

DELEGATEE: Brokered Delegation Using Trusted Execution Environments

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Abstract

We introduce a new concept called *brokered delegation*. Brokered delegation allows users to flexibly delegate credentials and rights for a range of service providers to other users and third parties. We explore how brokered delegation can be implemented using novel trusted execution environments (TEEs). We introduce a system called DELEGATEE that enables users (Delegates) to log into different online services using the credentials of other users (Owners). Credentials in DELEGATEE are never revealed to Delegates and Owners can restrict access to their accounts using a range of rich, contextually dependent delegation policies.

DELEGATEE fundamentally shifts existing access control models for centralized online services. It does so by using TEEs to permit access delegation *at the user's discretion*. DELEGATEE thus effectively reduces mandatory access control (MAC) in this context to discretionary access control (DAC). The system demonstrates the significant potential for TEEs to create new forms of resource sharing around online services without the direct support from those services.

We present a full implementation of DELEGATEE using Intel SGX and demonstrate its use in four real-world applications: email access (SMTP/IMAP), restricted website access using a HTTPS proxy, e-banking/credit card, and a third-party payment system (PayPal).

1 Introduction

Delegation, the ability to share a portion of one's authority with another, is a well-studied concept in access control. However, delegation remains mostly unsupported in today's online services. Email provides no delegation support at all, for example, while other services, such as Facebook, support delegation in a limited and coarse-grained way. Facebook allows a user to delegate to a third-party application the authority to post to the user's wall, but not to impose a limit of three posts per day. In any case, the expression and enforcement of delegation

policies lies entirely at the discretion of the services.

The ability to delegate access to existing online accounts and services, *safely and selectively*, could give rise to new forms of cooperation among users. Delegation may be useful for sharing digital content, such as access to streaming services like Netflix. Users may wish to delegate online tasks to remote workers, for example to reply to emails involving a particular topic or group. Delegation of access to financial services, such as PayPal, could enable broader access to banking.

Today, when delegation is needed in a way unsupported by the service, users must resort to credential sharing. This results in the *Delegates* gaining full access to the *Owners'* accounts. Such delegation mostly works only in closed circles with high levels of mutual trust.

In this work, we argue that the emergence of trusted execution environments (TEEs), such as Intel Software Guard Extensions (SGX), has enabled an alternative way to achieve fine-grained delegation without trust between the Owner and Delegatee. We refer this new type of delegation — specifically with delegation restricted under a policy enforced by a TEE enclave holding the credential — as *brokered delegation*. Brokered delegation is a new and powerful tool that allows users to flexibly share and delegate access, without requiring the explicit support (or even knowledge) of the service providers.

To demonstrate the potential of brokered delegation, we design DELEGATEE, a system that provides brokered delegation for many existing web services according to complex contextual access-control policies. DELEGATEE also preserves the confidentiality of the managed credentials. We develop several application prototypes to demonstrate how brokered delegation can support new forms of resource sharing and give rise to new markets: secure outsourcing of personal and commercial microtasks, tokenization (i.e., creation of fungible, tradeable units), resale of resources and services, and new payment methods - all without changes to the legacy infrastructure. One of the key features of DELEGATEE is that it

requires no changes to the service managing the resource or to users' accounts.

We present two design variations for DELEGATEE. The first design encompasses a purely decentralized peer-to-peer (P2P) system in which a Delegatee that wants to use brokered credentials executes the secure enclave on her machine. The Owner of the credentials connects to the enclave and delivers the credentials along with the access control policy under which the Delegatee can access a specific service. The second design is based on a centralized broker service operated by a third party. In this architecture, an Owner can register credentials and an accompanying policy, authorizing use by a specific population of Delegatees. Both system designs provide a comprehensive solution for brokered delegation and can be used based on users' preferences.

DELEGATEE also demonstrates a broader insight about the security consequences of trusted hardware: TEEs can fundamentally subvert access-control policy enforcement in existing online services. Depending on the application, DELEGATEE can either enrich a target service or undermine its security policies (or both). Brokered delegation can also facilitate violations of web services' terms of use. Users may thereby circumvent *mandatory access control* (MAC) policies, reducing them to *discretionary access control* (DAC). The effect is similar to allowing use of `setuid` [28] in Unix irrespective of MAC policies [39, 36].

The fine-grained delegation offered by DELEGATEE can support new forms of meaningful cooperation among users, which existing online services do not provide. In this way DELEGATEE may be related to new technology-fueled resource-sharing models such as Airbnb and Uber, which have challenged legal and regulatory frameworks while creating and delivering appealing new services. We thus view DELEGATEE as a catalyst for such new contributions to the sharing economy.

In summary, we make the following **contributions**:

- *Brokered delegation*: We advance a new model for user-specified safe delegation of resources and services governed by fine-grained access control. Our approach involves credential outsourcing to trusted hardware.
- **DELEGATEE**: We present DELEGATEE, a system that realizes brokered delegation via Intel SGX. We present two implemented versions: One based on a hardened third party acting as a credential broker and the other as a peer-to-peer system where users directly store, manage, delegate, and use credentials.
- *Security analysis*: We show that both DELEGATEE versions provide security in a strong adversarial model, protecting against some compromised SGX platforms as well as the full software stack of victims' machines.
- *Prototype implementations*: We describe and imple-

ment four applications on top of DELEGATEE: Delegated email, PayPal, credit card/e-banking, and full website access through an HTTPS proxy. We run these with commercial services such as Gmail and PayPal using real user credentials. We document minimal performance overhead and the ability to support many concurrent users.

- *Impact on access control*: We show that TEEs can be used to circumvent MAC policies in online services and allow discretionary access control, enabling users to delegate rights and access at their discretion.

2 Motivation and Problem Statement

2.1 Motivation

There are two major motivations for our work: To demonstrate the many settings in which brokered delegation gives rise to new functionality, and to demonstrate how (for good or bad) trusted hardware TEEs can transform practically any mandatory access control policy in an online service into a discretionary one. Our four different application scenarios illustrate both motivations.

Mail/Office. Full or restricted delegation of a personal mailbox or other office tasks can be appealing for many reasons. These include a desire to delegate work to administrative assistants (e.g., read-only access, send mail only to a specific domain) or to allow limited access to law-enforcement authorities (e.g., read emails from a certain time window relevant to a court case). The first is especially valuable for virtual-assistant services, which outsource office tasks off-site [26]. Today, these services require users to completely share their credentials, a dangerous practice that discourages many potential users.

Payments. Virtually all payments, cash and cryptocurrencies excepted, happen through intermediaries. Users may naturally desire a richer array of choices of these intermediaries. Consider, for example, a payment system where the users pay using each others' bank accounts, credit cards, or third-party providers (e.g., PayPal). This can have large benefits in terms of cost-saving, business operations, and anonymity guarantees.

Imagine that a company wants to allow its employees to execute online purchases with the company credit card or PayPal, but restricted to a certain limit per expenditure and specific merchants. Currently, this cannot be done since access to the card details or PayPal credentials allows users to execute arbitrary payments. Companies therefore typically provide such information only to a few employees who then execute payments for the rest, resulting in a highly inefficient process.

Delegation of payment credentials can also enable direct cost-savings for the end user. An example online system based on this premise is Sofort [25]. Sofort works as an internet payment middleman, with lower transac-

tion fees than for credit cards. Sofort pays merchants for clients' online purchases and is repaid by clients via bank transfer. To guarantee repayment, Sofort requires users to share their e-banking credentials with the service, a practice that clearly raises security and privacy risks.

Finally, delegation of payments can benefit "under-banked" populations with limited access to online payment systems, by enabling them to leverage social ties (e.g., via brokered delegation to the bank accounts of friends, family, and peers).

Full Website Access. The most versatile form of delegation is delegation for arbitrary existing web services, which typically authenticate user accounts through password challenges and then cookies over HTTPS. This model includes access to users' social networking sites, video services, online media such as news and music, and general website content available only to registered users. One appealing example from the academic world is *Sci-Hub*. "The site bypasses publishers' paywalls using a collection of credentials (user IDs and passwords) belonging to educational institutions which have purchased access to the journals." Many anonymous academics from around the world donate their credentials voluntarily [9]. Some services, such as Netflix and various news sites, already offer users the ability to log in from different devices. Users can thus share their subscriptions by sharing credentials, but only in a dangerous all-or-nothing manner. More fine-grained, e.g., service-specific, and secure delegation could facilitate much broader sharing (for good and bad).

Sharing Economy. The examples above involve an Owner delegating credentials to known Delegates, e.g., friends or colleagues. However, Owners can also offer access to their services on an open market to a wide range of potentially pseudonymous or anonymous Delegates. This would result in a shared economy in which Owners sell time-limited and restricted access to their accounts in return for other services or financial compensation. For example, users could sell access to Netflix accounts on an open market. They could also sell space in their social networking accounts to advertisers; e.g., a user could sell the ability to post in her name, enabling an advertiser to target her social network. The right to post could be restricted to a certain volume and type of content to prevent abuse by advertisers.

