

**Bachelor Thesis**

# **Password-Authenticated Key Exchange (PAKE)**

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## Travail de Bachelor 2021-2022

### Password-Authenticated Key Exchange (PAKE)

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# Préambule

Ce travail de Bachelor (ci-après TB) est réalisé en fin de cursus d'études, en vue de l'obtention du titre de Bachelor of Science HES-SO en Ingénierie.

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# Authentification

Le soussigné, Julien Béguin, atteste par la présente avoir réalisé ce travail et n'avoir utilisé aucune autre source que celles expressément mentionnées.

Yverdon-les-bains, le December 24, 2021

Julien Béguin





# Specification

## Context

Password-authenticated key exchange (PAKE) is a very powerful cryptographic primitive. It allows a server to share a key with a client or to authenticate a client without having to know or to store his password. For this reason, it provides better security guarantees for initializing a secure connection using a password than usual mechanisms where the password is transmitted to the server and then compared to a hash. Despite its theoretical superiority, PAKEs are not implemented enough in the industry. Many old PAKEs were patented or got broken which might have hurt the adoption of this primitive.

## Goals

1. Outline existing PAKE. This includes SRP, OPAQUE, KHAPE, EKE, OKE, EKE variants (PAK, PPK, PAK-X,), SNAPI and PEKEP. Also look for other less known PAKEs.
2. Study in detail the main PAKE — EKE, SRP, OPAQUE, KHAPE — and understand their differences.
3. Choose one of the modern PAKEs to implement. The choice is based on the properties of the PAKE, the existence of implementations for this PAKE and the existence of standards for this PAKE.
4. Design an interesting use case where using a PAKE is more appropriate than using a classical authentication method. The advantages of the PAKE are detailed in the report.
5. Implement the chosen PAKE and the use case using the desired programming language

## Deliverables

- Implementation of the chosen PAKE with the use case
- Report containing :
  - PAKEs' state of the art,
  - Description of the use case,
  - Advantages of using a PAKE over a classical authentication method for this use case,
  - Implementation details

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# 1 | Introduction

This chapter describe the context of this project. We discuss about classical authentication method, their weakness and the necessity to use stronger construction such as PAKEs.

## 1.1 Problematic

**How to authenticate a user ?** When a user want to connect itself to a online service, he sends its username or email for identification. Then, he needs a way to prove to the server that he is indeed the person he pretends to be. This is what we call authentication. Without it, anybody can impersonate the account of someone else. Authentication can be based on multiple factors. Something that the user *knows* (e.g. passwords, PINs, ...), something that the user *has* (e.g. digital certificates, OTP token devices, smartphones, ...) or something that the user *is* (e.g. fingerprints, iris, ...). Multiple factors can be combined to obtain a strong authentication.

Traditionally, the user send the authentication value to the server through a secure channel — generally TLS — to avoid eavesdropping and then the server compare the value that he received to the value that he stored for this specific user. This means that the server has to knows and store this sensible value before authentication — generally during register. Currently, the vast majority of websites and softwares use passwords as the authentication value. They are the easier to implement and the most familiar to the users.

**Attacks and mitigations.** This setup is not ideal and can lead to multiple attacks. In case where the server get compromised, the attacker immediately obtain access to all accounts since the server store the passwords. This means that the adversary can impersonate every user. To avoid this scenario, numerous techniques have been developed. Mainly, hashing the password and storing the result, adding hashing salt, adding hashing pepper — a secret salt — and using memory-hard password hashing function such as Scrypt [27] or Argon2 [9].

These techniques improve the security of storing password but they do not address the deeper problem; When the user wants to login, he has to send its *cleartext* password to the server in order for the server to authenticate the user. This necessity void any password storing improvement if the server is ever persistently compromised or if passwords are accidentally logged or cached.

**Why passwords are bad ?** Passwords are a problem. They are hard to remember and to manage for the user. They are generally low-entropy and users are reusing the same passwords too often. A password manager can help the client to handle this problem but there is a greater underlying problem. The problem is that “a password that leaves your possession is guaranteed to sacrifice security, no matter its complexity or how hard it may be to guess. Passwords are insecure by their very existence” [11]. Now-a-day, a majority of passwords use require that the password is sent in cleartext.

Even if the channel between the client and the server is appropriately secured — generally with TLS which can be vulnerable to PKI attack, cert miss-configuration, etc. — and even if on the server-side every password storing techniques are carefully implemented, the password still has to be processed in cleartext. As stated before, there can be some software issue like accidental logging or caching of the password. But hardware vulnerabilities are not to forgot. While the password is processed in clear, it reside on the memory. It use a shared bus between the CPU and the memory. Hardware attacks are less likely to occur but are no less severe (remember Spectre [23] and Meltdown [26] attacks).

In a ideal world, the server should never see the user’s password in cleartext at all. One could think that hashing the password on the client side would solve the problem but if the server ever gets compromised, every account is immediately accessible to the attacker. The client hash should be be hashed again on the server but this does not solve the initial problem. The password is just replaced by a longer password — the hash.

**Get rid of password.** In summary, password are not ideal. They are difficult to remember, annoying to type and insecure. So why don’t we try to get rid of them altogether ?

Promising initiatives to reduce or remove passwords are emerging and improving — e.g. WebAuthn — but they generally require a deep change for the developers and a sacrifice in convenience for the end user. For example, it can be difficult for an end user to manager private keys if he needs to transfer them securely between multiple devices or if he lose the device that store them. Overall, it will take time for these new solutions to grow mature and impose themself as industry standard. Password are so ubiquitous due in part to the ease of implementation and the familiarity for the users. So if we cannot get rid of passwords for now, we need a way to make them “as secure



as possible while they persist” [11]. and this is where PAKE become interesting. It allow password-based authentication without the password ever leaving the client.

**PAKEs at the rescue.** Password-Authenticated Key Exchange (PAKE) is a cryptographic primitive. There are two types of PAKEs:

- Symmetric (also known as balanced) PAKE where the two party knows the password in clear
- Asymmetric (also known as augmented) PAKE designed for client-server scenarios. Only the client knows the password in clear

For the moment, we will focus on asymmetric PAKE (aPAKE) because it is the one that can solve our authentication problem. aPAKEs guarantee that the client’s password is protected because it **never** leave the client’s machine in cleartext. It is done by computing a key exchange between the two parties and then mutually verifying that they share the same output key. The password is used to compute or retrieve values inputted in the key exchange protocol. This allow a client and a server to mutually authenticate without requiring a secure channel — except for the initial registration.

The goal of PAKEs protocol is to provide a shared key between two parties and that the only way for an attacker do a dictionary attack — test a list of password candidates — is to perform online guesses. The attacker is forced to become active and to interact with the server, which is easier to mitigate than passive attacks.

Overall, “a secure aPAKE should provide the best possible security for a password protocol” [10] and it should only be vulnerable to inevitable attacks such as online guess or offline dictionary attacks upon server compromise.

**Why PAKEs have almost no adoption ?** Despite existing for nearly 3 decades and providing better security guarantees than traditional authentication method, PAKEs have almost no adoption. So why are they so rare in the industry now-a-day ?

Firstly, for web site, it’s easier to setup a password form and handle all the processing on the server than to implement complex cryptography in the browser. But even in native app PAKEs are rarely used to authenticate. This could be caused by the fact that many old PAKEs was either patented, got broken or both. It probably hurted the reputation and adoption of PAKEs.

Another factor is the insufficiency of well-implemented PAKE library in some programming language which make them difficult to use. One exception to that is SRP, the most used PAKE protocol in the world [18]. It is a TLS ciphersuite, is implemented in OpenSSL and used in Apple’s iCloud Key Vault. Even though it has far more adoption than other PAKEs, is not the ideal PAKE.

In the last few years, a new generation of strong aPAKE [22, 20] has appeared. These new construction are better and provide more security guarantees than ever.

## 1.2 Our contributions

To our knowledge, there is currently no public implementation of KHAPE so we present the first ever implementation of the KHAPE protocol (Chapters 3 and 4). We also present an implementation of a practical use case using the developed KHAPE library (Chapter 5) and a performance test of the library (Chapter 6). In addition, we summarize the current state of PAKE protocol landscape with a description and comparison between four mains PAKEs; EKE, SRP, OPAQUE and KHAPE (Chapter 2).

## 1.3 Generalities

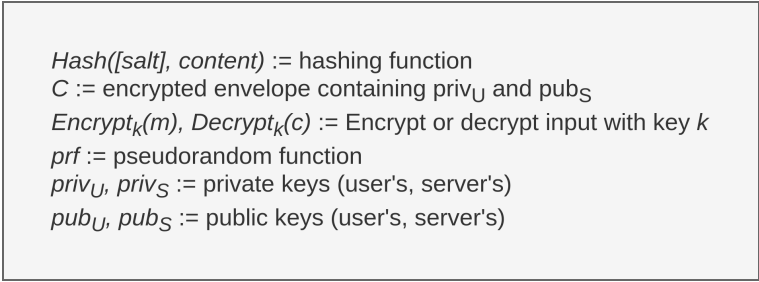
This bachelor thesis conclude a three year bachelor degree in information security at HEIG-VD. It started the 21st September 2021 and ended the 24th December 2021 with an intermediate evaluation the 26th October 2021. The expected workload is 450 hours.

## 2 | State of the art

This chapter aim to provide a detailed view of the current PAKE landscape and its main protocols.

### 2.1 Notation

Schemas will use the notation described in Fig 2.1.



*Hash*([salt], content) := hashing function  
*C* := encrypted envelope containing  $\text{priv}_U$  and  $\text{pub}_S$   
*Encrypt*<sub>*k*</sub>(*m*), *Decrypt*<sub>*k*</sub>(*c*) := Encrypt or decrypt input with key *k*  
*prf* := pseudorandom function  
*priv*<sub>*U*</sub>, *priv*<sub>*S*</sub> := private keys (user's, server's)  
*pub*<sub>*U*</sub>, *pub*<sub>*S*</sub> := public keys (user's, server's)

Figure 2.1: Schema notation.

### 2.2 Main PAKEs

This section describe in more details four fundamental PAKE construction. EKE as it is the first ever PAKE. SRP because it's the most used. OPAQUE because it is very promising, in the process of standardization and the first construction of this new generation of Strong aPAKE. OPAQUE because it is the first construction of Strong aPAKE KHAPE because it is most recent one and provide slightly better security guarantees than OPAQUE in certain conditions.

### 2.2.1 EKE

**Introduction.** EKE (for Encrypted Key Exchange) was proposed in 1992 by Bellovin and Merritt [6] and is the first PAKE protocol. It allows two parties that share a common password to exchange information over an insecure channel. It is a simple protocol that is designed to prevent offline dictionary attacks on the password. It uses a combination of asymmetric and symmetric cryptography. The asymmetric keys are ephemeral and are exchanged between the client and the server by encrypting it with the shared symmetric key — which is derived from the password. This allows securing the exchange against Man-in-the-Middle attack. It is a symmetric PAKE so it requires that both party share a secret — namely the password. This means that the server has to store and process the password in cleartext which is strongly discouraged.

Multiple cryptographic primitive can be used for the asymmetric part such as RSA, ElGamal or DH but the majority of EKE variants use DH [36]. Note that some of the EKE variants got broken.

EKE was patented until 2011 which might have severely impacted its adoption.

