful way.

3.2. Capabilities of the Attacker

The attacks to-be-introduced in this work have been strictly verified in the web attacker model [6]. In contrast to the network-based attacker model (also called the cryptographic attacker model), the web attacker does not have full control over the network and thus is unable to eavesdrop on or manipulate network connections.

He is, however, able to use a UA or a custom HTTP client to send arbitrary HTTP requests to every publicly available web application in the web (including the Client and the OP) and subsequently receive its responses.

For tests within live implementations the attacker is able to register as many accounts on a specific Client or OP as he wishes.

Furthermore, the attacker can use links (e.g., sent via email) or web-blog commentaries to lure the victim into opening a (manipulated) Uniform Resource Identifier (URI) to, for example, conduct CSRF attacks.

3.3. Attacker Goals

The scope of this paper are attacks against the End-User and attacks against the Client.

**Attacking the End-User.** Attacks on the End-User are focusing on token theft. In OpenID Connect, there are three different tokens: The code, the id_token and the access_token. Leakage of any of them can allow an attacker to get unauthorized access to restricted resources.

**Attacking the Client.** Attacks on the Client have different surfaces and can be categorized in two groups.

The first group contains impersonation attacks. In Phase 1 of the OpenID Connect protocol – during the registration – the Client receives the client_id and the client_secret. Both parameters are used for the Client’s authentication to the OP. If these credentials are compromised, the attacker can use them to impersonate the Client. In Phase 2 of the protocol, the Client receives at least one token. An attacker can then send manipulated tokens to the Client in order to impersonate different End-Users.

The second group contains classical attacks on web applications. These attacks include DoS techniques as well as code injection attacks, like XSS or SQL-Injection. Please note that in our work, we consider this group of attacks only in conjunction of the OpenID Connect protocol. Thus, only
attacks that are directly initiated through protocol messages are investigated.

4. Gap in Security Evaluations

By considering previous work regarding the security of SSO protocols, we observed that its analysis concentrates on Phase 2 and Phase 3 [34], [44], [9]. Concentrating on those two phases seems plausible, because the End-User authenticates in Phase 2 and the authentication tokens are transmitted in Phase 3. An attacker targeting Phase 2 or Phase 3 can achieve one or more of the goals defined in Section 3.3. As a result, previous work only revealed security vulnerabilities in Phase 2 and Phase 3. These were fixed and the specification was changed [9].

Nevertheless, the entirety of Phase 1 has not been considered so far. This is reasoned by the fact that the Client Registration and Key Transport between Client and OP are usually executed manually. For instance, the developer of a Facebook App has to visit his Facebook developer website, and click on create new App. Facebook will then generate a client_id and a client_secret. The developer then copies them into his App configuration manually.

In contrast to this manual execution, protocols like OpenID and OpenID Connect can also execute the Client Registration automatically. Especially for OpenID Connect, this issue is addressed by introducing a new approach for the Client registration: The so called Dynamic Registration [38] allows registration to be automatic, transparent and without any user interaction. However, an important security question raised about this development is: How does this feature affect the security of the protocol?

5. Second-Order Vulnerabilities in OpenID Connect

In this section we first describe the OpenID Connect extensions Discovery and Dynamic Registration in detail. Then, we present security considerations regarding the usage of the both phases. Based on the security considerations we introduce the concept of a novel class second-order vulnerabilities in SSO.

5.1. OpenID Connect: Discovery and Dynamic Client Registration

The information flow during the automated Client Registration is shown in Figure 3. Initially, the End-User submits his identity, for example alice@honestOP.com, to the Client. In order to initiate the SSO authentication, the Client needs to discover the corresponding OP controlling the identity of Alice.

Phase 1.1. The Client uses the provided identity and extracts the domain name of the OP [37, Section 2.1]. In our example, Alice’s identity is controlled by the domain honestOP.com. The domain name uniquely identifies the corresponding Discovery endpoint.