2.2 Problem Statement

If service providers regularly offered richly featured native delegation options, there would be no need for **brokered delegation**. Most do not, however, usually for business or regulatory reasons. Our work aims to change this situation fundamentally — DELEGATEE empowers users to delegate their authority, making use of any existing internet service, such that:

- The Owner's credentials remain confidential.
- The Owner can restrict access to her account, e.g., in terms of time, duration of access, no. of reads/writes etc.
- The system logs the actions of Owners and Delegates so that post-hoc attribution of their behaviors is possible (as a means of resolving disputes).
- The system minimizes the ability of a service to distinguish between access by the Delegatee and that of the legitimate Owner, thus, preventing delegation. (As we shall discuss, this is not achievable for all services.)

2.3 Why the Problem is Hard

DELEGATEE leverages SGX to implement functionality that without SGX or equivalent mechanisms would be infeasible or impossible to achieve. Consider our delegated payment scenarios involving PayPal, credit card or e-banking. Such delegation would be easy to support on the back end; e.g., PayPal could offer a delegation API.

Without back end support, however, there are only two possible implementation strategies. The first is that the Owner remains online and mediates requests, which forecloses on the possibility of private transactions or her inability to provide continuous service availability.

The second is that the Owner provides the Delegatee with a digital resource for unmediated access to the target resource. This, however, would require black-box obfuscation to construct a functionality that establishes a TLS connection, authenticates a user with a concealed password, and supports a series of policy-constrained transactions. General virtual black-box (VBB) obfuscation is known to be impossible [5]. It is unclear whether indistinguishability obfuscation ($i\mathcal{O}$), whose realization remains an open problem [12], could achieve this functionality. $i\mathcal{O}$, would in any case require circuit complexity well beyond the bounds of feasible deployment. It would also be subject to replay attacks unless the functionality could somehow change or revoke the credential atomically with permissible operations. In summary, SGX is required to solve our problem as stated, and even with SGX, as we now explain, solution remains challenging.

3 DELEGATEE

The main idea behind the DELEGATEE system is to send the Owner's credentials (passwords, etc.) to a Trusted Execution Environment (TEE) that implements the delegation policy. The Delegatee communicates with the resource (web service) indirectly, using the TEE as a proxy. In this section, we briefly introduce background on TEEs, then present the DELEGATEE system design.

3.1 TEEs and Intel SGX Background

Modern TEE environments, most notably ARM TrustZone [3, 42] and Intel SGX [13, 1], enable isolated code execution within a user's system. Intel introduced SGX

in the 6th generation of its CPUs as an instruction set architecture extension. Like TrustZone, an older TEE that permits execution of code in a “secure world” and is used widely in mobile devices, SGX permits isolated execution of the code in what is referred to as secure *enclaves*. In TrustZone, transition to the secure world involves a complete context switch. In contrast, the SGX’s secure enclaves only have user-level privileges, with `ocall/ecall` interfaces [20] used to switch control between the enclaves and the OS. The SGX architecture enables the application developer to create multiple enclaves for security-critical code and protect the software inside from malicious applications [43], a compromised OS, virtual machine manager [11], or BIOS [24], and even insecure hardware [16] on the same system. Additionally, SGX includes a key feature unavailable in TrustZone, called *attestation*. An attestation is a proof that a particular piece of code is running in an enclave.

In summary, the main protective mechanisms supported by SGX are: runtime isolation [33], `ocall/ecall` interfaces [20], sealing [2], and attestation [22, 13]. Due to space constraints, we relegate details to Appendix A; for in-depth treatment of SGX, see [13, 21].

3.2 System Design

We explore the DELEGATEE design space through two system architectures: a purely decentralized *P2P system*, and what we call a *Centrally Brokered* system, in which a third party runs the enclaves. Both architectures involve three distinct classes of parties: credential *Owner(s)* A , *Delegatee(s)* B , and *service(s)* G . Additionally, the system distinguishes 2 data types: *credential(s)* C and *access control policy(ies)* P . Owners and Delegatees are generically referred to as *users*.

The system supports a potentially large population of credential Owners $A_1 \dots A_n$ (henceforth referred to as Owners) and Delegatees $B_1 \dots B_n$. In general, the Owner A_i has access to a service G_k . The Delegatee B_j does not have access to the service, but she can get access by using credentials C_x of the Owner A_i . However, the Owner A_i does not want to reveal the credentials to the Delegatee B_j . The Owner A_i wants her credentials to remain confidential and used only by an authorized Delegatee. Additionally, the Owner wants to restrict access to the services that she enjoys (i.e. G_k) according to an access control policy P_{ijxk} specific to this delegation relationship. P_{ijxk} defines a policy involving Owner A_i , Delegatee B_j , credentials C_x , and service G_k . The type and structure of the access control policy depends on the service that the Owner delegates. Definition and enforcement of the policies are described in Section 3.4.

P2P system architecture. In our peer-to-peer system, there is no need for a central management entity to mediate between the Owners and the Delegatees. A Delegatee

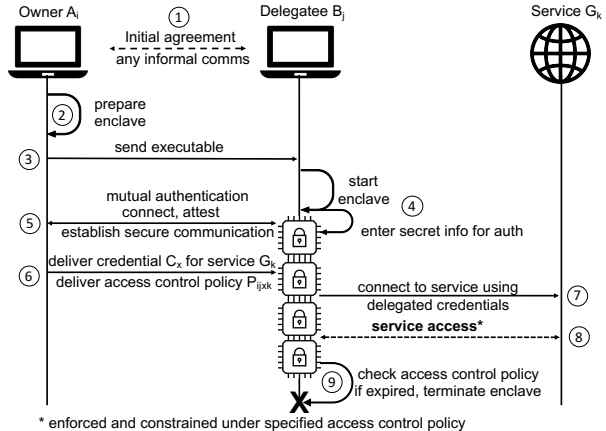


Figure 1: DELEGATEE’s P2P system architecture

can directly coordinate with the Owner to gain access to a specific service from group G . In order to execute this setup, a Delegatee from party B has to have a Intel SGX supported machine. The steps to execute secure credential delegation, also given in Figure 1, are:

- (1) The Owner A_i agrees directly with the Delegatee B_j for which specific service (G_k) access will be granted using her credentials (C_x). The agreement is done at the users discretion and through any available channel such as online messaging, email, etc. Additionally, users need to establish a method for authentication upon enclave start (e.g. pre-shared key, certificates).
- (2) (optional¹) After that, A_i prepares the enclave.
- (3) (optional¹) Owner A_i sends the executable to B_j .
- (4) The Delegatee B_j starts the enclave and enters the secret information (shared secret exchanged during the initial agreement) to the enclave needed for mutual authentication and secure connection establishment.
- (5) After the Delegatee B_j starts the enclave, the Owner A_i connects to the enclave, attests it to verify that it is the correct code with respect to the requested service delegation, and subsequently uses the secret information to authenticate and create a secure communication channel.
- (6) The A_i sends credentials C_x for the service G_k with the access control policy P_{ijxk} using the secure channel.
- (7) The Delegatee B_j now uses the enclave as a proxy to connect to the service G_k using the delegated credentials.
- (8) The scope of usage is strictly limited by the defined policy and therefore Delegatee B_j cannot use the parts of the service not allowed by the Owner A_i .
- (9) If the access control policy has a time limit, the Delegatee B_j ’s access to the service is terminated after the

¹Enclaves used for the credential delegation can also be downloaded from a trusted source. Each different service requires implementation of specific enclaves due to access complexity. The Owner and the Delegatee can verify the enclave trustworthiness with attestation.

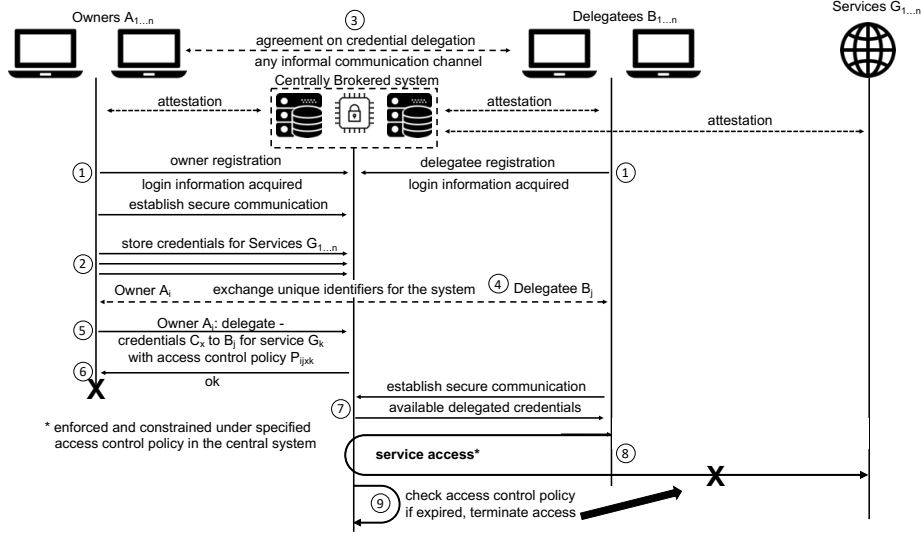


Figure 2: Centrally Brokered system architecture for credential delegation with DELEGATEE

time has passed, unless the Owner A_i extends the policy. The enclave restarts do not change this fact, requiring the connection from the Owner A_i to the enclave to deliver the information again. The enclave is stateless, meaning that any interruption, restart or termination after the initial start and the delivery of confidential information is going to result in service abortion.