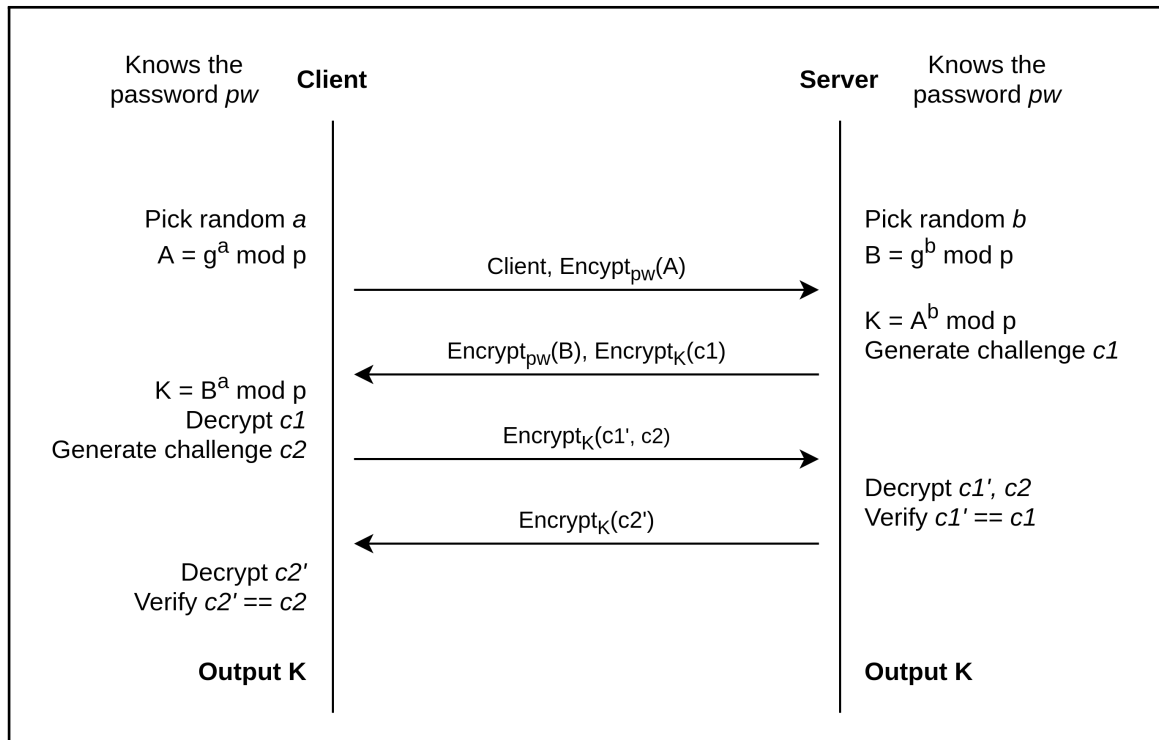


Figure 2.2: Login process with EKE (DH-EKE) protocol.

**Construction.** The figure 2.2 shows the EKE protocol — built with DH — during login process. The steps are the following :

1. Like a standard DH exchange, both client and server pick a random secret value  $a$  and  $b$ .
2. Client computes  $A$ , encrypt it using the password and send the result to the server in addition to it identifies (e.g., username).
3. Server decrypts ciphertext using the password to obtain  $A$ . He computes  $B$  and  $K$ . He encrypts  $B$  using the password and encrypt a randomly generated challenge  $c1$  using  $K$ . He sends the resulting ciphertext to the client.
4. The client decrypts  $B$  using the password and compute  $K$ . He decrypts  $c1$  with  $K$  and also generate a random challenge  $c2$ . He concatenate the two challenges, encrypt them using  $K$  and send the result to the server.
5. Server decrypt the ciphertext and check that both sent and received  $c1$  match. If it's the case, the server is assured that the client possesses the same password. The server has authenticated the client. He finishes by encrypting  $c2$  and sending the result.
6. Client decrypts the ciphertext and check that both sent and received  $c2$  match. If it's the case, the client is assured that the server possesses the same password and therefore is authenticated. The client has authenticated the server.

**Register.** The protocol doesn't mention registration. It is assumed that both parties already share a common secret, the password. A secure channel is therefore necessary to share the password in the first place.

### 2.2.2 SRP

**Introduction.** SRP [35, 34] (for Secure Remote Password) was proposed in 1998 and is the most widely-implemented PAKE protocol in the world [18]. It's largely used in iCloud Key Vault — which could make it one of the most widely-used cryptographic protocols [18] considering the number of active Apple devices worldwide — and in 1Password's password manager. It is well standardized and has numerous implementation in different programming languages. It is in fact a TLS ciphersuite [30], implemented in OpenSSL.

This success is partly due to the SRP's creators will to avoid patent — unlike most of the PAKE of its time — but also to avoid export restriction imposed by US law by not using any encryption schema [29]. Their goal was to provide a technology that improve the security of existing password protocols while keeping the ease-of-use of passwords. In other words, provide a drop-in replacement to the classical authentication methods where the implementation doesn't require a deep change in contrary to EKE where the

shared secret — the password — need to be stored in cleartext on the server making it difficult to manage correctly. This make SRP easy to implement for developers and transparent for the user.

One of the main strength of SRP is that the server doesn't store the cleartext password or the hashed password. Instead it store a password verifier that is a discrete logarithm one-way function of the password.

Even though SRP is in interesting construction and does some things right, it is not ideal. It got broken and patched multiple time — current version is SRP v6a, which is not broken.

It is vulnerable to pre-computation attack because the server send the cleartext salt to the client at the start of the exchange. With the salt, an adversary could build a table of password hashes — a time-consuming process — before compromising the server making it able to retrieve passwords instantaneously upon server compromise.

In addition, the construction is weirdly complex. The protocol mix addition and multiplication in calculation. Using both operations require a ring rather than a cyclic group. This requirement make it impossible to easily transfer the integer-based algorithm to elliptic curve.

This requirement, also make it challenging to provide a formal analysis of SRP because “existing tools provide no simple way to reason about its use of the mathematical expression  $v + g^b \bmod q$ ” [29].

**Construction.** The figure 2.3 shows the SRP-6a protocol during login process. The steps are the following :

1. Client picks a random  $a$  and compute  $A$ .
2. Client sends  $A$  and its identity  $I$  (username) to the server.
3. Server retrieves user's salt  $s$  and password verifier  $v$  from its database using the user's identity.
4.  $v$  is computed at registration and is equal to  $v = g^x$  where  $x = H(s, pw)$
5. Server also pick a random  $b$  and compute  $B$ .
6. Server sends  $s$  and  $B$  to the client.
7. Client and server both compute  $u$ ,  $S$  and  $K$  with their own values.
8. They finish with a mutual key confirmation where the client sends his proof of  $K$  first.

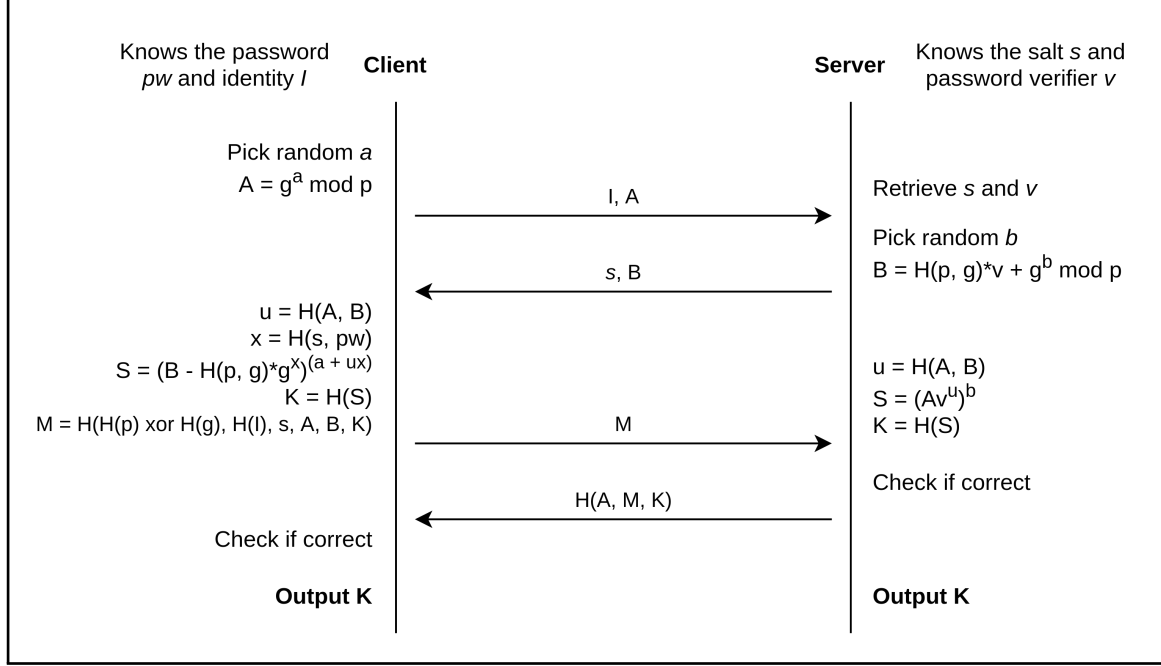


Figure 2.3: Login process with SRP-6a protocol.

9. If the server find that the user's proof is incorrect, he stop the exchange and doesn't sends its own proof of  $K$ .

If the password is correct, the client and the server end up with having the same  $S$  — and so the same key. The derivation of  $S$  is less straightforward than other constructions so it is detailed below.

$$\begin{aligned}
 S_{client} &\equiv (B - H(p, g)g^x)^{(a+ux)} \\
 &\equiv ((H(p, g)g^x + g^b) - H(p, g)g^x)^{(a+ux)} \\
 &\equiv (g^b)^{a+ux} \\
 &\equiv g^{ab+box} \\
 &\equiv (g^a(g^x)^u)^b \\
 &\equiv (Av^u)^b \\
 &\equiv S_{server} \pmod{p}
 \end{aligned}$$

**Register.** Registration process is not covered in SRP papers. Client must come with a password, and server need to generate a random salt. One of them also need to compute the verifier  $v = g^x$  where  $x = H(salt, password)$ .

This means that either the server sends the salt to the client and the client compute the verifier and send it back to the server through a secure channel (more secure as the server never see the user's password but more complicated to implement). Or the client sends its password to the server with its register request — through a secure channel — and the server generate a salt and compute the verifier (Easier to implement server-side, less transmission, but password is handled in cleartext on the server). Either way, the registration require to use a secure channel.

Upon a successful registration, the server store the following triplet :  
<username, verifier, salt>

### 2.2.3 OPAQUE

**Introduction.** Jarecki et al. [22]. introduce the definition of Strong aPAKE (SaPAKE): an aPAKE secure against pre-computation attacks.

They provide two modular constructions, called the OPAQUE protocol that allow building SaPAKE protocols. The first construction allows enhancing any aPAKE to a SaPAKE while the second allows enhancing any Authenticated Key-Exchange (AKE) protocol (that are secure against KCI attacks) to a SaPAKE. The security of these two construction is based on Oblivious PRF (OPRF) functions.

The OPAQUE protocol allows to secure authentication from the simplest applications to the most sensitive ones.

**OPRF.** OPRF [14] is a two-party protocol that allow to compute an output from two secret input. In other words, each party, namely the client and the server, input a secret value — a password for the client, a secret salt for the server — and the client can use the output as a key. What is interesting is that the client cannot learn the server's secret salt and the server cannot learn user's password or the OPRF output.

In addition to providing a Strong aPAKE protocol, OPRF provides other interesting security features that can be used with OPAQUE. Mainly, it supports the use of password hardening function, it allow an easy implementation of server threshold — instead of a single server providing its secret salt, multiple server would do it — and overall computing an OPRF provide a far more secure key than deriving directly from a password [22].

The figure 2.4 shows the OPRF process in the blue rectangle.