The Client sends an HTTP request to this Discovery endpoint and subsequently retrieves the OP’s configuration information including its endpoint locations: The (Dynamic) Registration Endpoint (regEndp), the Authorization Endpoint (authEndp), the Token Endpoint (tokenEndp) and further endpoints (c.f., Section 2.3).

Phase 1.2. In Phase 1.2 (Dynamic Registration) the Client can automatically register at the OP. For that purpose, the Client sends its own URL, for example http://client.com, to the regEndp URL. The OP responds with a client_id/client_secret pair. Finally, the Client and the OP store the credentials in their respective databases and use them during the next phases.

5.2. Influence of the Discovery phase on the OpenID Connect flow

By analyzing the Discovery and Dynamic Registration phases we make the following observations:

- The usage of any OPs is supported by the OpenID Connect protocol without any pre-configuration, installation or manual interaction (neither on the Client nor on the User-Agent). The End-User has to enter his identity on the Client, e.g. bob@honestOP.com, in order to start the authentication with his own OP.

- All discovered endpoints are URLs. No limitations are specified that restrict these URLs to domains, subdomains, or URL contexts.

Based on our observations, we discovered that we can trigger any Client supporting Discovery and Dynamic Registration to use our custom OP for authentication. Thus, we control the data sent to the Client and used in the following phases of the protocol flow. In Figure 4 we present how the retrieved information during the Discovery phase influences the OpenID Connect phases.

Figure 4: A detailed overview of the Discovery phase revealing how the metadata received by the Client influences the next OpenID Connect phases.

The first two messages are used to discover the URL where the metadata of the OP is stored based on the

2. This is usually realized by applying a modifier to the domain, e.g., https://honestOP.com/.well-known/webfinger.
identity entered by and End-User. The Discovery request (1.1.1) is an HTTP message sent to the OP’s discovery service (e.g. https://honestOP.com/.well-known/webfinger).

The response is a JSON message containing two parameters: (1.) href, which points to the metadata of the OP and (2.) rel, which identifies the type of service (e.g. http://openid.net/specs/connect/1.0/issuer).

Consequently, a new HTTP request is sent to the URL specified via the href parameter. The response contains the metadata with all information regarding the OP: endpoints, supported authentication flows, supported algorithms for signing and encrypting messages, public keys of the OP etc.

Figure 4 depicts the relation between the endpoints received in the last messages of the Discovery phase and the OpenID Connect phases. The regEndp will be used by the Client in order to register the Client on the OP and receive the client credentials (e.g. client_id/client_secret).

The authEndp points to the Authorization server responsible for the authentication of the End-User. Noteworthy is the fact that only the Authorization server is visible for the End-User during the authentication. All other endpoints are called by the Client directly and thus cannot be seen by the End-User.

The next three endpoints tokenEndp, userInfoEndp and jwksEndp are used in the last Phase (Phase 3) of the protocol: the End-User authentication.

5.3. Security considerations

OpenID Connect supports the usage of custom OPs. For that purpose, a Client uses the Discovery and the Dynamic Registration Phase to retrieve the OP’s configuration information including the endpoints regEndp, authEndp, tokenEndp/userInfoEndp/jwksEndp and registers on it.

Please note that a malicious Discovery service can freely choose all these parameters (cf., Phase 1.1 in Figure 3). By this means, the malicious Discovery service can influence (1.) on which URL the Client registers (regEndp), (2.) which URL is used by the End-User to authenticate (authEndp), (3.) and to which URL the token will be finally sent (tokenEndp/userInfoEndp).

5.4. Second-Order vulnerabilities in OpenID Connect

Based on the security considerations, we developed a new class of attacks referred to the second-order vulnerabilities. This new class differ from the class of conventional second-order vulnerabilities in the context of XSS, SQL-Injection and DoS. To clarify the difference we first explain how second-order vulnerabilities are exploited in general and then we introduce second-order vulnerabilities in distributed systems like SSO protocols.