Authentication mechanisms. The agreement between the users and their mutual identification and authentication is of utmost importance. The Owner needs to be certain that the enclave used to access a specific service with her credentials is running on the machine of the intended Delegatee. Attestation only gives us proof that the enclave is executing the presumed code, but without any information under whose control the machine is. To allow mutual authentication between the Owner and the Delegatee, a separate authentication method is needed.

Several authentication mechanisms are possible. First, the parties could use an out-of-band confidential and authenticated channel to exchange a shared secret key. After the enclave start, the Delegatee enters this pre-shared key into the enclave. The Owner uses the same key to establish a TLS (PSK mode) session with the enclave. If an attacker attempts to establish an impostor or man-in-the-middle session with the Owner, the keys will mismatch. As an alternative, we could use a trusted PKI so that the Owner obtains Delegatee's public key certificate, later used to establish a TLS session. This requires the Delegatee to provide her private and public keys to the enclave. Our design is agnostic to the used authentication method while the prototype uses the first option.

Centrally Brokered system architecture. Alternatively to the P2P configuration, the Centrally Brokered system consists of a central server that mediates all trans-

actions and communication between the involved parties and also serves as a management entity. The server has a trusted execution environment (SGX enclaves) that performs security-critical operations. Thus, the system can be attested to verify the running code and authenticated to verify the service provider. In this case, the Owners and the Delegateses do not need to have SGX. Steps needed to execute secure delegation follow Figure 2:

- (1) Both the Owners ($A_1...A_n$) and the Delegateses ($B_1...B_n$) need to register with the system to acquire unique login information (username and password) for access. After registration, both Owners and Delegateses can execute credential delegation for service access.
- (2) The Owners $A_1...A_n$ now establish a secure channel to the system (using the ordinary web PKI) and start storing the credentials $C_1...C_n$ for specific services $G_1...G_n$. The variety of credentials that can be stored depends on the supported services (see Section 5 for details).
- (3) The Owners $A_1...A_n$ may agree directly with the Delegateses $B_1...B_n$ for which specific service (G_k) the Owner will grant access using her credentials (C_x). The agreement is done at the users discretion through any available out-of-band channel and is limited by the implemented technical capabilities of the system (i.e., for supported use cases implemented by DELEGATEE).
- (4) During the agreement, users exchange their unique identifiers (i.e. system username) so that the Owner from party A knows whom to authorize from party B.
- (5) The Owner A_i establishes a secure channel to the system, specifies for which credentials (C_x) she wants to perform the delegation, for which service (G_k) and to whom (username of B_j), while she additionally specifies the access control policy P_{ijk} that restricts usage.

- (6) After receiving the confirmation, A_i disconnects.
- (7) The Delegatee B_j now establishes a secure channel to the system and can immediately see that she has been delegated credentials for a certain service. The credentials are hidden for the Delegatee B_j . If the Delegatee wants to access the service G_k , she may proceed.
- (8) The access to the service is always proxied through the central broker with no direct communication between the Delegatee and the service. Any attempt to circumvent this results in protocol termination (e.g., if the user clicks an external link outside the proxied service).
- (9) After the defined access control policy expires (e.g. if it is time limited) the Delegatee B_j loses access and the credentials are no longer delegated.

Interoperability. In Section 5 we describe the implementation of DELEGATEE. Our prototype implementation is based on the Centrally Brokered architecture, since this is the most plausible deployment scenario, although we discuss how the P2P model applies to each supported application. The implemented enclaves have two operation modes that can be chosen and set prior to the execution. In case of the Centrally Brokered system, the enclave retrieves important data regarding services, credentials, and access control from the management enclave, while in the P2P system, the enclave awaits the connection from its issuer to receive all information.

3.3 Usage with and without anonymity

DELEGATEE supports both anonymous and identity-based (non-anonymous) use models, as follows.

Anonymous model. As DELEGATEE conceals an Owner’s credentials, it naturally preserves her anonymity, even in the P2P model where the Delegatee operates the enclave executing DELEGATEE. Additionally, an Owner and Delegatee may negotiate and perform credential delegation without direct interaction. For example, a bulletin board (available on the Centrally Brokered system) might allow Owners to publicly list services they are willing to delegate, specifying accompanying access control policies and a schedule of costs (or offer of free service). Owners may identify themselves with pseudonyms, e.g., onion addresses. In the P2P model, the bulletin board can be hosted on a third-party website, while the protocol run through Tor Hidden Services, thereby ensuring privacy protection for both the Owner and Delegatee.

Identity-based model. An identity-based model follows directly from the model and examples given above. Here, the users know each other in some way, have a communication channel and can mutually identify each other. The Owner directly delegates her credentials to a specific Delegatee. Common use case examples include family sharing, delegation among friends and colleagues, etc.

3.4 Policy Creation and Enforcement

Securely enforcing defined policies presents a challenge on its own. We aim to prevent all attackers from modifying the policies or circumventing the enforcement by applying a combination of allowed actions in order to reach a desirable state. While the security analysis (Section 4) ensures that the owner-provided access control policy is respected, the burden remains on the Owner to choose an appropriate access control policy in the first place. An Owner who wants to delegate restricted access for a specific service needs to be able to define all allowed actions through a rich access control policy, denoted as P_{ijk} . For increased security, we prefer the white-listing of operations based on the least-privileges in order to prevent unwanted access and usage of the delegated account. Unfortunately, a general model for a wide variety of different services cannot be used. For every specific service category, and sometimes even for every specific service provider in the same category, a new policy must be created that resembles the exact capabilities and actions which a fully allowed user may invoke.

Policies in DELEGATEE. We designed and implemented policies for all scenarios defined in Section 2.1, namely, for mail, payments, and full website access.

In mail, DELEGATEE relies on the IMAP and SMTP protocols which are standardized and well defined. Inside the enclave we parse all incoming and outgoing request (to and from the Delegatee) and compare them against the defined access policy. Consider a concrete scenario: the organizer of a conference wishes to delegate her email account to an assistant to respond to logistical questions from attendees. The Delegatee should be granted read access to only *subset* of the organizer’s email (e.g., defined by a regular expression query like $(\#Usenix18^*)$). The organizer might also wish to enforce restrictions on message sending. Rather than sending to any possible email address, the assistant may only be allowed to *reply* to emails and deleting emails should be prevented. In general, for the inbox requests the Delegatee can be limited based on criteria such as date, time, sender, subject or content of the email. In outgoing requests, the limitation is set on the subject or content, and the intended recipient(s). Additionally, the Owner can rate-limit emails sent within a time interval, applying a spam and abuse filter for outgoing messages.

In payments, the main restriction is on limiting the allowed amount per transaction or the total amount using the delegated credential for either a credit card or any other third party payment service. Additionally, the DELEGATEE can enforce restrictions on the source, limiting the Delegatee to perform payments only on specific sites or identified merchants/services, and white-listed geographical locations based on the IP address.

In the full website access, DELEGATEE implements

limiting the use of login credentials to specific sites (e.g., the Owner can have the same credentials for two different services. However, full access is only achieved to the site allowed by the policy). As work in progress, the policies are expanded to restrict specific actions on sites after the login, including, clicks on various links, loading of specific site content or access to the account settings.

Our prototype implements delegation policies targeted at particular services, directly in C++. These policies rely on the mechanisms explained above; the Owner only needs to configure the value of the policy attributes (e.g., time limit, max amount, regular expression, etc.). In principle, the credential Owners could describe their own delegation policy in a general programming language. In Section 8 we mention existing and generic ways to extend our general functionality regarding access control. Specifying the policies is difficult to do correctly, however. We envision that a likely deployment scenario is a curated “app store”, to which entrepreneurs or power users submit useful policies they develop. These policies are then evaluated by experts and users. Web services are constantly updated, and the interfaces change over time, requiring delegation scenarios to be continuously maintained as well. In Section 7 we discuss further challenges if the services seek to actively prevent delegation.

4 Security Analysis

Brokered delegation provides a new usage pattern for potentially any existing online service. It, therefore, provides new security challenges as well, arising especially because each new service requires a customized delegation mechanism. In this section we describe the main security properties that DELEGATEE is designed to ensure across all applications:

- (a) *First and foremost, the Owner’s access credentials remain confidential.*
- (b) *The use of the delegated credentials is defined by the access control policy which will not be violated.*
- (c) *Use of the credentials should only be granted to the intended Delegatee, as authorized by the Owner.*

The DELEGATEE system is designed to provide these security guarantees even against a strong attacker model. We assume that an attacker neither corrupts the full software stack of the Owner’s and Delegatee’s machines (unless the Delegatee is the attacker), nor the online service, as existing web authentication mechanisms rely on them anyway. However, we consider an attacker that controls everything else (i.e., including the standard Dolev-Yao adversary [14] that can read and manipulate network traffic between parties). The two architectures we develop, P2P and Centrally Brokered, differ mainly in where the enclave is hosted (respectively, on the Delegatee’s own device or at an independent third-party). Although we

rely on a TEE, our system is designed to tolerate vulnerabilities in the SGX enclaves as long as the software stack on the machine running the enclave is also not compromised. Below we discuss several attacker configurations and the design decisions made to mitigate them. It is of utmost importance to note that our system is designed in a way that breaking the SGX protection mechanism on an arbitrary enclave will not subvert our system. The attacker would need to break the exact enclave running DELEGATEE, bypass the authentication mechanism, and compromise the full software stack on the same machine to violate the security properties.

4.1 Security through trusted enclaves

We first describe how these properties are ensured assuming the TEE enclaves are secure, even if the software stack of the Centrally Brokered system is compromised.