**Construction.** The figure 2.4 shows the OPAQUE protocol — built with OPRF and AKE — during login process. The steps are the following :



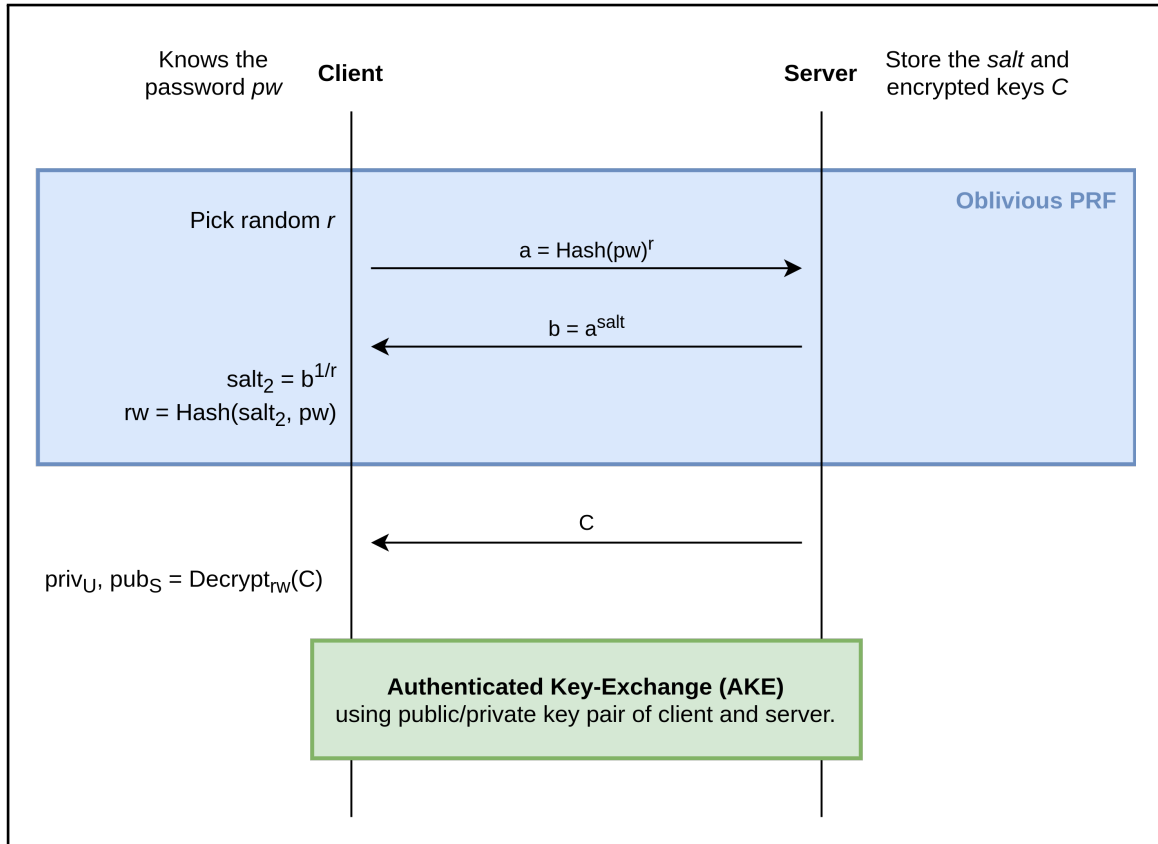


Figure 2.4: Login process with generic OPAQUE (OPRF-AKE) protocol.

1. Generate a random value  $r$  to blind the hash of passwords so that the server cannot retrieve the password from the mapping.
2. Send result to the server.
3. Server add the salt to the password.
4. The client calculates the exponent of the inverse of  $r$  to de-blind the value. He cannot retrieve salt.
5. With the secret salt  $salt_2$ , client compute secret key  $sk$ .
6. Server send encrypted keys  $C$  to clients.  $C$  contains server's public key and client's private key encrypted with  $rw$ .
7. If the password entered is correct, client uses  $rw$  to decrypt  $C$  and retrieve his private key  $priv_U$ .
8. With both keys, client and server run an authenticated key exchange for mutual authentication.

**Register.** The client registration is the only part of the protocol that requires a secure channel where both parties can authenticate each other.

The protocol is proposed with a server-side registration where the client sends his password through the secure channel. The server generates a salt and computes OPRF function with the client's password and salt. Server also generates two private keys (one for the client and one for the server) and their corresponding public key. He encrypts client's private key and server's public key with OPRF output as a key and store the ciphertext.

This method is not ideal as it requires that the user send its cleartext password to the server making it vulnerable to miss-handling or server-side vulnerabilities discussed in the introduction.

[22] also note that ideally, one wants to implement a client-side registration where the client choose a password and the server choose a secret salt and input them in the OPRF function. The client generates a public/private key pair, and the server do the same. Server sends his public key to the client. Client encrypts his private key and server's public key using OPRF output as a key. He then sends the ciphertext to the server with his public key. This way, the server never see the cleartext password, the OPRF output and the client's private key. This is a major improvement in terms of security.

However, this also comes with a downside as the server is no longer able to check password rules. This operation needs to be done client side.

**Login.** For the login phase, the client enters its password in the OPRF and the server send the ciphertext to the client. If the password entered is correct, the client can decrypt the ciphertext with OPRF output to obtain his private key and the server's public key. He then uses these keys to run an authenticated key exchange with the server.

On the other hand, if the password is wrong, the OPRF output is totally different and the ciphertext decryption makes the keys incorrect and the server will refuse it during the key exchange.

**Differences with the internet standard draft.** OPAQUE's paper [22] and OPAQUE's internet standard draft [10] have some differences. The standard draft has evolved in the last 3 years and is now at version 7 (15th iteration). The draft standard is now much more detailed than before.

One of the major difference in the core protocol design is the encryption of the client's private key.

In the paper, it is specified that the client use an authenticated encryption scheme to

encrypt and decrypt it's credentials — i.e., client's private and public keys and the server's public key. The encryption key is the OPRF output.

In the draft standard, it is rather different. Firstly the envelope does not contains the client's keys anymore. It only contains a nonce and an authentication tag. The nonce is used — with a derivation of the OPRF output — to derive an authentication key, and export key and a seed. The authentication key is used to verify the envelope's authentication tag to ensure that the envelope content has not been modified. The export key is exposed to the client for application specific usage. The seed is used to derive the client's key pair.

The envelope is not encrypted at rest anymore. It is only encrypted during transmission between the client and the server with a one-time pad encryption. The rest of the time, the envelope is stored in cleartext on the server. During registration, the client derive a masking key from the OPRF output and sends it to the server with the envelope. The server stores the envelope and the masking key. Then, at login, the server generate a masking nonce and derive a one-time pad key using masking key and masking nonce. He encrypt the envelope and his public key with the one-time pad key and sends the ciphertext with the masking nonce to the client. The client can compute the masking key with the OPRF output to compute the one-time pad key and decrypt the envelope.

Note that the standard is still in a draft state and is susceptible to be modified.

## 2.2.4 KHAPE

**Introduction.** OPAQUE security relies entirely on the strength of the OPRF. If OPRF gets broken — for example by cryptanalysis, quantum attacks or security compromise — an adversary can compute an offline dictionary attack on the user's password. This is especially critical considering that there are currently no known quantum-safe OPRFs.

KHAPE (for Key-Hiding Asymmetric Pake) [20] is a variant to the OPAQUE protocol. Instead of using OPRF as a main tool to archive security, it becomes an optional part of the protocol and KHAPE use two other concepts to archive security: non-committing encryption and key-hiding AKE.

KHAPE is not a Strong aPAKE like OPAQUE. But it can be made a SaPAKE following the aPAKE to SaPAKE compiler from [22] using OPRF.

So OPRF is optional with KHAPE and just allow making it a SaPAKE. In addition, it also allows using OPRF features such as server-side threshold implementation that doesn't require any change from the client (see all feature in section 2.2.3). If OPRF fails, KHAPE just loss these functionalities but the rest of the security remain in contrary to OPAQUE.

**Security without OPRF.** Like OPAQUE, in KHAPE each party has a private/public key pair that is used to compute the key exchange and the client store it's private key and server's public key on the server, encrypted by his password.

Without using an OPRF, an adversary could try to retrieve the ciphertext and the server's public key from a valid key exchange between an existing client and the server. He can then compute an offline dictionary attack using a list of password candidates to decrypt the ciphertext until he find a match with the server's public key that he recorded sooner. To avoid this kind of attacks, KHAPE use two mains mechanisms: Non-committing encryption and key-hiding AKE.

**Non-committing encryption.** Non-committing encryption make it impossible for an adversary to identify the key used to encrypt the ciphertext event with an list of key candidates. This implies that the decryption of the ciphertext under any possible key provide a valid plaintext (i.e. a valid asymmetrical key pair that can be used in the key exchange).

**Key-hiding AKE.** The key-hiding feature make it impossible for an adversary to use the key exchange (output) to identify the correct private/public key decrypted from the ciphertext using a list of password candidates.

Even if provided with a full transcript of a key exchange between a client and a server and a list of key pair candidates — including the correct key pair — the adversary has no better chance than random to guess the right key pair that was used.

**Construction.** Figure 2.5 shows the KHAPE protocol during login process. The steps are the following :

1. Optionally, an OPRF can be used to archive Strong aPAKE following the aPAKE to SaPAKE compiler using OPRF from [22]. The OPRF takes the client's password and server's salt as an input. Client uses the output in place of his password for the rest of the protocol.
2. The server sends the client's encrypted envelope containing the client's private key and server's public key.
3. The client decrypts the ciphertext using Ideal Cipher encryption schema. He uses his password or OPRF output as a key.
4. Both parties use the public/private keys to compute a Key-Hiding Authenticated Key-Exchange.
5. Mutual key confirmation initiated by the client.

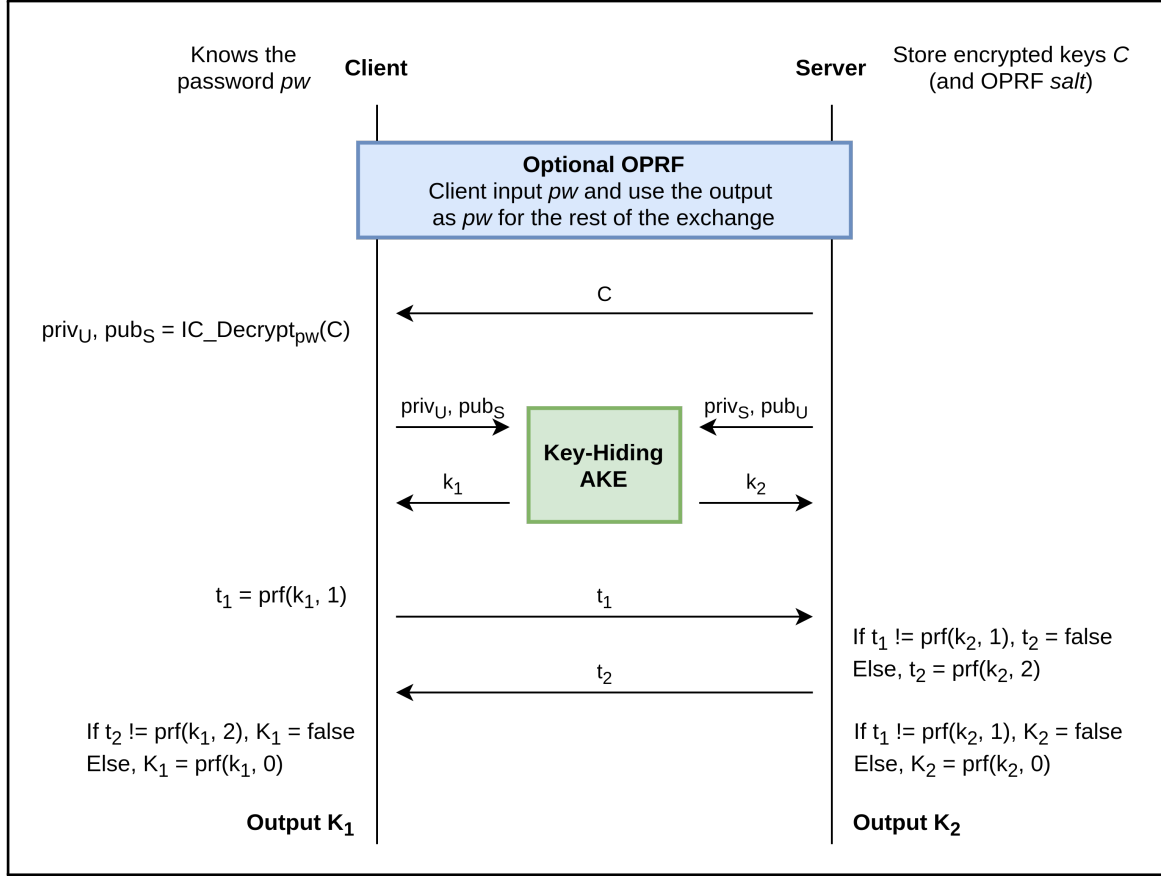


Figure 2.5: Login process with generic KHAPE protocol.