Web application. Common second-order vulnerabilities in web applications as shown in [11], [27] have only three entities involved: (1.) the attacker acting with his browser, (2.) the server hosting the web application and (3.) another End-User (the victim). In case of DoS attacks as shown in [27], there is no third entity involved, since the victim is the server hosting the web application itself.

Figure 5 shows an example of a second-order vulnerability on a web application.

During the first step, the user input containing an attack vector will be stored in the database of a web application.
In this step, no attack, but its preparation will be processed. Later on, the stored attack vector will be pulled from the database and executed leading to an SQL-Injection, XSS or even DoS.

**OpenID Connect.** Second-order vulnerabilities in SSO protocols are more complex than on web applications, since the attack consists of multiple steps and messages exchanged between different participants, for example, End-User and Client, Client and OP, and End-User and OP. Due to the nature of SSO, we have more entities: (1.) the End-User who wants to login. This can be either a benign End-User or the attacker; (2.) the Client which is the main target of our attacks; (3.) a honest OpenID Provider (OP); (4.) an attacker hosting his own service on the Internet. We will use this service to host a malicious Discovery service later on.

Figure 6 shows the data flow within a second-order vulnerability in a SSO protocol. Initially, the attacker stores the attack vectors. The main difference is that the user input $\alpha$ is not the attack vectors. $\alpha$ just starts the SSO authentication. The injection of the attack vectors occurs during Phase 1 of the protocol – the Discovery phase within a Server-to-Server communication. The attacker returns data used later during the protocol. In case of OpenID Connect this is a metadata file containing endpoints of the OP, supported protocol flows and supported cryptographic algorithms.

![Diagram of OpenID Connect](image)

Figure 6: Data flow of a second-order vulnerability in OpenID Connect. User’s input $\alpha$ triggers the authentication. Within the Server-to-Server communication in Phase 1, the attack vectors will be placed. These will be used later during Phase 2 or/and Phase 3. Please note that the contacted discovery services depend on the value of $\alpha$.

Later on, the stored attack vectors $\beta_1, ..., \beta_n$ will be loaded. Please note that each attack vector can be used during different SSO phases. Thus, $\beta_1, ..., \beta_i$ are used during Phase 2 of the protocol resulting. They can either lead to successful completion of this phase or to an successful attack. The further attack vectors $\beta_j, ..., \beta_n$ will be used in Phase 3 and lead to security issues.

To summarize, in Step 1 the attacker can place a harmless\(^3\) payload on the Client in such a way that the further communication process between the participants is influenced resulting in the following issues:

\(^3\) Harmless in this context means that the payload is not directly executed.

1. The attacker gets access to resources owned by an benign End-User (Section 6.1).
2. The attacker gather sensitive information regarding the Client (Section 6.2) and thus breaking privacy?.
3. The attacker injects further attack vectors like XSS or SQL-Injection (Section 6.3).
4. The further communication process between Client and End-User or Client and OP is slowed down significantly due to a DoS attack (Section 6.4).

### 6. Malicious Endpoints Attacks

This section describes four different attacks, which belong to the class of Malicious Endpoints attacks. All attacks use the malicious Discovery service and influence the OpenID Connect flow. Since each attack pursues different goals, we describe for each attack the main goal, the setup including the attacker model and the attack itself.

#### 6.1. Broken End-User Authentication

The idea behind the attack is to influence the information flow in the Discovery and Dynamic Registration Phase in such a way that the attacker gains access to sensitive information. The attacker pursues the theft of the credentials between the honest OP and the honest Client. Additionally, he steals a valid code authorizing the Client to access End-User’s resources on the honest OP.

**Setup.** The basic setup for the attack is as follows:

- The End-User (victim) has an active account on the genuine honest Client. We assume that the End-User trusts this Client and the Client follows the OpenID Connect protocol rules.
- The End-User is registered at the honest OP on the domain `https://honestOP.com`. The End-User trusts this OP and the OP also follows the OpenID Connect protocol rules.
- To perform the attack, the attacker has to set up his own Discovery service running on the domain `http://malicious.com`. This Discovery Service acts maliciously in that it deviates from the OpenID Connect protocol flow as described in Figure 3. Note that there is no need to disguise `http://malicious.com` as the regular Discovery service belonging to the honest OP in any way.
- According to the attacker model, the attacker does not hold any control over the honest Client, the End-User, the honest OP or the network traffic between these instances. The attacker is able to send an HTTP request through End-User’s browser, e.g. by embedding an image in a benign HTML website that causes the browser to automatically issue a request when the website is viewed.