In the Centrally Brokered architecture, the TEE guarantees security properties (a) and (b) even if the central broker and the Delegatee are otherwise corrupted. The Owner only transmits her credential after validating the attestation that the enclave is running the correct code and if the authentication is successful. The mechanism for authenticating the Delegatee to the broker also lies inside the enclave, in the broker’s API enclave. This means that property (c) is guaranteed even if the broker’s full software stack is compromised since all security-critical operations are performed inside the enclave.

In the P2P architecture, even if the Delegatee’s software stack is corrupted, the Owner’s credentials are kept confidential. In Step (5), the Owner receives a TEE attestation before communicating further over the TLS channel, and validates it against the DELEGATEE enclave executable. Since the Owner only sends her credentials along this channel directly to the enclave, it is never exposed to the Delegatee’s host machine, thereby ensuring property (a). The only way the Delegatee can make use of the credentials is by providing commands as input to the enclave (all access is proxied through the enclave), where they are processed according to the access control policy P_{ijk} , ensuring the enforcement of (b). Since the TEE is hosted locally by the Delegatee (that also has to authenticate to the Owner using the agreed shared secret), then property (c) is ensured against an external attacker if he cannot steal the shared secret; against a rogue Delegatee, this property is not meaningful anyway.

We note that in either architecture, the code running in the enclave must use the credentials in application-specific ways. We stress that in our proposed system, the owner-provided access control policy P_{ijk} for service G_k is a configuration parameter given as input to one of the supported application specific enclaves. Hence the proof burden is on us to show that properties (b) and (c) hold for any policy P_{ijk} . We refer the reader to Section 3.4

and Section 5 for a detailed explanation. To summarize, each application makes use of the credentials only to authenticate with the corresponding service.

Finally, we note that Denial-of-Service attacks is outside the scope of our security guarantees since an external (network) adversary can always drop messages.

4.2 Robustness to compromised enclaves

Our system relies on the TEE to provide security against a compromised Delegatee or the broker service. However, DELEGATEE is also designed to provide defense in depth where possible, such that even a partial compromise of the TEE does not impact security (as long as the host machine is also not compromised). In particular, we consider an attacker that can recover the internal keys (e.g. sealing, memory encryption, etc.) of the Intel SGX. This strong attacker would be able to decrypt any sealed persistent storage or encrypted memory pages and create false attestations. As of the time of writing, there have not been any such attacks on Intel SGX keys. Regardless, by arguing security against this attacker model we reduce the harm if such a vulnerability should be found.

We address these concerns by designing our protocol so that all communication channels are authenticated end-to-end, even when communicating with an attested SGX. To illustrate, first consider the P2P architecture. Our authentication mechanism defends against such an attacker by requiring authentication input from the Delegatee before establishing the TLS endpoint in the enclave. Notice that by Step (5), the Owner A_i opens the TLS endpoint to the Delegatee’s enclave, over a potentially insecure channel. At this point, if the attacker can forge an enclave attestation, then the TLS channel may actually be an impostor channel. However, by authenticating the TLS channel against the pre-shared secret initially established with the Delegatee, the Owner would detect and invalidate such an impostor channel. This authentication occurs before the Owner ever transmits the credentials, ensuring desired property (a). Furthermore, the enclave software is guaranteed to be the correct DELEGATEE executable transmitted by the Owner, as long as the Delegatee’s host OS is uncorrupted. This ensures that properties (b) and (c) hold as well. However if a rogue Delegatee colludes with an attacker that can forge TEE attestations, or if the Delegatee’s software stack is fully compromised, then the credentials would be forfeit.

Our Centrally Brokered architecture is also designed with end-to-end authentication to mitigate against a potentially compromised TEE. The Delegatee and the Owner each establish authenticated TLS channels to the central broker (authenticating the broker’s enclaves using the typical certificate PKI), and only communicate to the broker over this channel. Hence all three security properties are ensured as long as the service’s own software

Enclave type	Core	mbedt1s	Total
API	4.0 (7.3%)	51.0 (92.7%)	55.0
Mail	1.9 (3.6%)	51.0 (96.4%)	52.9
Paypal	2.6 (4.9%)	51.0 (95.1%)	53.6
CreditCard	2.5 (4.7%)	51.0 (95.3%)	53.5
HTTPS Proxy	2.7 (5.0%)	51.0 (95.0%)	53.7

Table 1: TCB of DELEGATEE in LoC (thousands).

stack is not accessible to the attacker, regardless of any forged TEE attestations the attacker may produce or if the attacker can guess the SGX keys used by the enclave.

We also avoid the use of persistent encrypted storage in the P2P model. Thus preventing potential rollback attacks [32], which may otherwise occur if the enclave’s sealing keys can be derived by the attacker. Our DELEGATEE enclaves, therefore, do not provide any means to resume a previously-established delegation session if the processor is power cycled. Instead, their state is restarted from scratch. In the Centrally Brokered system, we do presume that the attacker has no presence on the full software stack, thus, for continuous operation of the system we make use of the persistent encrypted storage. If the attacker model would be expanded to allow attacker presence on the software stack, methods and techniques described in [32] could be applied to prevent rollback.

For ease of exposition, we have only discussed the highlights of our security design. A systematic security analysis can be found in the Appendix B.

4.3 Other Security Properties

Mandatory Logging. A well-chosen policy should ideally prevent any misuse from occurring. To be prudent, we would also like to ensure support for forensic investigation in the case that an incorrect policy is abused. We propose that all the requests and responses exchanged between the service provider and the Delegatee are securely logged using a timestamped statement signed by the enclave, for a possible later review. For example, in the payment scenario, if the Delegatee uses the Owner’s credit card, the following events are registered: time and date, the website and the amount of the executed payment. As another example, in the mail scenario, if the Delegatee manages to evade the abuse filter and send offensive emails, these messages should be logged. We imagine such logs may be used later on to prove that the Delegatee herself performed some action and indemnify the credential Owner. This discourages the Delegatees to perform any actions that could harm the Owner. To detect suppression of log entries, we could make use of a hardware monotonic counter. The enclave could additionally require a “receipt” from an independent backup service that replicates the log entry, before continuing.

Delegatee protection. So far our security analysis has only focused on protecting the Owner. Security for the Delegatees may be important too. For example, if a Dele-

gatee wishes to use the Owner’s payment account to purchase a sensitive item, they may not wish for the transaction details to be disclosed to the Owner. A delegation policy supporting the Delegatee could, in this case, offer a way to automatically delete payment transaction logs (if this is possible at all using the payment service).

5 Prototype Implementation and applications

In this section we describe our prototype implementation for the selected use cases mentioned throughout the paper. All enclaves rely on the OS to handle incoming and outgoing TCP connections while the SSL endpoints reside in the trusted enclaves. We use the `mbedtls` library developed by ARM [29], which also comprises the bulk of our trusted-computing-base (TCB). The interface between the OS and the enclaves consists of one `ecall` and ten `ocalls`, all of which are needed by the SSL library to use the OS’s capability to handle the TCP connections. The small number of calls and the small TCB, as shown in Table 1, facilitate code verification and reduce the surface area that may be affected by vulnerabilities.

To demonstrate our use cases, we implemented four service specific enclaves for delegated use of mail, PayPal, credit card/e-banking, and full website access through an HTTPS proxy. Additionally, a fifth management enclave is used to authenticate the users and store credentials, implemented as a RESTful API, further referred as the API. The API enclave is not used in the P2P system since it is not needed. Only service specific enclaves are deployed on the Delegatee’s machine. Additionally, we implemented a browser extension that communicates directly with the Centrally Brokered system and allows ease-of-use for the delegated credentials by the Delegatee (page parsing, detection of forms, choosing delegated credentials, etc.). All communication between the users, the enclaves and the browser extension is done using TLS with replay protection. We refer the reader to Appendix C for prototype screenshots of chosen examples. In these implementation details we presume that the Owner A_i and Delegatee B_j already registered to the system and that the Owner authorized the Delegatee by storing the credentials C_x and defining the access policy P_{ijxk} for a specific service. Thus, the Owner A_i is not shown in the figures.

Multithreading in Intel SGX. Intel SGX does not support traditional multithreading within an enclave. Additional threads cannot be started by an enclave, instead multiple threads of the untrusted app can simultaneously perform an `ecall`, resulting in parallel enclave execution. The amount of concurrency is specified during compilation of the enclave and is limited by the number of logical cores in the processor.

Authentication challenges. In Section 7, we dis-

cuss limitations concerning the modern authentication challenges and DELEGATEE. Our implementation supports one advanced authentication method involving *CAPTCHA*. In case of website login or PayPal, a captcha may be required as an additional authentication step. We successfully overcome this issue by extracting the secret image, presenting it to the Delegatee through browser extension generated pop-up, allowing her to solve it and continue with executing the desired operation. We refer the reader to Appendix C for prototype screenshots.