**Login.** When the client wants to login, the server sends its encrypted credentials and the client use its password to decrypt the credentials (with or without OPRF depending on the implementation). Then he can use his credentials to compute a Key-Hiding AKE with the server. Both party finish with a mutual key confirmation initiated by the client.

**Register.** KHAPE has the same problem that is addressed in 2.2.3. The protocol proposes a server-side register which is less than ideal because the server can see the client's password and client's private key in cleartext at registration.

Instead, the paper proposes a client-side registration process.

## 2.3 Comparing main solutions

This section compares the main PAKEs on their security guarantees and performances. Details and comments on each criterion can be found on Section 2.3.1.

### 2.3.1 Details

**1. Server doesn't process passwords in cleartext.** This is the main security property of asymmetric PAKE [17]. Server doesn't have to store passwords in cleartext which should make it more resilient in case of server compromise. Adversary has to compute an offline attack to retrieve passwords from the compromised server.

**2. Avoid sending cleartext password to the server.** Even though it seems similar to criteria 1, it's not. Criterion 1 is about password processing, but this criterion is about password transmission. Transmission and processing of passwords are vulnerable to different attacks vectors. The server doesn't receive passwords in cleartext which avoid any miss-handling vulnerabilities such as logging or caching cleartext passwords on the server.

COMMENT: May be required during register depending on the implementation (See Section 2.2.3).

**3. Secure against pre-computation attacks.** This is the main security property of Strong aPAKE [22]. The server doesn't leak any data that could allow an attacker to perform a pre-computation attack (for example SRP send the salt in cleartext in the first message). This attack allows an attacker to compute a table *before* the server even get compromised. Once the attacker succeeds in compromising the server, he can use the precomputed table to retrieve the passwords *instantaneously*. With this protection, an attacker can only perform an offline dictionary attack *after* successfully compromising the server. This protection is provided by the OPRF (see Section 2.2.3).

**4. Forward secrecy.** In key-exchange protocol, Forward Secrecy (also called Full Forward Secrecy or Perfect Forward Secrecy) ensures that upon compromise of any long-term key used to negotiate sessions key, an attacker cannot compromise previous session keys. In detail key-exchange protocol use long-lived keys to authenticate the user and short-lived keys to encrypt sessions. With Forward Secrecy, an attacker that successfully compromised a long-lived key cannot retrieve any previous session data even if he recorded the previous encrypted transmissions.

COMMENT: For EKE, only DH-EKE provide forward secrecy. ElGamal-EKE and RSA-EKE doesn't.

**5. Mutual authentication.** Mutual authentication explicit that users must be authenticated to the server but also that the server must authenticate itself to the user to avoid that an adversary impersonates the server to maliciously communicate with the client.

**6. PKI-free.** The transmissions between client and server doesn't require to be secured with Public Key Infrastructure (PKI). This is a big improvement over classical authentication method (password-over-TLS) considering the occurrence of PKI failures nowadays.

**7. User-side password hardening.** Users can use password hardening technique to increase the cost of an offline attack if the server gets compromised. This is done by using resource-heavy functions such as Scrypt [27] or Argon2 [9] instead of computing a simple and efficient hash. These functions allow to drastically slows down hashing process and so making offline attacks and online guessing attack much slower.

COMMENT: For EKE, it could be possible to compute a KDF function on the password before using it as a symmetrical key but this is closer to Augmented EKE [7] where the password is hashed client side and the server store the hash results.

For SRP, the client-side operation  $x = H(salt || pwd)$  can be modified to use a resource-heavy hashing function [16].

**8. Built-in mechanism to store client's secrets on the server.** Securely store client's sensible data such as secrets or credentials in the server without the server being able to read it. With OPAQUE and KHAPE, the user credentials (private/public keys) are encrypted with the password or OPRF output and then stored in the server. Additional secrets specific to the application could be added to this encrypted envelope and stored on the server.

**9. Server threshold implementation.** Require the interaction with  $n$  server to authenticate. This means that  $n$  server has to be compromised in order for an adversary to compute an offline dictionary attack on the password. This scenario can be useful in the case of an highly sensitive application. OPRF transparently provide this functionality where each server add its independent secret salt to the blinded password hash before sending it back to the client.

**10. Resistant upon Oblivious PRF compromise.** This criterion is a bit arbitrary because only the two recent PAKE use an OPRF but it is still an important criterion because it is the main difference of security guarantees between OPAQUE and KHAPE.

If OPRF breaks for example by cryptanalysis, security compromise or even quantum attacks, the consequences could be disastrous depending on the way it is used. This is especially important because there is “currently no known efficient OPRFs considered to be quantum safe” [20]. OPAQUE use OPRF as a main tool to builds Strong aPAKE. If OPRF breaks, the client’s password is vulnerable to an offline dictionary attack. KHAPE has a weaker reliance on OPRF. It is optional and only used to archive Strong aPAKE. If OPRF breaks, KHAPE only fall back to a non-strong aPAKE (making it vulnerable to pre-computation attacks). This makes KHAPE more resistant to OPRF compromise than OPAQUE.

**11. Standardization status.** The standardization status is a good indicator to the maturity and adoption of an construction.

**12. Security proof.** COMMENT: EKE only provide informal security analysis [5] SRP provide no valuable security proof [15, 19]. It only prove that it can stands up to passive attacks, which is not enough for an authentication protocol. A proof against active attacks would be welcomed for a such widely-used protocol.

**13. Easily adaptable to elliptic curves.** Elliptic curves cryptography allow to greatly reduce the size of asymmetric key. This is crucial in term of performance because keys size recommendation are always growing to ensure security and asymmetrical key are getting giant and difficult to manage — in particular for key that require long-term protection (up to 50 years). For example, for such a long-term protection, the discrete logarithm group is recommended to be 15’360 bits according to ECRYPT-CSA [3]. In comparison, with elliptic curves, only 512 bits are recommended to archive similar security level.

COMMENT: In SRP,  $\mathbb{Z}_p$  is used as a field, not a group. Therefore, SRP cannot be easily adapted to elliptic curves [15].

For DH-EKE, it is required that the content that will be encrypted — namely  $A$  and  $B$  — must be indistinguishable from random data. This requirement make it impossible to implement it on elliptic curves [12].

**14. Number of messages.** more messages means “increasing latency and load on the network”



- 15. Number of exponentiations.
- 16. Computational cost compared to a KE (see [20] presentation).
- 17. Communication size.
- 18. Server-side storage size.
- 19. Patented.
- 20. Year published.
- 21. Got broken.

### **2.3.2 Table**

For value where there is an “\*”, please refer to the appropriate comment in Section 2.3.1 for precision.

#	Criteria	EKE	SRP	OPAQUE	KHAPE
1	Server doesn't process passwords in cleartext	No	Yes	Yes	Yes
2	Avoid sending cleartext password to the server	No	Yes	Yes*	Yes*
3	Secure against pre-computation attacks	- (no hash)	No	Yes	Yes, if using OPRF
4	Forward secrecy	Yes*	Yes	Yes	Yes
5	Mutual authentication	Yes	Yes	Yes	Yes
6	PKI-free	Yes, except during register	Yes, except during register	Yes, except during register	Yes, except during register
7	User-side password hardening	No*	Yes*	Yes	Yes, if using OPRF
8	Built-in mechanism to store client's secrets on the server	No	No	Yes	Yes
9	Server threshold implementation	No	No	Yes, user-transparent	Yes, if using OPRF
10	Resistant upon Oblivious PRF compromise	- (no OPRF)	- (no OPRF)	No, entire security is compromised	Fall back to non-strong aPAKE
11	Standardization status	RFC for EAP-EKE [28]	3 RFC [33, 32, 30], 1 ISO [2], 1 IEEE [1]	Internet standard draft [10]	CRYPTO 2021 Paper [20]
12	Security proof	No*	No valuable security proof	Yes, in the random oracle model	Yes, in the ideal cipher model

#	Criteria	EKE	SRP	OPAQUE	KHAPE
13	Easily adaptable to elliptic curves	No*	No*	Yes	Yes
14	Number of messages	4 ?	4 ?	3	4 (3 if client initiate)
15	Number of exponentiations	4 ?	4 ?	3 or 4 ?	2 + 1 hash-to-curve
16	Computational cost compared to a KE (see [20] presentation)	1x	TBD	2x	1x without OPRF, 2x with OPRF
17	Communication size	TBD	TBD	TBD	TBD
18	Server-side storage size	TBD	TBD	TBD	TBD
19	Patented	Yes, expired in 2011	No	No	No
20	Year published	1992	1998	2018	2021
21	Got broken	Some versions got broken	Yes and patched [15]	No	No



## 3 | KHAPE

This chapter explain the details of the KHAPE protocol in term of implementation and explain the design choices.

### 3.1 Choice of implementing KHAPE

The choice is based on the properties of the PAKE and the existence of implementations and/or standard for this PAKE.

OPAQUE and KHAPE provide the highest level of security amongst aPAKE protocols. But while OPAQUE is becoming more mature with a draft standard and multiple high-quality implementations — including in rust ??, KHAPE is still very recent. In fact, KHAPE paper was published only 6 month ago at the time of the writing. To my knowledge, there is currently no public implementation of KHAPE and this is why I will be implementing it.

### 3.2 Generic algorithm

This sections details a generic KHAPE protocol. Algorithm 1 and 2 show the pseudocode of a login process from both client-side and server-side. Algorithm 3 and 4 show the register process.

### 3.3 Design choices

This section explain the design choices made to implement KHAPE. Since the only resource for KHAPE is the rather theoretical paper, lots of design choice have to be made. However, since OPAQUE and KHAPE share similarities, some implementation choices are inspired by the OPAQUE standard draft whenever it's possible.

### 3.3.1 Client-side register

Both client-side and server-side registration are possible but in order to use the aPAKE benefit to the fullest, it is preferable to handle the registration on the client. This allow to keep the main goal of aPAKEs: the server NEVER see the user's password. For more details, see Section 2.2.3.

### 3.3.2 Key Exchange

PAKE protocol compute a key exchange to perform authentication. The key exchange has to be authenticated to avoid attacks such as Man-in-the-Middle attacks that can be exploited on unauthenticated KE protocol like plain Diffie-Hellman.

In AKE protocols, each party has two asymmetric keys pair. One long-term key pair that authenticate the exchange and one short-term (ephemeral) key pair that is used in the actual key exchange and only live for a single session.

KHAPE require that the underlying key exchange protocol is a “key-hiding AKE” (See Section 2.2.4 for more details about this construction). [20] shows that HMQR, 3DH and SKEME are key-hiding AKE.

SKEME is a AKE based on key encryption mechanism where HMQR and 3DH are Diffie-Hellman based AKE. [22] and [20] shows concrete instantiation of their protocol using HMQR. These instantiations are easily adapted to other Diffie-Hellman based AKE like 3DH.

Algorithm 5 and 6 show both key computation for HMQR and 3DH protocol. We can see that the 3DH protocol require to compute more exponentiation. In fact, between the two protocols, HMQR is more efficient but it is patented so 3DH is used for the KHAPE implementation.

### 3.3.3 Encryption scheme

KHAPE require that the encryption scheme is non-committing (See Section 2.2.4).

Non-committing encryption is archived by combining ideal cipher and curve encoding.

**Ideal cipher.** As its name may suggest, the ideal cipher model is an idealised model used to prove the security of cryptographical systems.

In practice, an ideal cipher is not implementable but it's possible to construct an encryption scheme that is indifferentiable from an ideal cipher. Multiple constructions have been investigated in the literature. The simplest construction is the one detailed

in [21] which is an update from [13] that got broken. The encryption scheme consist of 14 rounds of Feistel where function  $F_i = H(key|i|input)$ .

The hashing function must be large enough to receive half of the encryption envelope. Since this envelope store two group element, the hashing function must output 256 bits which is the size of a single group element.

In term of performance, this construction is not very efficient but its one of the only found that is easily instantiatiable.