**Attack description.** In the following, we describe the attack protocol flow, which we depicted in Figure 7.
**Phase 1.1 - Injecting malicious endpoints**
The attacker’s intention in the first phase is to force a valid Client to use the attacker’s malicious Discovery service. For this purpose, he constructs a malicious link and stores it on a benign website, e.g. in a web forum. For example, this can be a link to the valid Client containing an identity alice@malicious.com.

Listing 2: Endpoints returned by the malicious Discovery service

| issuer:                  | http://malicious.com |
|-------------------------|----------------------|
| regEndp:                 | https://honestOP.com/register |
| authEndp:                | https://login.honestOP.com/ |
| tokenEndp:               | http://malicious.com/  |
| userInfoEndp:            | http://malicious.com/  |

By visiting the website containing the malicious link, an HTTP request will be sent to the Client through the End-User’s (victim’s) browser. Consequentially, the Client starts a discovery phase with the malicious Discovery service http://malicious.com. The Client sends a request to determine the corresponding endpoints. The attacker’s Discovery service responds with the following values, initiating the actual attack:

**Phase 1.2 – Dynamic Registration**
In the next step, the Client accesses regEndp for the Dynamic Registration. It sends a registration request to https://honestOP.com/register and receives a client_id and client_secret in the response.

*Note:* The Client automatically starts the Dynamic Registration, even if it is already registered on the honest OP. The reason for this behavior is that the Client believes that http://malicious.com is the responsible OP, since it is not known from previous authentication procedures. Thus, http://malicious.com is a new OP for the Client and it starts the registration procedure.

**Phase 2 – End-User Authentication and Authorization**
In the next phase, the Client redirects the End-User to authEndp, https://login.honestOP.com/, where the End-User has to authenticate himself and authorize the Client. The End-User is not able to detect any abnormalities in the protocol flow: Phase 1.1 and Phase 1.2 cannot be observed by the End-User, and in Phase 2 the End-User will be prompted to authenticate to the honest OP and authorize the honest Client, both of which he knows and trusts. Thus, the End-User authorizes the Client and the OP generates the code, which is sent to the Client.

*Note:* Phase 2 exactly follows the original OpenID Connect protocol flow – there are no parameter manipulations, no redirects to malicious websites and no observation of the network traffic between the End-User, the honest OP and the Client. Thus, the attack started at the beginning of the protocol flow can be neither detected nor prevented by any of the participants at this point.

**Phase 3 – The Theft**
In dependence of the protocol flow, Code or Implicit, the messages sent to the attacker differ. Within the Code flow the Client redeems the received code from the previous phase: It sends the code together with the corresponding Client’s credentials received during the Dynamic Registration (client_id/ client_secret) to the tokenEndp originally specified by the malicious Discovery service – in this example http://malicious.com, see Listing 2.

Since the Implicit flow does not use the tokenEndp, the attacker is not able to receive the information send in phase 2. However, he can use another malicious endpoint – userInfoEndp used in Step 3.3 in Figure 7 to retrieve further information about the authenticated user. In the request, the Client sends a freshly generated Access Token. As a result, the attacker receives this Access Token and is able to access
the authorized resources on the OP.

6.2. Server Side Request Forgery (SSRF)

A SSRF attack describes the ability of an attacker to create requests from a vulnerable web application to the application’s Intranet and the Internet. Usually, SSRF is used to attack internal services placed behind a firewall and not accessible from Internet. In context of OpenID Connect, the malicious Discovery service can be used to start such attacks in order to (1.) gather information about the Intranet infrastructure of the Client, and (2.) disseminate attack vectors.