5.1 Mail/Office

Delegation of email accounts under a specific access policy, one of the DELEGATEE motivated applications, is implemented in the mail enclave. IMAP and SMTP clients are implemented to allow a Delegatee B_j to read and send emails using the delegated credentials C_x . Below we describe the architecture depicted in Figure 3a:

- (1) The Delegatee B_j wants to use some credentials C_x that have been delegated by A_i . B_j connects securely to the centralized API using her username and password (for P2P model the communication is established as described in Section 3.2, with both methods supported). She then requests to perform some action using C_x .
- (2) The API verifies that the Delegatee has access to C_x and then forwards the request, C_x and the corresponding policy P_{ijxk} to the mail enclave.
- (3) The mail enclave connects to either the SMTP server (for sending mail) or the IMAP server (for receiving mail) and executes the requested operation.
- (4) P_{ijxk} gets applied to the response from the external servers (IMAP) or to the outgoing requests (SMTP) and the resulting response gets forwarded to the API.
- (5) The API delivers the final response to B_j .

5.2 Payments

PayPal. PayPal does not want to endorse giving away your credentials or automating the payments as this could compromise their security. Thus it is non-trivial to automate a PayPal payment and there is no public API. We must emulate a browser inside our enclave that accurately simulates a real user. Normally the payment process relies on a javascript library but running a javascript interpreter in Intel SGX would bloat the TCB, and create potential vulnerabilities associated with running an unmeasured, externally provided script inside an enclave. We instead use the no javascript fallback mechanism from PayPal. Our implemented emulated browser follows redirects, fills known forms, and handles cookies until the final confirmation page is reached. The enclave then returns a confirmation id to the issuer that is used by the merchant to finalize the payment. Our implementation was tested using PayPal’s sandbox and

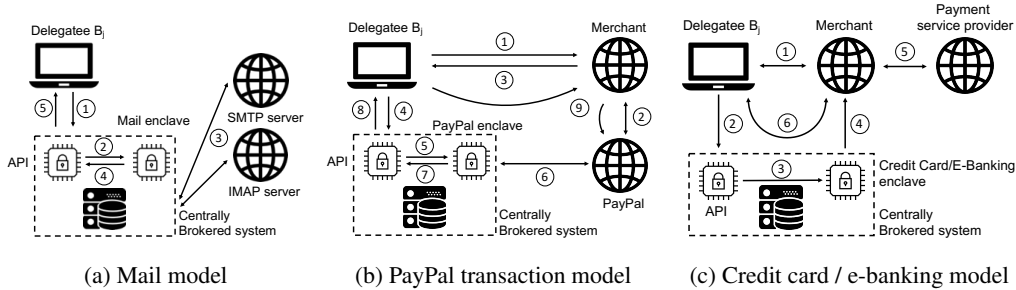


Figure 3: Architecture overview for the Centrally Brokered system

real world environment. Our browser extension simplifies the use of delegated PayPal credentials by adding a DELEGATEE checkout button next to the original PayPal checkout button if the Delegatee is logged in to our system and has some delegated credentials. Upon clicking on the DELEGATEE checkout the Delegatee can choose one of the available PayPal credentials delegated to her and then the automated payment process starts (please see Appendix C for screenshots). After that, no further user interaction is needed and the Delegatee will be forwarded to the confirmation page of the merchant if the payment succeeds. Below we describe the architecture depicted in Figure 3b:

- (1) The Delegatee B_j wants to buy something from a merchant using credentials C_x delegated by A_i . B_j connects to the merchant and asks for a PayPal payment.
- (2) The merchant uses PayPal API to create a payment.
- (3) The payment is then forwarded to B_j .
- (4) B_j connects securely to the centralized API enclave using her username and password (for P2P model the communication methods are described in Section 3.2). She then requests to pay with PayPal using C_x .
- (5) The API enclave verifies that the user can access to C_x and then forwards the request, C_x and the corresponding policy P_{ijxk} to the PayPal enclave.
- (6) The PayPal enclave connects to PayPal and pays the payment with C_x if it is allowed by the policy P_{ijxk} . The PayPal service responds with a confirmation number.
- (7) The confirmation number is forwarded to the API.
- (8) The API delivers the confirmation number to B_j .
- (9) B_j forwards the confirmation number to the merchant and then the PayPal payment is finalized by the PayPal API using the received confirmation number.

Credit card/e-banking. Payments are similar to PayPal payments: upon checkout on the merchant’s website, the browser extension is triggered if the payment form is available. The Delegatee chooses any delegated credentials she is authorized to use. The enclave fills the form with the credentials received either from the centralized API or directly from A_i using the P2P model. Our imple-

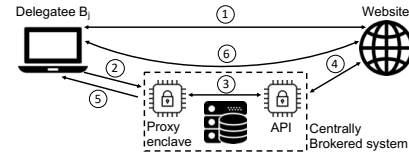


Figure 4: Login model

mentation was tested without any service provider that would finalize the transaction. Figure 3c shows the detailed architecture and the steps follow below:

- (1) The Delegatee B_j wants to buy something from a merchant using some credentials C_x containing credit card or e-banking information that have been delegated by A_i . B_j connects to the website and the browser extension renders a second button beside the normal credit card and e-banking credentials submit button.
- (2) Upon clicking the injected button, the browser extension requests a payment with C_x from the API.
- (3) The API verifies that the user has access to C_x and then forwards the request, C_x and the corresponding policy P_{ijxk} to the credit card/e-banking enclave.
- (4) The enclave fills C_x into the request while taking the policy P_{ijxk} into account and forwards it to the merchant.
- (5) Finalization is done by the payment service provider.
- (6) Response is routed through the enclaves to B_j .

5.3 Full Website Access

HTTPS Proxy. For secure browsing we implemented a HTTPS proxy enclave. We want to proxy selected websites and if a user leaves the website, he also leaves the proxy. We implemented this by using cookies to set the correct host name. The user sends any request to the proxy and he sets a cookie with the host name he wants to visit through the proxy. The enclave then parses the request, replaces the host name and sends it on to the real website. The response is also modified by the enclave so that the host name points to the proxy again. All links in the response are left unmodified so all relative links point to the proxy but all absolute links direct to a different website. The website certificates are checked against

Type	Test case	Mean (\pm std)
a) SSL handshake	openssl	52.12ms (\pm 3.62)
	mbedtls	57.14ms (\pm 3.37)
	mbedtls in SGX	105.22ms (\pm 4.23)
b) Mail	direct	1.12s (\pm 0.27)
	mail enclave	1.19s (\pm 0.22)
	API/mail enclave	1.45s (\pm 0.25)
c) PayPal	direct	25.92s (\pm 6.83)
	direct, no js	29.96s (\pm 8.51)
	PayPal enclave	27.00s (\pm 4.35)

Table 2: Latency for a) SSL handshakes, b) receiving e-mails in inbox, and c) executing PayPal transactions. Sample: 1000.

the statically compiled root certificate list in the enclave.

Login. To log into a service using delegated credentials we leverage similar technologies as in the HTTPS proxy and we thus only extended the proxy enclave to support delegated authentication for websites. Analogous to the HTTPS proxy we use cookies to specify the Delegatee’s *session token* and which credentials C_x she wants to use. The enclave then asks the API whether the Delegatee with the specified *session token* is allowed to use C_x . If everything checks out, the API responds with the details of C_x and P_{ijk} and the proxy enclave fills the login form before forwarding it to the website. As websites *session tokens* are usually stored in cookies, we encrypt all cookies forwarded to and from the website in order to prevent session stealing by an adversarial Delegatee. We use the browser extension in the same way as in the PayPal example: a button is rendered next to the original login. Figure 4 depicts the architecture and the detailed steps:

- (1) The Delegatee B_j wants to log into a website using some credentials C_x that have been delegated by A_i . B_j connects to the website and the browser extension renders a second button beside the normal login button.
- (2) Upon clicking this button, the browser extension changes the URL pointing to the proxy and appends cookies, specifying the credentials B_j wants to use.
- (3) The proxy asks the API for C_x . The API checks if B_j has the rights to use C_x and then forwards C_x .
- (4) The proxy enclave fills in the username and password into the login request and proceeds to send it to the website and receives the response.
- (5) The proxy rewrites the header of the response to encrypt cookies and then forwards it to B_j .
- (6) All subsequent connections have to go through the proxy where the policy P_{ijk} can be enforced.

6 Performance analysis

In this section we show that the overhead imposed by our solution stays within reasonable bounds. The performance testing was done using two i7-7700 machines with 16 GB RAM, connected via the internet and local network. We can serve around 100 users concurrently

Target (site)	Test case	Mean (\pm std)
small (2.6KB)	direct	5.0ms (\pm 2.7)
	proxy enclave	64.3ms (\pm 2.5)
medium (411KB)	direct	12.2ms (\pm 1.2)
	proxy enclave	76.8ms (\pm 3.3)
big (15.7MB)	direct	202.6ms (\pm 19.9)
	proxy enclave	432.2ms (\pm 16.0)

Table 3: HTTPS proxy latency with various page sizes.

even running on the consumer grade hardware.

Table 2-a shows an overhead of around 50ms for a full SSL handshake using `mbedtls` inside an enclave. The handshake involves three exchanged messages, thus at least three `ocalls/ecalls`, all of which have to copy buffers. In our measurements we recorded 19 `ocalls` during a request to the enclave. Overhead for `ocalls` and `ecalls` is measured and analyzed in [40] and is significant for copying buffers from the untrusted memory.

The mail enclave incurs minimal overhead (Table 2-b) with the extra handshake to the IMAP server (P2P system). In our test we retrieve all emails from the account inbox. In the Centrally Brokered system an additional handshake with the API is leading to a higher delay.