**Curve encoding.** The cleartext group elements that will be encrypted need to be encoded as a bitstring that is indistinguishable from random. This has the consequence that if plaintext is encrypted with password  $pw$  and then decrypted with a different password  $pw'$ , the result is a random valid element.

This is done by implementing a quasi bijection from field elements to bitstrings. Elligator-squared [31] and Elligator2 [8] are implementation for such curve point encoding. Both these constructions are suitable for the implementation of KHAPE but since the elliptic curve used is Curve25519, it is suitable for Elligator2.

**Authentication.** Authenticated encryption is generally recommended for encryption. It is interesting to note that this encryption scheme must not be authenticated.

In contrary to the OPAQUE Paper, the OPAQUE standard draft doesn't encrypt the client's private key in the envelope. Instead, the envelope store a nonce of 32 bytes and an authentication tag. The envelope is not encrypted. The nonce is used — with the randomized password — to compute a seed, which is then used to derive the client's private and public keys. The authentication tag stored in the envelope is used to verify the derived public key.

### 3.3.4 Group $\mathbb{G}$

The key exchange is computed on a group  $\mathbb{G}$  of prime order  $p$  with generator  $g$ . The group is generic which means that we are free to use an integer group or an elliptic curves group.

For performances reasons, elliptic curves are used for the implementation (See Section 2.3.1). The curve must be compatible with the curve encoding algorithm selected (Elligator-squared, Elligator2, etc.).

For current usage, it is recommended to use 256 bits elliptic curve [3]. For a more long-term usage (up to 50 years), it is recommended to use 512 bits elliptic curve.

For KHAPE implementation, curve25519 is used. It is a safe elliptic curve that provide

the sufficient security level and is well suited for implementing Elligator2 on it. Group element are represented on 32 bytes.

### 3.3.5 OPRF

In KHAPE, the OPRF is optional — in contrary to OPAQUE — but allow to make it a strong aPAKE resistant against pre-computation attacks 2.3.1. This is a major improvement in term of security and therefore an OPRF should be used.

OPRF operations also need their own group and hashing function. There is also an ongoing standard draft protocol for OPRF [14] that present multiple ciphersuites for OPRF and different variants. The OPRF used for the KHAPE implementation is based on this standard draft using the ristretto255-SHA-512 ciphersuite and the standard non-verifiable variant.

### 3.3.6 Slow Hash

It is possible and recommended to use a memory-hard hashing function on the password to make it slow and expensive to compute. This make it more costly for an adversary to compute hashes.

For the implementation, Argon2id [9] is used because it is a recent memory-hard hashing function with a simple construction and it has better security analysis than others resource-heavy hashing function like scrypt, bcrypt and PBKDF2 [15]. The Argon2id variant is used as it provide resistance against both GPU attacks and side-channel attacks — and is the recommended version.

For OPAQUE, [10] propose to implement this function on the OPRF output  $rw$  and use the result to derive the encryption key. Section 3.3.7.1 shows how this hashing function is used in the key derivation process.

### 3.3.7 Key derivation

This section describe the process of derivating keys from existing secrets. The design is heavily inspired by OPAQUE's standard draft [10] since the context is similar.

The primitive used to derive the encryption key, the export key, the output key and the key verification tags is HKDF [24]. It is well suited for expanding key from existing secret and is already used in OPAQUE rust's implementation [25]. It follows the “Extract-then-Expand” paradigm where these two functions are used with the following API :



- $\text{Extract}(\text{salt}, \text{ikm})$ : Extract a fixed length pseudorandom key  $\text{prk}$  with high entropy from the input keying material  $\text{ikm}$  and the optional  $\text{salt}$
- $\text{Expand}(\text{prk}, \text{info}, L)$ : Expand the length of an existing pseudorandom key  $\text{prk}$  with the optional string  $\text{info}$  to produce an output keying material  $\text{okm}$  of  $L$  bytes.

HKDF is based on HMAC which in turn is based on an hashing function. The underlying hashing function used should output at least 256 bits to fit the group element size. SHA-3 256 is used for its robust design.

### 3.3.7.1 Encryption key and export key

OPRF output — or password — is used to derive multiple keys with HKDF. The encryption key and the authentication key for computing authenticated encryption on the credential envelope. And the export key which is exposed at register and login and can be used by the application to encrypt application specific data. In Chapter 5, it is shown how to use this key to encrypt user's passwords for an online password manager. Algorithm 7 shows how these keys are derived.

### 3.3.7.2 Output key and key verification

HKDF is also used to compute the output key  $K$  and both key verification tag  $t_1$  and  $t_2$ . Instead of exposing the handshake secret  $k$  and computing each verification tag and the output key individually, these 3 values are computed at the same time and stored until needed. Algorithm 8 shows how these keys are derived.

## 3.4 Limitations

In opposition with classical authentication method where the client only send an authentication request and receive a response. With KHAPE, the registration and the authentication processes require multiple messages (round-trip) between the client and the server. This add new difficulties for both side that need to be considered.

### 3.4.1 Client

Necessity to send 2 messages. If the client is a web browser, he cannot only send a login form to the server. Behind the scenes request has to be made to compute the 2 round-trip. This means that some javascript has to be implemented but this was

known from the beginning that PAKE protocol require a greater implication of the client (code-wise).

### 3.4.2 Server

Pre register secret, ephemeral key, session The server communicate with multiple client at the same time so when a request come, he needs to know from which client/session it is from to be able to use the correct value. This is even more complicated because during both authentication and registration, the server generate some secret value in the first round trip and needs these values in the second round trip.

During authentication, the server needs to store his ephemeral private key for the second round-trip. He can store this value in the user's file entry or in a separated session file.

He can : - Store this value in the file entry associated to the user - Store this value in a session file entry (this require that client generate a session id and sends it with every request) (can be used to store session key later) - Encrypt the value and send it to the client which send it back (like JWT) In every case, the client has to resend the uid in the 2nd round-trip request

The second solution will be used. Allow multiple session

During register, the server generate his keys (private and public) and the secret salt. He sends the public key but the private key and the secret salt has to remain secret.

He can : - Pre register the client in a incomplete file entry. - `file[uid] = <secret_salt, b, INCOMPLET>` - `file[uid] = <e, b, A, secret_salt, COMPLET>` - Solution 2 and 3 from auth

The first solution will be used

---

**Algorithm 1** KHAPE : Authentication on the client (generic algorithm)

---

**Require:** Knows username `uid` and password `pw`

```

if OPRF then
     $r \leftarrow \text{GenerateRandomNumber in } \mathbb{Z}_p$ 
     $h_1 \leftarrow \text{HashToGroup}(pw)^r$ 
    Sends authentication request to the server with uid and  $h_1$ 
else
    Sends authentication request to the server with uid
end if
 $x \leftarrow \text{GenerateRandomNumber in } \mathbb{Z}_p$ 
 $X \leftarrow g^x$ 
if OPRF then
    Wait to receive  $e$ ,  $Y$  and  $h_2$  from the server
     $\text{salt}_2 \leftarrow h_2^{\frac{1}{r}}$ 
     $rw \leftarrow \text{Hash}(\text{salt}_2, pw)$ 
     $(a, B) \leftarrow \text{Decrypt}(rw, e)$ 
else
    Wait to receive  $e$  and  $Y$  from the server
     $(a, B) \leftarrow \text{Decrypt}(pw, e)$ 
end if
 $o_c \leftarrow \text{KeyHidingAKE}(X, Y, B, x, a)$ 
 $k_1 \leftarrow \text{Hash}(\text{sid}, C, S, X, Y, o_c)$ 
 $t_1 \leftarrow \text{PRF}(k_1, 1)$ 
    Sends  $t_1$  and  $X$  to the server
    Wait to receive  $t_2$  from the server
if  $t_2 \neq \text{PRF}(k_1, 2)$  then
     $K_1 \leftarrow \text{False}$ 
else
     $K_1 \leftarrow \text{PRF}(k_1, 0)$ 
end if
output  $K_1$ 

```

---

---

**Algorithm 2** KHAPE : Authentication on the server (generic algorithm)

---

**Require:** Store password file *file* containing  $\langle e, b, A[, salt] \rangle$ **if** OPRF **then**    Wait to receive authentication request from the client with uid and  $h_1$ **else**

Wait to receive authentication request from the client with uid

**end if** $y \leftarrow \text{GenerateRandomNumber in } \mathbb{Z}_p$  $Y \leftarrow g^y$ **if** OPRF **then**     $(e, b, A, salt) \leftarrow \text{file}[\text{uid}, S]$      $h_2 \leftarrow h_1^{salt}$     Sends  $e, Y$  and  $h_2$  to the client**else**     $(e, b, A) \leftarrow \text{file}[\text{uid}, S]$     Sends  $e$  and  $Y$  to the client**end if**Wait to receive  $t_1$  and  $X$  from the client $o_s \leftarrow \text{KeyHidingAKE}(X, Y, A, y, b)$  $k_2 \leftarrow \text{Hash}(\text{sid}, C, S, X, Y, o_s)$ **if**  $t_1 \neq \text{PRF}(k_2, 1)$  **then**     $t_2 \leftarrow \text{False}$ **else**     $t_2 \leftarrow \text{PRF}(k_2, 2)$ **end if**Sends  $t_2$  to the client**if**  $t_1 \neq \text{PRF}(k_2, 1)$  **then**     $K_2 \leftarrow \text{False}$ **else**     $K_2 \leftarrow \text{PRF}(k_2, 0)$ **end if**output  $K_2$ 

---

---

**Algorithm 3** KHAPE : Registration on the client (generic algorithm)

---

**Require:** Choose username  $uid$  and password  $pw$

**if** OPRF **then**

$r \leftarrow \text{GenerateRandomNumber in } \mathbb{Z}_p$

$h_1 \leftarrow \text{HashToGroup}(pw)^r$

Sends registration request to the server with  $uid$  and  $h_1$

**else**

Sends registration request to the server with  $uid$

**end if**

$a \leftarrow \text{GenerateRandomNumber in } \mathbb{Z}_p$

$A \leftarrow g^a$

**if** OPRF **then**

Wait to receive  $B$  and  $h_2$  from the server

$salt_2 \leftarrow h_2^{\frac{1}{r}}$

$rw \leftarrow \text{Hash}(salt_2, pw)$

$e \leftarrow \text{Encrypt}(rw, (a, B))$

**else**

Wait to receive  $B$  from the server

$e \leftarrow \text{Encrypt}(pw, (a, B))$

**end if**

Sends  $e$  and  $A$  to the server

---

---

**Algorithm 4** KHAPE : Registration on the server (generic algorithm)

---

**Require:****if** OPRF **then**    Waits to receive registration request from a client with uid and  $h_1$ **else**

Waits to receive registration request from a client with uid

**end if** $b \leftarrow \text{GenerateRandomNumber in } \mathbb{Z}_p$  $B \leftarrow g^b$ **if** OPRF **then**     $salt \leftarrow \text{GenerateRandomNumber in } \mathbb{Z}_p$      $h_2 \leftarrow h_1^{salt}$     Sends  $B$  and  $h_2$  to the client**else**    Sends  $B$  to the client**end if**Waits to receive  $e$  and  $A$  from the client**if** OPRF **then**    Store file[uid, S]  $\leftarrow (e, b, A, salt)$ **else**    Store file[uid, S]  $\leftarrow (e, b, A)$ **end if**

---

---

**Algorithm 5** HMQV protocol key computation for the client

---

**Require:** C := Client identity, S := Server identity $d_c \leftarrow \text{Hash}'(\text{sid}, C, S, 1, X)$  $e_c \leftarrow \text{Hash}'(\text{sid}, C, S, 2, Y)$  $o_c \leftarrow (Y \cdot B^{e_c})^{x+d_c \cdot a}$  $k \leftarrow H(\text{sid}, C, S, X, Y, o_c)$ 

---

---

**Algorithm 6** 3DH protocol key computation for the client

---

**Require:** C := Client identity, S := Server identity $o_c \leftarrow B^x || Y^a || Y^x$  $k \leftarrow H(\text{sid}, C, S, X, Y, o_c)$ 