Setup. The attacker sets up a malicious Discovery service returning endpoints called by the Client during the protocol flow. The endpoints are URL strings specifying protocol (http(s), ftp, smb etc.), port, path, and parameters. Since there are no restrictions regarding the URLs, these can point to the Intranet infrastructure of the Client. The Client will use these URLs and performs HTTP GET requests on them. In this manner, the Client can, for example, be enforced to invoke internal REST-based web services. This capability of the attacker is considered by the attacker model, since the attacker is able to use his UA and send arbitrary HTTP requests to every publicly available domain. Thus, he can cause the Client to establish connection with the malicious Discovery service.

Attack description. In comparison to the Malicious Endpoint attack, now the attacker initiates the OpenID Connect authentication on the Client by entering his identity (e.g. oskar@malicious.com). Thus, no CSRF attack is needed. In the end of the Discovery phase, the malicious Discovery service returns the malicious endpoints called during the different phases of the protocol. Previous researches reveal how the execution of URLs can be used to (1.) connect and execute commands on different services like Memcached, (2.) Port scanning and (3.) data retrieving [4], [28].

6.3. Code Injection Attacks

User’s input sent through the web interface of the Client is usually treated as untrusted and thus filtered to prevent attacks like Cross-Site-Scripting (XSS) and SQL-Injection. In order to bypass the existing filter an attacker can use other channels to inject the attacks vectors – for instance within the server-to-server communication in Phase 3.

Setup. The attacker configures his server to inject malicious content in the messages returned in Step 3.2 (e.g. in the ID Token) or in Step 3.4 (informations about the authenticated user), which are sent to Client in Phase 3 (see Figure 2). Please note that the ID Token and Access Token returned by the malicious server are valid according to the specification, since there are no restrictions regarding the values of parameters like “sub”, “name” or “preferred_username”.

Attack description. Initially, the attacker starts the OpenID Connect authentication on the Client by entering his identity (e.g. oskar@malicious.com). He proceeds with the protocol execution until Steps 3.1 and 3.3. The malicious server then responds with valid tokens (ID Token and Access Token) containing the attack vectors. A toy example of such attack vector is shown in Listing 3 where an XSS attack vector is injected into the field presenting the name of an authenticated user in Step 3.4.

Listing 3: An example of an XSS attack vector hidden in the "name" filed within an Access Token.

```
1 "sub":"90342.ASDFJWFA",
2 "name":"<script>alert(1)</script>",
3 "preferred_username":"admin",
4 "email":"bob@malicious.com",
5 "email_verified":true
```

Now, the placed XSS attack vector is stored in the web application (persistent XSS). Other webpages on the client will use it, for example on a guestbook page, and embed the code, so that other page visitors get harmed. The same schema can be used to place SQL-Injection attack vectors.

6.4. Denial-of-Service (DoS) Attacks

By applying DoS attacks the attacker allocates resources on a Client and negatively affects its workflow. Such resources are CPU usage, network traffic or memory. The attack can target one or multiple of these resources during the execution of DoS attack.

(a) Memory usage on the Client within 5 parallel OpenID Connect authentication flows to an honest OP.

(b) Memory usage on the Client within 5 parallel OpenID Connect authentication flows to a malicious Discovery service pointing to a large file (in this case, we used a Debian Linux image file with 3.7GB).

Figure 8: Direct comparison between the memory usage on the Client using (a) an honest OP and a (b) malicious Discovery service.

Setup. The setup is similar to the SSRF attack – the attacker sets up a malicious Discovery service returning endpoints...
called by the Client during the protocol flow. The attacker is able to use his UA and send HTTP request to the Client causing the Client to establish connection with the malicious Discovery service.

**Attack description.** An attack can be started by using a malicious endpoint pointing to a large data file, which will be downloaded. The Client calls later on the malicious endpoint URL, allocates network resources as well as large amount of the memory, which will be unnecessarily used.