The PayPal example does not seem to suffer from any delay added by our implementation (Table 2-c). Note that we performed tests using the sandbox environment, provided by PayPal itself for testing integration with their services. This environment is feature-complete but slow as it is only functionality-oriented. Most time falls in waiting for the PayPal servers. As the enclave uses the fallback mechanism to execute PayPal transactions without JavaScript, we tested both variants: one allowing JavaScript and one blocking it. We also conducted tests in the real PayPal environment, however, due to the *CAPTCHA* protective mechanism involving the Delegatees’ actions, it is not feasible to measure performance.

Table 3 shows that the proxy adds the biggest latency overhead compared to normal browsing but still below 0.1 seconds for small to medium websites, a response time limit for seamless user interaction [35]. A part of the high delay stems from the enclave waiting for the whole web server response before forwarding it to the Delegatee. Message parsing, the additional handshake, and the fact that all communication has to cross the `ocall/ecall` interface twice also adds to the overhead. A full HTTPS proxy enclave is in the works to reduce the waiting time and support all client connections. We have also tested video streaming through our proxy, supporting DELEGATEE’s streaming service examples, and there is no overhead compared to normal streaming (the standard deviation is larger than the initial waiting time, for both the normal streaming and the proxied one).

Our multithreaded implementation was tested using 8 threads. Incoming connections are kept in a queue and served by the enclave threads, thus reaching maximum

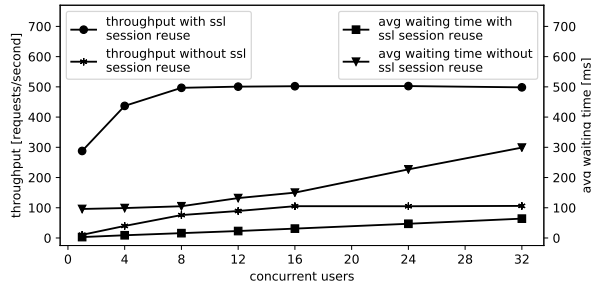


Figure 5: Concurrency shown in throughput and average waiting time. Each user tries to send 100 requests.

throughput with 8 concurrent users sending requests, as shown in Figure 5. The average waiting time stays constant until the same 8 user threshold, increasing linearly as new requests get queued. Our implementation supports SSL session reuse which significantly improves the throughput and lowers the waiting time. Without session reuse we can accommodate maximum 100 req/sec for 32 concurrent users, while with session reuse this grows to 500. Numbers could vary depending on the chosen cipher suite (ECDHE-RSA-AES256-GCM-SHA384).

7 Discussion

In this section we explore how brokered delegation faces technical challenges in the authentication process, as well as business and regulatory challenges arising from users controlling their own resources in a more flexible and fine-grained way than service providers intend.

Authentication challenges. Authentication in modern web services is complex. It can involve not just passwords but additional factors such as personal questions, email challenges, phone challenges, and “two-step authentication” apps such as Authy and Google Authenticator. Contextual factors often additionally come into play, such as the IP address, time of day, and nature of service requests. Financial services, e.g., PayPal, have particularly sophisticated fraud detection regimes; e.g., ordering unusual products with Paypal may trigger a fraud alert. Consequently, a single credential in the form of a password may not suffice to delegate a resource or service via DELEGATEE. In Section 5 we outline a solution for an additional authentication method in form of a CAPTCHA, that is required by some online services.

To illustrate, consider a scenario in the P2P mode where an Owner Alice (an inhabitant of the U.S.) delegates a password to DELEGATEE and allows her PayPal account to be rented. Suppose then that Delegatee Bob, in Nigeria, rents Alice’s PayPal account in a prescribed way and attempts to execute a transaction. Paypal will see an unusual request coming from an IP address in a country with a different risk profile than the U.S., and potentially one that Alice has never visited. Bob’s trans-

action request is likely to be suspicious. PayPal may then deny the transaction or request additional confirmation, e.g., via e-mail, to proceed. If Alice is unavailable or denies the transaction - which she may fail to recognize as originating with her delegation - the transaction will fail.

For future production deployment of DELEGATEE, we will address these complications in several ways:

- *Application-specific delegation:* Authentication systems vary considerably across applications and service providers. Each DELEGATEE application will include configuration not just for the APIs of a given target Service, but also its authentication policies.
- *Delegation of multiple credentials:* For services that require multiple credentials, DELEGATEE may require more than a password from an Owner. For example, two-step authentication apps can be executed within the enclaved DELEGATEE application and set up by an Owner as an additional authentication factor. Similarly, an Owner may delegate her email to the enclave to respond to email-based authentication challenges. The SGX platform performing the delegation may be situated in the same country or region as the Owner. Finally, an Owner can perform a set of legitimate transactions through DELEGATEE in order to confirm that required credentials are present and to white-list the platform with the authentication system of the target service.
- *Failure modes:* Periodic delegation failures are inevitable, just as legitimate users’ transactions fail sporadically due to false positives in the fraud-detection systems. As DELEGATEE is not intended for mission-critical uses, it could include graceful failure modes.

Authentication collisions. Attempts at simultaneous use of a resource may fail, as many web services do not support multiple concurrent sessions for a given account. For example, if Alice has delegated use of her bank account to Bob, then she may be unable to use it herself while Bob (or DELEGATEE, to be precise) is logged in. Such collisions can be treated by invoking failure modes like those for basic authentication failures. Other policies are possible, however. For example, Owner Alice may set a policy that only delegates her resource at times when she is unlikely to use it. A small enhancement to DELEGATEE can also enable Alice to preempt the session of a Delegatee if desired.

Secondary markets. Brokered delegation could give rise to offerings that compete directly with those of the very platforms hosting the delegated resources.

Facebook users could sell opportunities for “sponsored post” - unsolicited advertisements sent to their networks of friends or shown on their walls, as discussed above. Facebook users would then compete with Facebook itself in selling ads. Similarly, users could rent use of their Netflix account. Account sharing is already com-

mon within families and close friend circles. Brokered delegation could enable broad reselling and foster competition with direct sales of the subscription service.

Such secondary markets would in many cases violate providers' existing terms of service and might resemble markets for underground sales of virtual goods [27, 44]. Those underground markets have met with two responses, sometimes used in tandem: (1) providers aim to detect facilitators of secondary markets and penalize or ban them, and (2) providers themselves seek to capture the revenue streams generated by secondary markets; e.g., online role-playing game providers have offered virtual goods for sale through their own shops [31]. DELEGATEE could provoke similar responses.

Peer-to-peer cryptocurrency-for-fiat exchanges is another setting that can benefit from DELEGATEE. Today, websites like LocalBitcoins.com receive Bitcoin deposits and hold them in escrow. Then they match-make and allow a buyer and a seller to negotiate a e-banking transfer. When the receiver gets the bank transfer, they instruct the LocalBitcoins service to complete the payment from the escrowed funds. If the receiver raises a dispute, then the service must investigate and ultimately determine whether to release the funds. However, such services naturally have limited investigative ability. They may call the user's bank, or ask both parties for evidence (i.e., screenshots). Neither option is satisfactory; the latter is prone to forgery, while the former may inadvertently draw suspicion to the user's bank account. Credential delegation provides an alternative, simplifying this business model and implementing a secure intermediary that guarantees execution and fair exchange.

8 Related Work

TEEs are widely used today. ARM TrustZone, for example, is commonly used to protect data on mobile devices, e.g., biometric templates and encryption keys in iOS devices [4]. Intel SGX has been proposed for a number of applications, including confidential map-reduce tasks [37], trustworthy data feeds for blockchain oracles [45] and retrofitting of legacy applications [7], secure payment channels [30], etc. With DELEGATEE we extend this line of work with a new class of applications based on credential delegation.

Delegation of authority has been an important focus in access control security. Two mechanisms are commonly used. First, the credential Owner can interact with an authentication service to mint new credentials or tokens (representations of capabilities) for the Delegatee (e.g., Active Directory, Kerberos, and Oauth [17, 18]). Second, using chains of cryptographic assertions or certificates (as in X.509 or SPKI/SDSI), which can be digitally signed and communicated without interacting with a central server [10, 15, 34, 8, 6]. In either case, the dele-

gation mechanism must be supported by the resource (or a reference monitor guarding the resource). Our system is different in that we use a trusted enclave-based proxy that stores the user's credentials and is transparent to the resource. It is, therefore, used to retrofit delegation for existing web services, without requiring additional effort (or even explicit support) from the provider.

Many web services like Facebook, and Twitter, support delegation for third-party applications typically using OAuth or OpenID (e.g., a user may delegate to a Facebook app the authority to read her friends-list but not to post new messages on her behalf). However, this delegation is not very expressive. The authority to post on a users Facebook wall is all-or-nothing, for example; we cannot express restrictions such as no more than 1 post per day. Much of the research literature has focused on flexible languages for specifying and reasoning about delegation policies [10, 6, 38, 19]. Our approach is complementary, as our enclave-based proxy can be used to apply more expressive policies to existing services.

Without support for fine-grained delegation, users sometimes resort to sharing passwords with each other or with third parties [38]. For example, to use the financial dashboard service Mint.com, users often need to share their bank account passwords with the service [41].

Delegation based on TEEs promises a more secure alternative to this status quo. Credential delegation using SGX was first explored in [45] to support "oracle" queries. Use of SGX for credential management was also proposed in [23]; there the goal was validation and resale of credentials for criminal purposes. More recent work involves the delegation of private keys for cryptocurrencies in order to secure a payment channel [30]. DELEGATEE is much more general than these prior works, as it supports delegation of credentials for any desired goal.