---

---

**Algorithm 7** KHAPE's encryption key and export key computation

---

**Require:**  $rw$  := OPRF output

$rw_{hardened} \leftarrow \text{SlowHash}(rw)$   
 $rw_{randomized} \leftarrow \text{Extract}(\text{salt}="", \text{ikm}=\text{concat}(rw, rw_{hardened}))$   
 $k_{\text{encryption}} \leftarrow \text{Expand}(rw_{randomized}, \text{"EncryptionKey"}, \text{HashLength})$   
 $k_{\text{auth}} \leftarrow \text{Expand}(rw_{randomized}, \text{"AuthKey"}, \text{HashLength})$   
 $k_{\text{export}} \leftarrow \text{Expand}(rw_{randomized}, \text{"ExportKey"}, \text{HashLength})$   
 Output  $k_{\text{encryption}}$ ,  $k_{\text{auth}}$  and  $k_{\text{export}}$

---



---

**Algorithm 8** KHAPE's output key and key verification computation

---

**Require:**  $o$  := AKE output,  $preamble$  := protocol's identities and messages

$prk \leftarrow \text{Extract}(\text{salt}="", \text{ikm}=o)$   
 $k \leftarrow \text{Expand}(prk, \text{concat}(\text{"HandshakeSecret"}, \text{Hash}(preamble)), \text{HashLength})$   
 $K \leftarrow \text{Expand}(prk, \text{concat}(\text{"SessionKey"}, \text{Hash}(preamble)), \text{HashLength})$   
 $t_1 \leftarrow \text{Expand}(k, \text{"ClientMAC"}, \text{HashLength})$   
 $t_2 \leftarrow \text{Expand}(k, \text{"ServerMAC"}, \text{HashLength})$   
 Output  $K$ ,  $t_1$  and  $t_2$

---





## 4 | Implementation

### 4.1 Parameters

Both client and server has to define their parameters. For a client and a server to authenticate, they need to have the same parameters. Generally parameters are fixed by the application developer and are the same for every clients of the application. They can also be negotiated during registration but this require the server to store each client specific parameters as it can be different. This use case is not in the scope of the KHAPE library.

**OPRF** Strongly encouraged, improve security by a lot, doesn't take much time/resource.

**Slow Hash** Encouraged, improve security, take lot of time and resources

Overall, it is strongly discouraged to use neither of them because this mean that the credentials envelope is encrypted by a weak key resulting only of an HKDF of the low-entropy password.

### 4.2 Exchanges

#### 4.2.1 Register

```
(register_request, oprf_client_state) = client.register_start(password);
-----register_request----->
(register_response, pre_register_secrets)
    = server.register_start(register_request);
<-----register_request-----
register_finish
    = client.register_finish(register_response, oprf_client_state);
-----register_finish----->
```

```
file_entry = server.register_finish(register_finish, pre_register_secrets)

                                store file_entry
```

## 4.2.2 Login

```
(auth_request, oprf_client_state) = client.auth_start(password)
-----auth_request----->
(auth_response, server_ephemeral_keys)
    = server.auth_start(auth_request, &file_entry)
<-----auth_response-----
(auth_verify_request, ke_output)
    = client.auth_ke(auth_response, oprf_client_state)
-----auth_verify_request----->
(auth_verify_response, server_output_key)
    = server.auth_finish(auth_verify_request, server_ephemeral_keys,
                        &file_entry)
<-----auth_verify_response-----
client_output_key = client.auth_finish(auth_verify_response, ke_output)
```

## 4.3 Function definition

### 4.3.1 Client

- `register_start(Password) -> (RegisterRequest, ClientState)`
  1. Compute OPRF initialization (optional)
  2. Build `RegisterRequest` with uid and OPRF blinded result
  3. Build `ClientState` with OPRF state
- `register_finish(RegisterResponse, ClientState) -> (RegisterFinish, ExportKey)`
  1. Generate asymmetric key pair
  2. Compute OPRF output (optional)
  3. Compute slow hash (optional)
  4. Derive encryption key and export key
  5. Encrypt envelope containing private key and server's public key
  6. Build `RegisterFinish` with envelope ciphertext and own public key

- `auth_start(Password) -> (AuthRequest, ClientState)`
  1. Compute OPRF initialization (optional)
  2. Build `RegisterRequest` with uid and OPRF blinded result
  3. Build `ClientState` with OPRF state
- `auth_ke(AuthResponse, ClientState) -> (AuthVerifyRequest, KeyExchangeOutput, ExportKey)`
  1. Generate ephemeral asymmetric key pair
  2. Compute OPRF output (optional)
  3. Compute slow hash (optional)
  4. Derive encryption key and export key
  5. Decrypt envelope containing private key and server's public key
  6. Compute key exchange output
  7. Build `AuthVerifyRequest` with uid, verify tag and ephemeral public key
- `auth_finish(AuthVerifyResponse, KeyExchangeOutput) -> Option<OutputKey>`
  1. Verify server's verification tag
  2. Return output key

### 4.3.2 Server

- `register_start(RegisterRequest) -> (RegisterResponse, PreRegisterSecrets)`
  1. Generate asymmetric key pair
  2. Generate OPRF secret salt (optional)
  3. Compute OPRF evaluation with secret salt (optional)
  4. Build `RegisterResponse` with public key and OPRF evaluation
  5. Build `PreRegisterSecret` with private key and OPRF secret salt
- `register_finish(RegisterFinish, PreRegisterSecrets) -> FileEntry`
  1. Build storable `FileEntry` structure with encrypted envelope, server's private key, client's public key and OPRF secret salt
- `auth_start(AuthRequest, FileEntry) -> (AuthResponse, EphemeralKeys)`

1. Generate ephemeral asymmetric key pair
  2. Retrieve encrypted envelope and OPRF secret salt from file entry
  3. Compute OPRF evaluation with secret salt (optional)
  4. Build `AuthResponse` with encrypted envelope, ephemeral public key and OPRF evaluation
  5. Build `EphemeralKeys` with ephemeral key pair
- `auth_finish(AuthVerifyRequest, EphemeralKeys, FileEntry)`  
-> `(AuthVerifyResponse, Option<OutputKey>)`
    1. Retrieve server's private key and client's public key from file entry
    2. Compute key exchange output
    3. Verify client's verification tag
    4. Build `AuthVerifyResponse` with own verification tag
    5. Return output key

## 4.4 Messages structures

```
pub struct RegisterRequest {
    pub uid: String,
    pub(crate) oprf_client_blind_result: Option<Vec<u8>>,
}

pub struct RegisterResponse {
    pub(crate) pub_b: PublicKey,
    pub(crate) oprf_server_evaluate_result: Option<Vec<u8>>,
}

pub struct RegisterFinish {
    pub uid: String,
    pub(crate) encrypted_envelope: EncryptedEnvelope,
    pub(crate) pub_a: PublicKey
}

pub struct AuthRequest {
    pub uid: String,
    // pub sid: String, // TODO sid
    pub(crate) oprf_client_blind_result: Option<Vec<u8>>,
}
```

```
}
```

```
pub struct AuthResponse {
    pub(crate) encrypted_envelope: EncryptedEnvelope,
    pub(crate) pub_y: PublicKey,
    pub(crate) oprf_server_evaluate_result: Option<Vec<u8>>,
}
```

```
pub struct AuthVerifyRequest {
    pub uid: String,
    // pub sid: String, // TODO sid
    pub(crate) client_verify_tag: VerifyTag,
    pub(crate) pub_x: PublicKey,
}
```

```
pub struct AuthVerifyResponse {
    pub(crate) server_verify_tag: Option<VerifyTag>,
}
```

## 4.5 Library choices

- `curve25519-dalek v3.2.0` : Pure rust implementation of group operations on Ristretto and Curve25519. Audited in 2019 [?]. Patched with PR [?] to implement `elligator_decode`
- `voprf v0.3` : Implementation of a verifiable OPRF based on the standard draft [14].
- `sha3 v0.9` : Pure rust implementation of the SHA-3 (Keccak) hash function
- `hkdf v0.11` : Pure rust implementation of the HMAC-based Extract-and-Expand Key Derivation Function (HKDF) generic over hash function
- `argon2 v0.3` : Pure rust implementation of the Argon2 password hashing function
- `rand v0.8` : Random number generators
- `serde v1` : Framework for serializing and deserializing Rust data structures efficiently and generically

- `serde-big-array v0.3` : Big array helper for `serde`

```
[patch.crates-io]
curve25519-dalek = { path = "../07-curve25519-dalek-fork" }

[dependencies]
curve25519-dalek = { version = "3.2.0", features = ["serde"] }
voprf = "0.3.0"
rand = "0.8.4"
serde = { version = "1.0", features = ["derive"] }
serde_json = "1.0"
#bincode = "1.3.3"

sha3 = "0.9.1"
hkdf = "0.11"
argon2 = "0.3.1"
serde-big-array = { version = "0.3.2", features = ["const-generics"] } # for ciphert
```

.

## 4.6 API

### 4.6.1 Client

### 4.6.2 Server

### 4.6.3 Messages

### 4.6.4 Common

- `generate_asymmetric_key`

### 4.6.5 Client register

- `client_register_start(uid, pw): RegisterRequest`
- *Sends uid and h1. Receive B and h2*
- `client_register_finish(B, pw, h2) : e`
- *Sends e and A*

### 4.6.6 Server register

- *Receive uid and h1*
- `server_register_start(uid, h1): (b, B, salt, h2)`
- *Response B and h2*
- *Receive e and A*
- `server_register_finish(e, A, b, salt): file_entry`

### 4.6.7 Client login

- `client_auth_start(uid, pw): RegisterRequest`
- *Sends uid and h1. Receive e, Y and h2*
- `client_auth_ke(e, Y, h2, r, pw) : (k1, t1, X)`



- *Sends  $t1$  and  $X$ . Receive  $t2$*
- `client_auth_finish(t2, k1) : K1`

#### 4.6.8 Server login

- *Receive  $uid$  and  $h1$*
- `server_auth_start(uid, h1, file): (e, Y, h2)`
- *Response  $e$ ,  $Y$  and  $h2$*
- *Receive  $t1$  and  $X$*
- `server_auth_finish(X, Y, A, y, b, t1, file): (K2, t2)`
- *Response  $t2$*

#### 4.6.9 Structure

Ciphersuite file

### 4.7 Dependencies/Libraries choices

- OPRF : <https://crates.io/crates/voprf>
- Curve : <https://crates.io/crates/curve25519-dalek> (Support Elligator2)

### 4.8 Code structure

### 4.9 Interesting functions

#### 4.9.1 Discharge password from RAM directly after use

#### 4.9.2 (Timing attack mitigation)



## 5 | Use case

This chapter shows a practical use case of using the newly implemented KHAPE library and demonstrate the security benefits.

### 5.1 Context

This section details use cases where using an aPAKE provide advantages over a classical authentication method.

#### 5.1.1 Online password manager

Online password managers are among the most sensitive applications out there because the leakage of users' data cascades into numerous compromised accounts on other services such as email accounts, social media, online banking. Using an asymmetric PAKE for an online password manager makes a lot of sense because the client does not have to disclose its master password to the password manager host. In other words, the client does not have to trust the password manager host not to decrypt its personal data or leak the master password (or any other intentional or unintentional miss-handling). In fact, multiple well-known online password manager such as iCloud Key Vault or 1Password uses an aPAKE (SRP).

#### 5.1.2 Other use cases

More generally, using an aPAKE makes a lot of sense on applications where the server-side stored user data should not be visible to the server. This is the case for applications where the server does not process the user's data. For example, online backup, secure vault, password managers, etc. This is achieved with encryption and so require an encryption key for the client. Depending on the client, it is not feasible to store an additional symmetric key because it has to be securely stored — e.g., with an HSM — which cause problems of portability and key recovery. For example, for an

online encrypted backup of a laptop or a smartphone, if the user loses its device, he cannot retrieve his online backup because the encryption key is stored on its lost device. For portability, the encryption key is typically derived from the user's password — the same password that he uses to authenticate with the server (you could require that the user input two different passwords but this is generally avoided because of bad user experience). Using a classical authentication method, the server store the user's encrypted sensitive data and also process the password in cleartext which is used to compute the encryption key. This void all the security of encrypting the sensitive data in the first place because the server — or a malicious party who compromised the server — could store the cleartext password, compute the encryption key and decrypt the sensitive user's data. This is the reason why aPAKEs are very interesting in this case scenario. The server **never** see the user's password, so he cannot use it to decrypt user's data.