We provide a measurement shown in Figure 8 on an Apache Tomcat server with 1280 MB memory and 4x2.4 Ghz CPU. In Figure 8a we first measured the memory usage on the Client within five parallel OpenID Connect protocol runs with an honest OP. Once can say that almost imperceptible changes in the memory consumption occur. In Figure 8b we repeated the same tests, but this time we used our malicious Discovery service pointing to a large file. After few seconds, the memory usage increased almost threefold. After 60 seconds, the Client was not accessible for any incoming requests.

### 7. Implementation

We implemented a web service that is publicly available on [http://ssoattacks.org/OIDC_MaliciousDiscoveryService/](http://ssoattacks.org/OIDC_MaliciousDiscoveryService/) and it can be used by Clients for verifying the security against the attacks described in Section 6. In order to avoid misuse we do not provide tests for DoS, SSRF and injection attacks.

The service contains the following informations: (1.) Attack description presenting the main concept of Malicious Endpoints. (2.) A Demo showing a normal OpenID Connect flow and additionally the broken End-User authentication attack described in Section 6.1. For that purpose we configured an honest Client and an honest OP. The usage of own Clients is supported by the service. (3.) The configuration of the malicious Discovery service, enabling the view on the used malicious endpoints. (4.) Database viewing all collected credentials.

**Testing Clients.** Security auditors can test their Clients by using our service. No pre-configuration or installation of any software is needed.

In order to start the security evaluation, the auditor has to enter the URL of our malicious Discovery service on the target Client – [http://ssoattacks.org/OIDC_MaliciousDiscoveryService/](http://ssoattacks.org/OIDC_MaliciousDiscoveryService/). The Client calls the malicious Discovery service and caches the metadata returned by it. The metadata contains now the malicious endpoints. The Client proceeds with the OpenID Connect protocol flow and starts the next phases. At the end, the service prints out a report that includes all stolen information, see Figure 9, for example, the stolen code, access_token, id_token and Client credentials. Security auditors can use it to test arbitrary Clients and evaluate the impact of the attack.

We tested the Client applications of MITREidConnect and phpOIDC and attacked them successfully with our attacks. An online demo Client is also available for testing, see run demo on [http://ssoattacks.org/OIDC_MaliciousDiscoveryService/](http://ssoattacks.org/OIDC_MaliciousDiscoveryService/).

![Figure 9: The implementation collects all stolen tokens and credentials and prints out a report containing the results. Thus, security auditors can test their Clients and evaluate the results of the tests.](image)

### 8. Countermeasures

During our search for applicable countermeasures, we tried to find a solution requiring minimal changes to the protocol and to the existing implementations. In the following, we present four possible countermeasures to our attacks and discuss the advantages and disadvantages. Noteworthy is the fact that each countermeasure mitigates only partially the existing issues. Thus, a combination of the proposed countermeasures is needed to improve the security on the Client.

**OPs Whitelisting.** A suitable option to prevent the Malicious Endpoints attack is to whitelist the allowed OPs on Client side. By this means, an attacker will not be able to start the authentication process with his Discovery service. As shown in Figure 10, the administrator of the Client should manually whitelist the URL of each OP when it receives a discovered URL in Step 1.1.2 (the href parameter).

If the whitelisting approach is applied suitable, the attacker can only influence the first two messages of the discovery phase. After Step 1.1.2, the Client compares the returned href value with the stored values and breaks the execution in case that the URL is unknown.

Whitelisting mitigates both the Malicious Endpoints and the SSRF attack. This countermeasure however limits the
flexibility of the Client and reduces the support of custom OPs, which, depending on the according Client, could cause problems. Additionally, the management overhead regarding the provided whitelist can lead to further problems.

Endpoint Restrictions. A similar approach to prevent the attack would be to restrict the possible contents of the tokenEndp according to the contents of the authEndp. For example, it could be required that the tokenEndp MUST be located on the same domain as the authEndp and may only differ in subdomain and/or path. This way, an honest Client receiving a Discovery response can detect this attack and abort the protocol.