9 Conclusion

In this paper we propose a new concept called brokered delegation, using TEEs to enable flexible delegation of credentials and access rights to internet services. We explored two design spaces, the decentralized P2P mode as well as a more pragmatic Centrally Brokered mode. Our implementation and experiments show that Delegatee in either mode can be applied to several real-world applications with minimal overhead, while preserving security against a strong attacker. Delegatee therefore has potential to enable delegation for any existing services, even without support from the service itself. This raises significant questions for future work: Can we enable robust delegation even against services that act to prevent it? Or can services defend against unwanted delegation? Lastly, given secure delegation, how would the economy of online services change?

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A SGX Background

In this section we briefly describe the main protection mechanisms of SGX from the main body of the paper:

Attestation. Attestation is the process of verifying that enclave code has been properly initialized. We distinguish between two types:

- In *local attestation*, a prover enclave requests a statement containing measurements of its initialization sequence, enclave code, and issuer key. Another enclave on the same platform can verify this statement using a shared key created by the processor.
- In *remote attestation* the verifier may reside on another platform. A system service called Quoting Enclave signs the local attestation statement for remote verification. The verifier checks the attestation signature with the help of an online attestation service that is run by Intel. The signing key used by the Quoting Enclave is based on a group signature scheme called EPID (Enhanced Privacy ID) which supports two modes of attestation: fully anonymous and linkable attestation using pseudonyms [22, 13].

Runtime isolation. As mentioned, the SGX security architecture guarantees enclave *isolation*, using protective mechanisms enforced in the processor, from all software running outside of the enclave. The control-flow integrity of the enclave is preserved and the state is not observable. The code and data of an enclave are stored in a protected memory area called Enclave Page Cache (EPC) that resides in Processor Reserved Memory (PRM) [33].

Sealing and Memory encryption. Enclaves can save confidential data across executions through sealing, a process for encrypting and authenticating enclave data for persistent storage [2] controlled by the untrusted OS. Each enclave is provided with a sealing key, private to the executing platform and the enclave. The sealing key is derived from a Fuse Key (unique to the platform, not known to Intel) and an Identity Key (either Enclave Identity or Signing Identity). Additionally, all runtime enclave memory is encrypted and cannot be accessed by

the OS as described above. In Section 4 we consider an attacker that cannot break the SGX hardware protection mechanism but can have all SGX keys used to, e.g., decrypt seals or the extracted memory content.

Ocall/Ecall. The interface between the trusted enclave and the untrusted application is implemented using *ocalls* and *ecalls*, calls from the trusted to the untrusted part, and vice-versa, respectively. During an *ocall/ecall* all arguments are copied to trusted/untrusted memory and then executed in order to maintain a clear partition of trusted and untrusted parts. These interfaces are defined and implemented by Intel in the Intel SGX SDK [20].

B Case by case Security analysis

In this section we show that even in specific cases where the attacker controls machines with compromised SGX or holds secret SGX keys, our system still preserves the relevant security properties. Below we outline assumptions along with the attacker model, followed by a detailed analysis on how the security properties hold.

In both models, we presume that the attacker has full control of the network described as the standard Dolev-Yao network adversary [14]. Additionally, we trust the service provider since the Owner and the Delegatee are already using its service. There will be no collusion between the service provider and the Delegatee. Also, the external attacker and the Delegatee as an attacker are two separate entities and when one is present the other is not, thus collusion between them is not possible as well. We intrinsically trust Intel, as the manufacturer of processors and SGX creator on top of which the secure enclaves are running. We trust the secure enclaves to execute code under properties of its architecture.

Our system is designed to provide the following main security properties:

- (a) *First and foremost, the Owner's access credentials remain confidential.*
- (b) *The use of the delegated credentials is defined by the access control policy which will not be violated.*
- (c) *Use of the credentials should only be granted to the intended Delegatee, as authorized by the Owner.*

The security analysis is structured by different case scenarios (further referred as Case 1-4) that might occur as an intersection of both the P2P and Centrally Brokered system of DELEGATEE with an external or Delegatee as an attacker. Furthermore, the cases are divided with respect to each of the security guarantees (Subcases a-c).

The attacker can re-route the network traffic, delay or modify the messages, but due to the use of an authenticated and confidential channel the attacker cannot gain any advantage, yet only cause a DoS attack. These attacks are out of scope in this paper.

1) External Attacker in the P2P system

- We assume that the attacker has access to an arbitrary number of SGX-enabled systems and *can* compromise a set of SGX enclaves (i.e., can extract all SGX keys)².
- We assume that the attacker *cannot* compromise the system of the Owner.
- We assume that the attacker *cannot* compromise the systems of the Delegates. However, the attacker *can* have the SGX keys of the Delegates' machines.

Case 1-(a): In order to obtain the Owner's credentials the external attacker can do the following. She can try to steal the credential from the Owner at the time of input into the P2P system, however, the attacker is not present on the Owner's software stack, and the connection to the enclave is secured end-to-end. Thus the credentials cannot be stolen. Additionally, she can try to use one of her machines that have compromised SGX in order to trick the Owner into delivering the credentials. However, the Owner and the Delegatee perform an initial agreement over an authenticated and confidential channel (e.g. messenger, a cup of coffee, etc.). They use the channel to exchange a symmetric key (or a certificate; depending on the implementation³, as discussed in Section 3.2) that is used for subsequent authentication when the credentials are delegated. Since the external attacker cannot compromise the system (full software stack) of both the Owner and the Delegatee, the initial exchange of the shared secret and further authentication of the enclave is secure. Thus, the attacker's ability to own a set of machines with compromised SGXs yields no advantage and all re-routed requests to some machines other than the Delegatee's will fail upon authentication. The attacker's knowledge of the Delegatee's SGX keys is useless due to the inability to be present on the Delegatee's software stack. Thus, the attacker cannot decrypt the runtime memory where the credentials reside after they are delegated to the enclave since she cannot access that part of the system.

Case 1-(b): The external attacker wants to violate the access control policy defined by the credential Owner to extend the rights and use the credentials in an unwanted way, causing harm to the Owner. Due to the fact that the attacker cannot compromise the full software stack of the Owner, she cannot modify or influence the process of defining the policy. After the policy has been defined, it is delivered to the enclave of the Delegatee and remains confidential. Even though the attacker possesses the SGX keys of the Delegatee's system, she has no access to the software stack of the Delegatee, thus modifying

the policy is not possible. Furthermore, as explained, the attacker cannot impersonate the Delegatee by using one of his compromised SGX machines, thereby she cannot gain access to the service even under the defined access control policy, nor perform a violation of it.

Case 1-(c): In order to achieve that an unauthorized user can access some service using the Owner's credentials the attacker might try to steal the exchanged secret key used for authentication. However, if we presume that the attacker does not have the control over the full software stack of the Delegatee and the Owner, she cannot acquire the shared secret that they agreed upon. Without it, the attacker is not able to authenticate to the Owner after the enclave starts even with the machines that have the compromised SGX. Thus, only the authorized Delegatee will be able to use the credentials.

2) Delegatee Attacker in the P2P system

- We assume that an attacker has access to an arbitrary number of SGX-enabled systems and *cannot* compromise a set of SGX enclaves.
- We assume that the attacker *cannot* compromise the system of the Owner.
- We assume that the attacker controls the system of the Delegatee. However, the attacker *cannot* compromise the enclaves running on the Delegatee's machine nor has access to the SGX keys of that machine.

Case 2-(a): In this case the delegatee/attacker aims to obtain the Owner's credentials. The Delegatee can use any of the machine available to her to initiate the credential delegation according to the P2P system model. However, the attacker cannot compromise the SGX nor does it have the underlying SGX keys of those machines and is, therefore, unable to extract the delivered credentials that remain in the runtime memory of the enclave. Additionally, the attacker does not have access to the Owner's system which prevents her from sniffing the credentials on input into the enclave. Taking into consideration all given abilities of the attacker, the attacker cannot reveal the confidential credentials if we presume safe delivery of them to the enclave (Owner performs attestation of the enclave after which Delegatee authenticates and secure communication is established from the Owner directly to the enclave, delivering the credentials subsequently...).

Case 2-(b): The Delegatee aims to violate the access control policy set by the Owner in order to use the delegated credentials in ways not defined by the policy. The security reasoning for this case closely follows the above Case 2-(a). Since the adversary cannot compromise the SGX in the machine she uses for delegation, she cannot access the runtime memory of the enclave and perform modifications to the access

²Although attacks that extract SGX keys have not been demonstrated, we still consider them in this model.

³The method does not influence the security analysis and in this case we have chosen the pre-shared key mode.

control policy. Thus, if we presume that the policies are defined correctly, the Delegatee cannot violate them during enclave execution. Additionally, the P2P system model is operational only on a single run, indicating that when credential delegation is executed, the enclave does not store or seal any data to disk. This prevents the adversary from performing a rollback attack [32]. Enclave monitors the usage of delegated credentials and records all activities. If the execution could be stopped and continued at a later time, the attacker could offer an older seal to the enclave thereby evading the limits defined in the policy. We prevent these attacks with a simple constraint that all data is lost after the enclave is stopped and the whole system has to be re-initiated to allow further use of delegated credentials.