## 5.2 Design

This section describes the design of the use case: a multi-user online password manager. The basic concept is that the server stores the encrypted user's data. Each client can only access his personal encrypted data from the server.

KHAPE is used for authentication between the client and the server. OPRF and SlowHash parameters are enabled to provide the highest level of security.

### 5.2.1 Encrypted user data

Each user stores his encrypted user data on the server. This data include an Encrypted password registry and an Encrypted master key. Every encryption is computed by the authenticated encryption scheme XChaCha20-Poly1305.

The Encrypted password registry is a structure that contains the user's password. Passwords are double encrypted. The external structure — the password registry — is encrypted and then each individual password is also encrypted. Each encryption is performed with a different key, all derived from the master key.

The Encrypted master key is simply a key — the Master key — that is encrypted with another key — the KHAPE's export key. One could derive the Master key from the KHAPE's export key but this means that if the user wants to change his authentication password, it is necessary to decrypt and re-encrypt every single password entry and the password registry with the new export key. This is not conceivable for a scalable password manager. Instead, in case of change in the authentication password, only the Master key is re-encrypted with the new export key. This idea is inspired from

Bitwarden's online password manager design [4].

### 5.2.2 General process

The figure 5.1 shows the entire process of reading a protected password from the authentication request to the password decryption.

1. The user input his password in the client and the KHAPE authentication start (see section 3.2 for details on the process).
2. KHAPE authentication output a session key and an export key to the client. The session key is verified with the server. If the inputted password is invalid, no session key is outputted. An export key would still be outputted since it is not verifiable.
3. Client request to download its encrypted data from the server using the session key as an authentication token. The server also stores the session key and can verify that the client has been successfully authenticated. An authentication token expires after 24 hours.
4. If the authentication token is valid, the client receives his Encrypted master key and his Encrypted password registry.
5. He decrypts the Encrypted master key with the KHAPE's export key to obtain his private key
6. He computes two HKDF Expand with the Master key as an input and constant labels to obtain an External encryption key and an Internal encryption key
7. He decrypts the Encrypted password registry with the External encryption key to obtain the Indexable password registry
8. Now that the client has decrypted the external layer of the password registry, he remove the following value from memory: Export key, Master key, Encrypted master keys and Encrypted password registry. He still has to keep the Session key to communicate with the server and the external encryption key to re-encrypt the password registry upon modification.
9. In the Indexable password registry each entry's label and username are in cleartext but the password is still unreadable.
10. When the user chooses to read a password entry, the client uses Internal encryption keys to compute an HKDF Expand with the entry's label and username as context. The result is a key that is unique for this password.

11. The client finish by decrypting the encrypted password with the computed key. He obtains the readable password.
12. After sending the cleartext password to the user, the client remove the cleartext password and the Individual password key from memory. This means that in IDLE the client only keeps Session key, External encryption keys, Internal encryption keys and Indexable password registry in memory.

When the client adds, update or remove a password, he needs to update his Encrypted password registry and upload it to the server. This is done by computing an Individual password key from the Internal encryption key and the password entry's label and encrypting the password with this key. Then the password entry is added or updated in the password registry which is then encrypted with the External encryption key. The resulting ciphertext is sent to the server.

### 5.2.3 Server endpoints

The server has only four endpoints:

- Registration (KHAPE)
- Authentication (KHAPE)
- File download
- File upload

Registration and authentication are handled by KHAPE's protocol (see Section 3.2). Upon successful authentication, the client can use the outputted session key as an authentication token. He sends his session token with every request to prove to the server that he is authenticated. The session token expires after 24 hours.

File download and file upload allow the user to retrieve and commit his protected data from the server. The interactions between the client and the server are defined in the figure 5.2 for the file download endpoint and in the figure 5.3 for the file upload endpoint.

### 5.2.4 Client actions

The end user interacts with the client to access its passwords. At client start, the user can either register or login. After a successful registration, he still needs to login.

Upon successful authentication, the client automatically download the user's data file and the user can select one of the following actions :

- Read a password
- Add a new password
- Modify a password
- Delete a password

For actions where the password registry is modified (adding, modifying or deleting a password), the password registry is re-encrypted by the client (with the External encryption key) and uploaded to the server.

The interactions between the user and the client are defined in the figure 5.4 for reading a password entry, in the figure 5.5 for adding a new password entry, in the figure 5.6 for adding a modifying an existing password entry and in the figure 5.7 for deleting a password entry.

### 5.2.5 Advantages of KHAPE

Using KHAPE for the authentication has two main advantages. Firstly, and most importantly, it allows to authenticate the client to the server with a password without the password being ever visible to the server. As specified in the context section ??, it is especially important for an application where the sensitive data is encrypted with a key that is also derived from the password.

Secondly, the utilization of the export key for the password registry decryption, make it more secure and more efficient. More secure because computing an OPRF is more secure than just deriving a key in local since it forces the client to interact with the server. Only the server knows the secret salt used to compute the OPRF output. This mean that an attacker would be forced to compute online password guesses making it easier to mitigate by the server.

More efficient because KHAPE already compute an OPRF and a SlowHash for the authentication and derive multiple keys from the output — including the export key. If the export key was not provided to the application, the client would be forced to compute another SlowHash function on the password to derive a master key. This would drastically impact the performances of the application.

### 5.2.6 Security considerations

It is important to consider that even though each password is double encrypted, it is still possible to an attacker to retrieve all passwords. Since both the Indexable password registry and the Internal encryption key are kept in memory at rest, an

attacker could dump the client's memory and derive every Individual password key to decrypt all passwords. Mitigation to this would be to add a secret value to the Individual password key derivation. This secret value would be stored outside of the memory in a secure location such as an HSM or a YubiKey. This way, even if an attacker can dump the client's memory, he cannot derive any Individual password key and so he cannot retrieve any cleartext password.

## 5.3 Implementation

The online password manager has been developed <sup>1</sup> in Rust. It is a functional proof of concept that demonstrates the usefulness of KHAPE for such applications. The implementation is based on an existing online password manager project that was developed earlier this year by Gil Balsiger and me.

Currently, the client is a CLI (command line interface). It is planned to be adapted. The server uses an SQLite database to store user information. Each user's encrypted data structure is stored on the server in a separated file. The network between the client and the server is simulated meaning that the client simply call server's function instead of sending an actual TCP or HTTP request.

In the future, it is planned to adapt this prototype to be usable in practice. This will be done by implementing the network part. The client will also be adapted to compile the rust code in WebAssembly. The final goal is to build a client for web browsers.

---

<sup>1</sup>Implementation can be found here : <https://github.com/jul0105/OnlinePasswordManager>



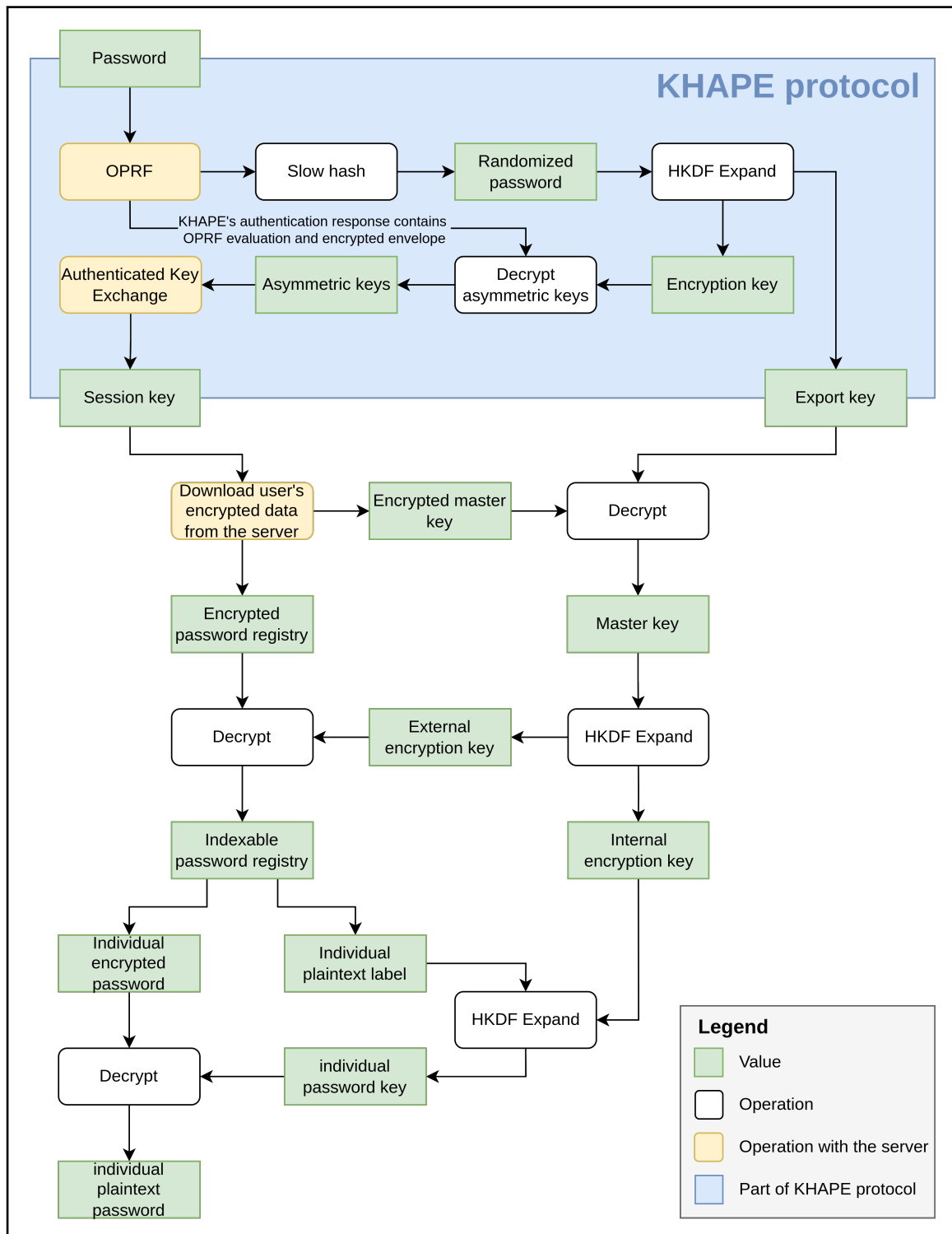


Figure 5.1: Online password manager key derivation process to read a password.

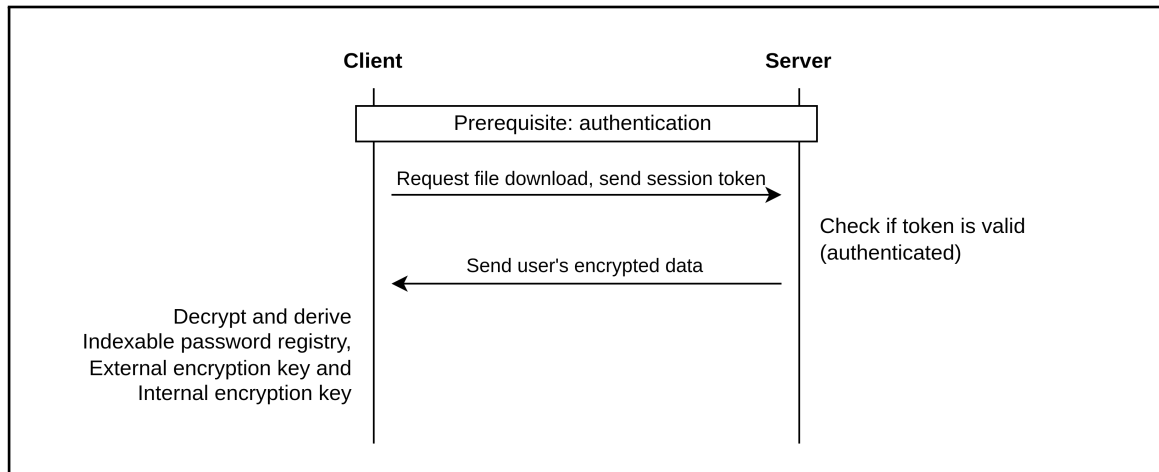


Figure 5.2: Interaction between the client and the server for the file download endpoint.