Even though this countermeasure restricts the introduced attack, it does not mitigate it completely. In case the attacker runs his malicious Discovery service on the same Infrastructure-as-a-Service cloud environment as the honest OP, he could bypass this proposed countermeasure by using the same domain or subdomain.

DoS protection. In order to prevent DoS the Client could simply do an HTTP HEAD request — before doing a GET request — and check the Content-Length HTTP header. In this way, the Client can retrieve the size of the file. Please note that this will only work on benign HTTP servers. The attacker could prepare his own webserver that responds with a wrong Content-Length header if a HEAD request receives. To protect against this, the implementation should stop downloading files after receiving a specified number of Bytes (e.g. 5MB).

CSRF/Clickjacking protection. Our attack to break the End-User authentication (cf. Section 6.1) requires the injection of the malicious identity (e.g. alice@malicious.com) in the first step, see Figure 7. To prevent this kind of attack, we propose each client to implement a proper CSRF² and Clickjacking protection⁵.

Please note that this will only prevent the broken End-User attack. SSRF, code injection, and DoS is still possible, because for this kind of attacks, the attacker itself sends a login request with alice@malicious.com.

Client authentication via client_secret_jwt or private_key_jwt. During the attack described in Section 6.1, the attacker steals the client_id/client_secret of the Client in step 3.1 (see Figure 7). In order to mitigate the attack, the Client can use alternatively the client_secret_jwt or private_key_jwt flow for authentication in Phase 3 [36, Section 9]. Within both flows, the Client does not send the client_secret through the channel. The Client signs a JSON message by using either the client_secret or an asymmetric private key. The OP verifies the message with the corresponding key and authenticates the Client.

Just signing the message does not mitigate the attack since the attacker can reply it on the honest tokenEndp. According to the specification the JSON message includes an audience parameter specifying the URL of the tokenEndp. During the attack the audience points to http://malicious.com. Thus, the attacker can steal the code and the signed JSON message, but he cannot replay them on the honest tokenEndp since it will detect the different values.

Please note that DoS and SSRF attacks are still possible and should be considered by the implementation of the Client.

Binding Discovery and Client Registration Phase. We discussed our findings with the OAuth Working Group. As a result, the OAuth specification will be extended in such a way that the Discovery phase is bound to the Authentication Response sent in Phase 2. We depicted this approach in Figure 11.
the Client.

Summary. By implementing CSRF and Clickjacking countermeasures on the Client the attack described in Section 6.1 will be mitigated. However, we believe that more general and protocol-based solution should be provided by the OpenID Connect specification. Thus, we prefer the countermeasure binding the Discovery and Client Registration Phase. Additionally, we advise the usage of both flows client_secret_jwt or private_key_jwt for Client authentication avoiding the transmission of the client_secret between the Client and the OP.

In order to reduce the impact of DoS attacks, the Client should expect short messages. Thus, it can be configured to wait small period for an answer and accepts messages less than several KBytes. The Client should restrict the usage of URLs, protocols and Ports in order to reduce the attack surface of SSRF attacks. For instance only HTTP requests of URLs, protocols and Ports in order to reduce the attack surface of SSRF attacks. For instance only HTTP requests should be allowed.

9. Related Work

Attacks on SSO systems. In 2012, Wang et al. [41] concentrated on real-life SSO and the analysis of SSO protocols and implementation flaws via Browser related messages (BRM). The authors have well demonstrated the problems related to token verification with different attacks. Additionally, they introduced a tool named BRM-Analyzer, which analyses the traffic passing through a user’s browser and detects abnormalities in the protocol flow, attempting to notice attacks. However, since the Malicious Endpoints attack described in this paper follows the protocol specification, no abnormalities can be detected by tools like BRM-Analyzer. Moreover, the BRM-Analyzer cannot observe the communication during the Discovery and Dynamic Registration phase, since the communication between Client and OP occurs directly and not via the End-User’s browser.