Case 2-(c): Here we consider that Delegatee is the attacker. She is therefore already authorized to use the Owner's credentials. This property can be violated only if the Delegatee forwards the shared secret created with the Owner to another user. This action is out of scope.

3) External Attacker in the Centrally Brokered system

- We assume that an attacker has access to an arbitrary number of SGX-enabled systems and *can* compromise a set of SGX enclaves.
- We assume that the attacker *cannot* compromise the system of the Owner.
- We assume that the attacker *cannot* compromise the systems of the Delegates⁴.
- 1st possibility: Attacker *can* compromise the full software stack of the Centrally Brokered system. However, we assume that he doesn't have access to the SGX keys and *cannot* compromise the system enclaves.
- 2nd possibility: Attacker *cannot* compromise the full software stack of the Centrally Brokered system. Thus, he *cannot* compromise the enclaves on the servers, but he *can* have access to the SGX keys of the server.

Case 3-(a): In order to obtain the Owner's credentials, the attacker has the following choices. She can try to forward all requests addressed to the central system into her own set of machines where the SGX is compromised. Here we have two possibilities. Firstly, the attacker has the ability to compromise the full software stack of the central system but not the SGX enclaves running there. In this way, all requests can be re-routed with ease. However, we use an end-to-end secure connection from the users to the enclaves and the attacker cannot modify the communication. Additionally, users can always attest and authenticate the enclave, verifying its origin⁵. This prevents the attacker from impersonating

the server and acquiring confidential credentials into machines with compromised SGX. Secondly, if the attacker cannot compromise the full software stack and the running enclaves, she might possess the SGX keys of the central system. She can try to use these keys in machines with compromised SGX to trick users into believing that they communicate with the correct system. Nevertheless, the authentication step will fail even though the attestation will succeed due to the inability of the attacker to own the secret certificate key (note that without access to the software stack of the central system the attacker has no way of obtaining the full certificate information nor to extract the enclave seal which could be later on decrypted with the SGX keys she owns). Thus, impersonating the central system is not possible by the external attacker. The attacker can try to steal the credentials from the Owner at the time of input to the system but since she does not control the Owner's software stack, credentials remain confidential.

Case 3-(b): In this case the attacker aims to violate the access control policy defined by the credential Owner. The attacker may try to modify the credentials when the Owner is defining them in the system. However, the attacker has no control over the Owner's system and the connection to the central system is secured (see Case 3-(a)). Thus, this attack vector is not successful. The attacker might try to circumvent the policy enforcement in the enclave during execution of some service with the delegated credentials or change the policies inside the central system. In respect to the two possibilities that the attacker has, the policy cannot be violated since the attacker cannot change the defined policy (if he has access to the software stack he does not have the SGX keys and cannot compromise the running enclaves, thus preventing any modification of the policy, while if the attacker has the SGX keys of the central system, she is not present on the system and cannot extract the encrypted sealed nor the runtime memory where the policy resides) and cannot interrupt and compromise the policy enforcement (the attacker cannot compromise running enclaves when the system is compromised and when the system is not compromised she has no access to the execution environment, thus preventing any circumvention of the defined policy).

Case 3-(c): In order to use the Owner's credential without implicit authorization the attacker has the following possibilities. She might try to steal the login information of the authorized Delegatee in order to access the central system or obtain the login information of the Owner to modify the details of the credential delegation and authorize somebody else (i.e. herself). However, since

⁴Delegates do not use SGX in the Centrally Brokered system, thus the difference from the external attacker model from the P2P system

⁵The Centrally Brokered system has a public certificate signed by a

certificate authority, such as Verisign. Delivering the certificate private key to the enclave is presumed to be secure and works on the trust-on-first-use principle when the central system is bootstrapped.

the system uses end-to-end secure connection between all users and enclaves residing on the central system, and since the attacker does not control the software stack of either the Owner nor the Delegatee, she cannot sniff the network traffic or log the user input upon login into the system. Without knowing the login information (i.e. username and the password) of the Owner and the Delegatee, the attacker has no other means of accessing the central system and using the delegated credentials. Additionally, she can try to modify the information about the authorized Delegates directly on the central system, however, analysis shown in Case 3-(a) implies that the attacker cannot perform any modifications.

4) Delegatee Attacker in the Centrally Brokered system

- We assume that an attacker has access to an arbitrary number of SGX-enabled systems and *can* compromise a set of SGX enclaves.
- We assume that the attacker *cannot* compromise the system of the Owner.
- We assume that the attacker controls the system of the Delegatee. Furthermore, the Delegatee's SGX system is not involved in the protocol and thus out of scope.
- 1st/2nd possibility: Same as Case 3 (external attacker in the Centrally Brokered system).

Case 4-(a): In this case the Delegatee's role is the same as in the case of an external attacker and the Centrally Brokered system. No other attack capabilities exist (except the control over the full software stack at the Delegatee, which yields no advantage) that extend the external attacker and thus the same security analysis is applied as in the Case 3-(a), the Owner's credentials remain confidential. SGX at the Delegatee's side is not relevant when the Centrally Brokered system is deployed.

Case 4-(b): Similarly as above, the Delegatee's role is

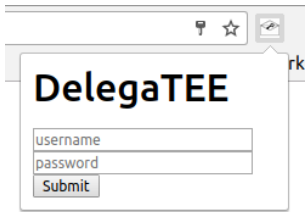
the same as of the external attacker with the difference that the Delegatee own login information to connect to the central system. However, this does not enable any new attack vectors that could be used to violate the access control policy. Even the external attacker could register to the central system, thereby acquiring authorized login information. Following the analysis of Case 3-(b), it is straightforward to conclude that the policy referring to the use of Owner's credentials cannot be violated.

Case 4-(c): Here we consider that the Delegatee is the attacker. She is therefore already authorized to use the Owner's credentials. As in Case 2-(c), this property can be violated only if the Delegatee forwards her login information to another user. This action is out of scope in this analysis.

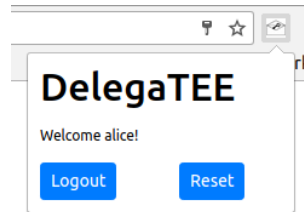
C DELEGATEE Prototype Demo

In this section we show prototype screenshots when a Delegatee, Alice, is buying something or logging in to a website using DELEGATEE. First, Bob enters his credentials into DELEGATEE and delegates them to Alice. Alice then logs into the browser extension (Figure 6a, Figure 6b) and the new button appears next to the PayPal checkout button (Figure 6c), the credit card/e-banking checkout button (Figure 6d) or the login button (Figure 6e). After clicking the DELEGATEE button, Alice is presented with a list of delegated credentials to choose from (Figure 6f). Upon selecting some credentials, the enclave takes over and completes the transaction and Alice is redirected to the confirmation page. If a CAPTCHA has to be solved to continue with the transaction, the user is asked to solve (Figure 6g).

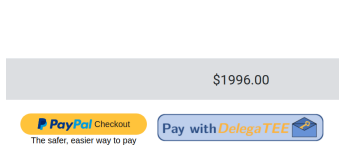
Receiving and sending emails using delegated credentials can be done with our mail client for DELEGATEE. It allows to view the inbox and read single mails of the delegated mail account (Figure 7a). Sending emails is also supported (Figure 7b).



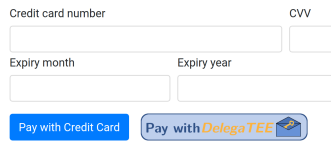
(a) Browser extension: Login



(b) Browser extension: Welcome



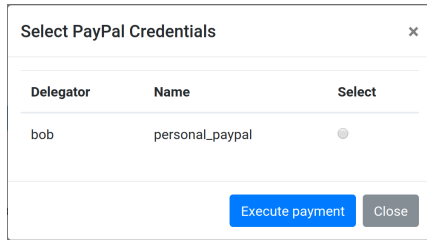
(c) Extra button rendered next to the PayPal checkout button



(d) Extra button rendered next to the credit card checkout button



(e) Extra button rendered next to the login button

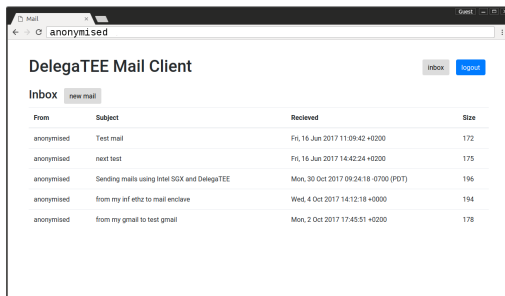


(f) Delegated credentials selection.

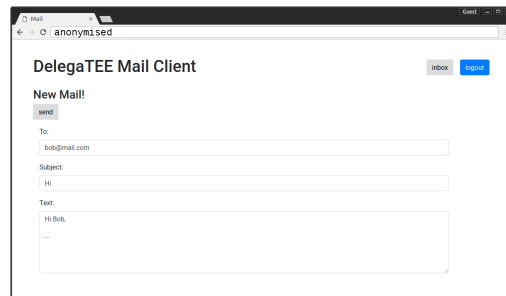


(g) The Delegatee is asked to solve CAPTCHA

Figure 6: Demo of a payment/login process using DELEGATEE. The buttons and the dialog get injected to the website by the browser extension.



(a) Receiving mail



(b) Sending mail

Figure 7: DELEGATEE mail client example. All links and other details have been anonymized for review.