In 2012, Sun et al. [34] analyzed nearly 100 OAuth implementations, and found serious security flaws in many of them. The research focused on the impact of classical web attacks like XSS, CSRF and TLS misconfiguration on the OAuth implementations. In [12], [13], [14], [25], [26], [44], further attacks on OAuth implementations were discovered and reported. However, all these works concentrated on individual attacks and especially implementation misconfiguration.

In 2013, Wang et al. introduced a systematic process for identifying critical assumptions in SDKs, which led to the identification of exploits in constructed Apps resulting in changes in the OAuth specification [42]. Chen et al. revealed in 2014 serious vulnerabilities in OAuth applications on mobile devices caused by the developer’s misinterpretation of the OAuth protocol [9].

In 2014 Cao et. al. studied vulnerabilities in existing SSO protocols that allow impersonation attacks and analyzed the main reasons leading to these flaws [8]. The authors concentrated only on phase 2 and phase 3 of the SSO protocol flow and did not consider phase 1. Interestingly, the authors of the paper recognized that one main problem in SSO is the lack of authentication between the OP and Client, which is part of the Malicious Endpoints attack.

Please note that none of the previous papers considers the OpenID Connect protocol flow and the Discovery and Dynamic Registration phases.

Formal approaches. An open problem that we see as important future work (see below) is the introduction of a formal language and an verifier tool that will be able to automatically detect vulnerabilities as described in this paper. In 2012 Sun et al. [35] provided a semi-automated analysis on OpenID by modeling CSRF, replay, impersonation, parameter forgery and session swapping attacks. However, the authors did not consider that any of the OP’s components can act maliciously (e.g. the Discovery service). In 2014 Fett et al. [15] introduced a formalization for the (now defunct) SSO service BrowserID. Nevertheless, in this formal model they still perform a manual security analysis.

We refrain from modeling OpenID Connect in such a formal model for two reasons: (1) We believe that a thorough understanding of (second-order) vulnerabilities is essential to developing a formal model for automated analysis, and therefore concentrate on readability. (2) The model from [15] depicts only BrowserID and thus has to be modified for each SSO protocol separately.

Second-order vulnerabilities. In 2014 Dahse et. al. introduced an approach for static detection of second-order vulnerabilities in web applications [11]. The authors considered attacks like SQL-Injection and XSS and methods to prevent such vulnerabilities. More complex attacks including multiple steps for injecting attack vectors and their execution in distributed systems interacting with each other were not considered. One year later Olivo et.al. introduced new class of DoS attacks referred to the second-order vulnerabilities [27]. Additionally, the authors developed a static analysis approach for detecting second-order DoS vulnerabilities in web applications. More complex systems, for example distributed systems like SSO, were not considered and analyzed.

10. Discussion and Future Work

In this paper, we analyzed the OpenID Connect protocol considering all phases of the protocol. During analyzing the OpenID Connect’s the Discovery and Dynamic Registration phases we found several novel second-order vulnerabilities resulting in broken user authentication, DoS, SSRF and injection attacks. Summarized, we found an existing gap in previous security evaluations, since these concentrated only on the security critical phases – Phase 2 and Phase 3.

Speaking of SSO, other protocols like OpenID [33, Section 7.3], SAML [10] and BrowserID [23] support features similar to the Discovery and Dynamic Registration extensions described in OpenID Connect. It is essential that these protocols are further studied to avoid similar security gaps. We refer this research to the future work.
Second-order vulnerabilities in distributed systems like SSO are barely studied. The explanation for this gap is the complexity of such distributed systems. Since this complexity has not yet been tamed by an automated analysis tool, many of the SSO vulnerabilities today are discovered by manual security evaluation, which is time consuming and inefficient.

Developing such an automated analysis tool requires deep knowledge of the distributed information flows in a SSO system, and potential vulnerabilities. In this paper, we aim to provide exactly this information for the novel and important OpenID Connect SSO protocol, especially for the discovery phase.

An important task in the future is the development of techniques and automated tools facilitating the modeling, evaluation and detection of security issues in distributed systems like SSO. Currently, there is a gap, which should be in the scope of further researches.

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