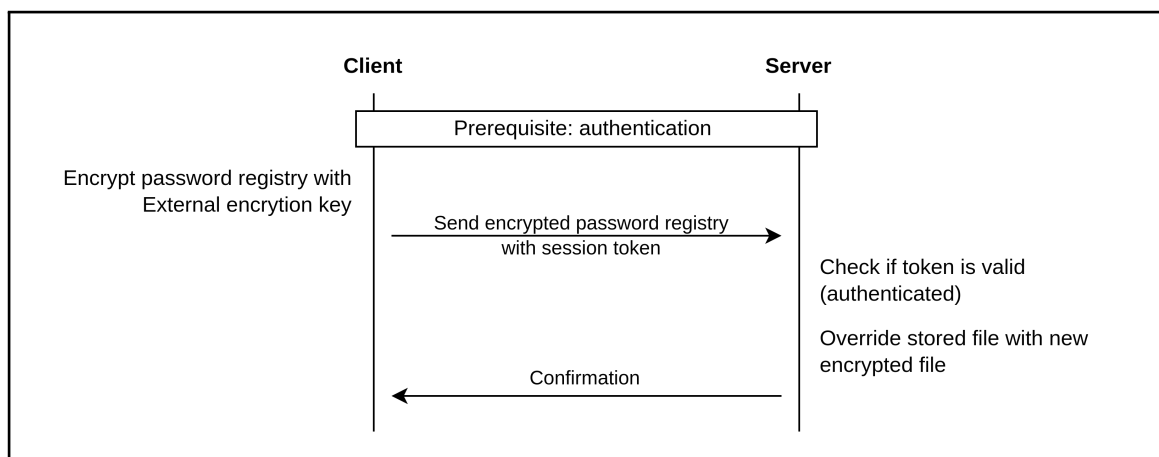


Figure 5.3: Interaction between the client and the server for the file upload endpoint.

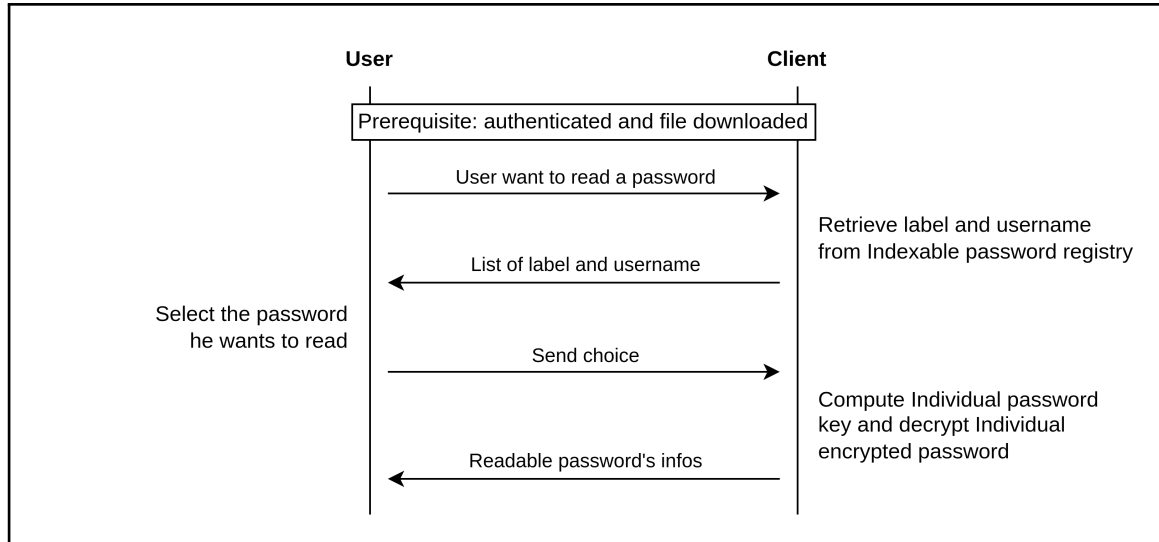


Figure 5.4: Interaction between the user and the client for reading a password entry.

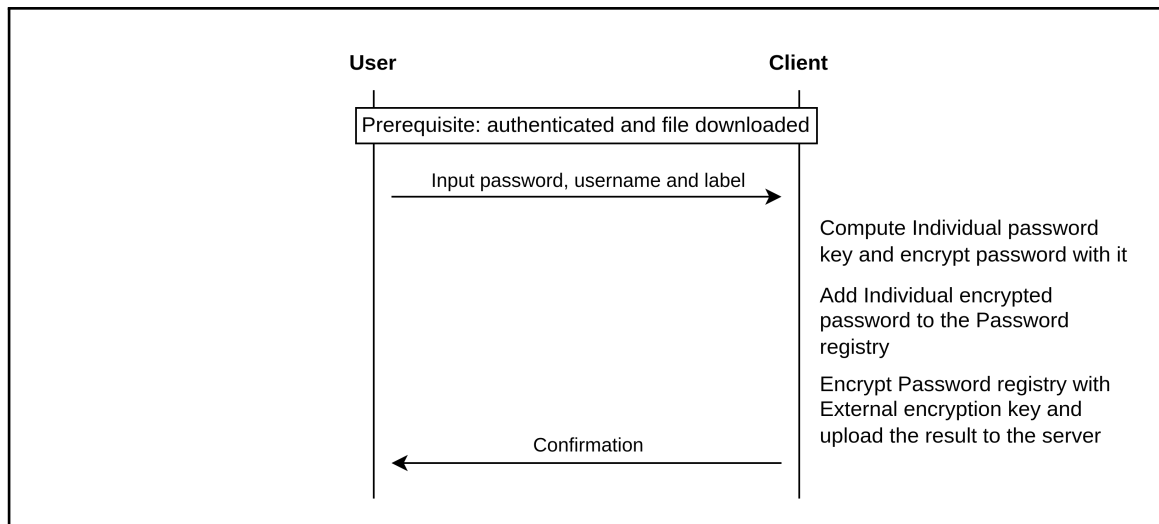


Figure 5.5: Interaction between the user and the client for adding a new password entry.

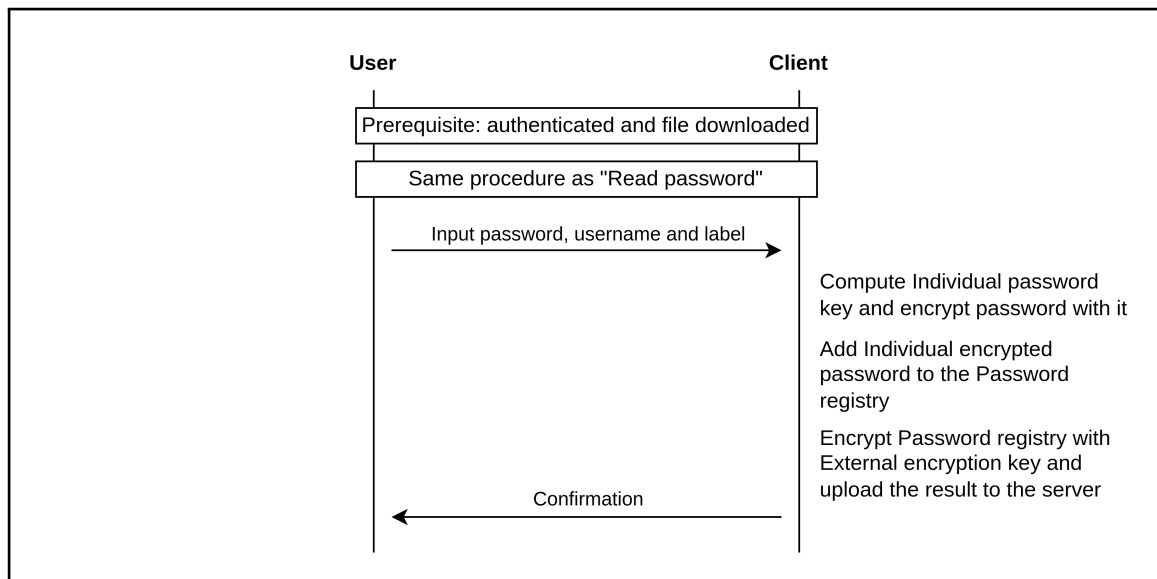


Figure 5.6: Interaction between the user and the client for modifying an existing password entry.

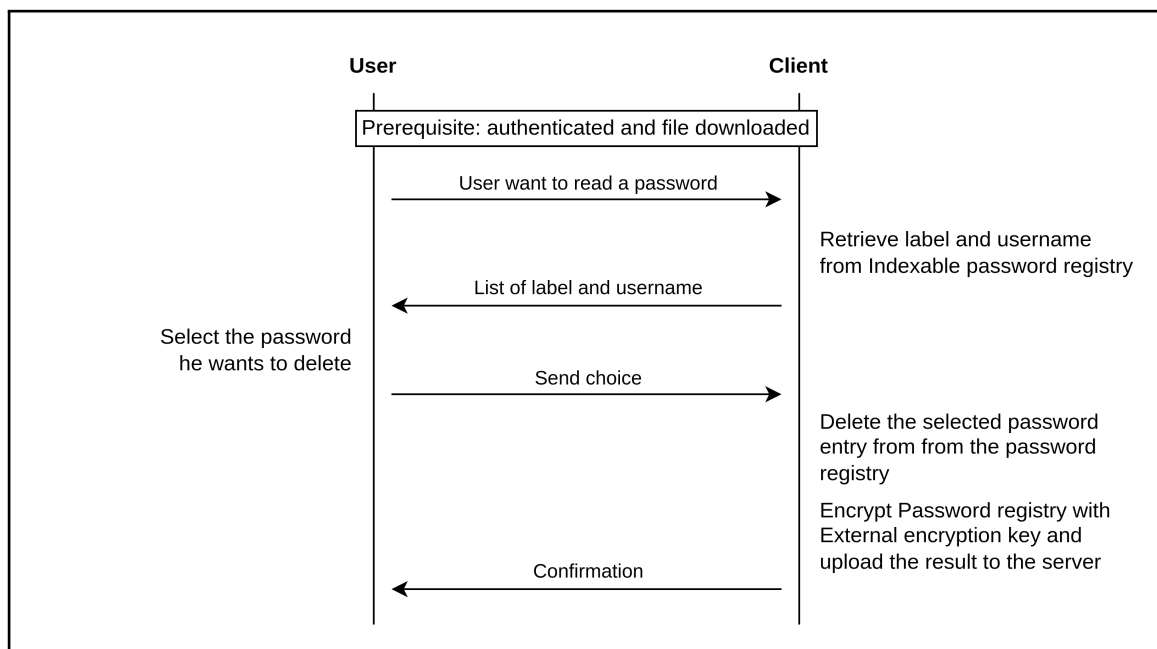


Figure 5.7: Interaction between the user and the client for deleting a password entry.

## 6 | Results

This chapter presents the performances obtained by the implemented KHAPE library using different parameters and analyzing the performance of some of the components. A performance comparison with the OPAQUE rust implementation [25] is made. The password manager use case is not in the scope of the test.

### 6.1 Testing environment

For computation benchmark, the rust library Criterion is used. It computes each benchmark 100 times. Each benchmark is sampled 100 times and each sample linearly increase the number of iterations on the tested function. The median is used for the charts. Benchmarks are computed on a HP Elitebook 850 G5 laptop with an Intel i7-8550U processor.<sup>1</sup>

### 6.2 KHAPE components benchmark

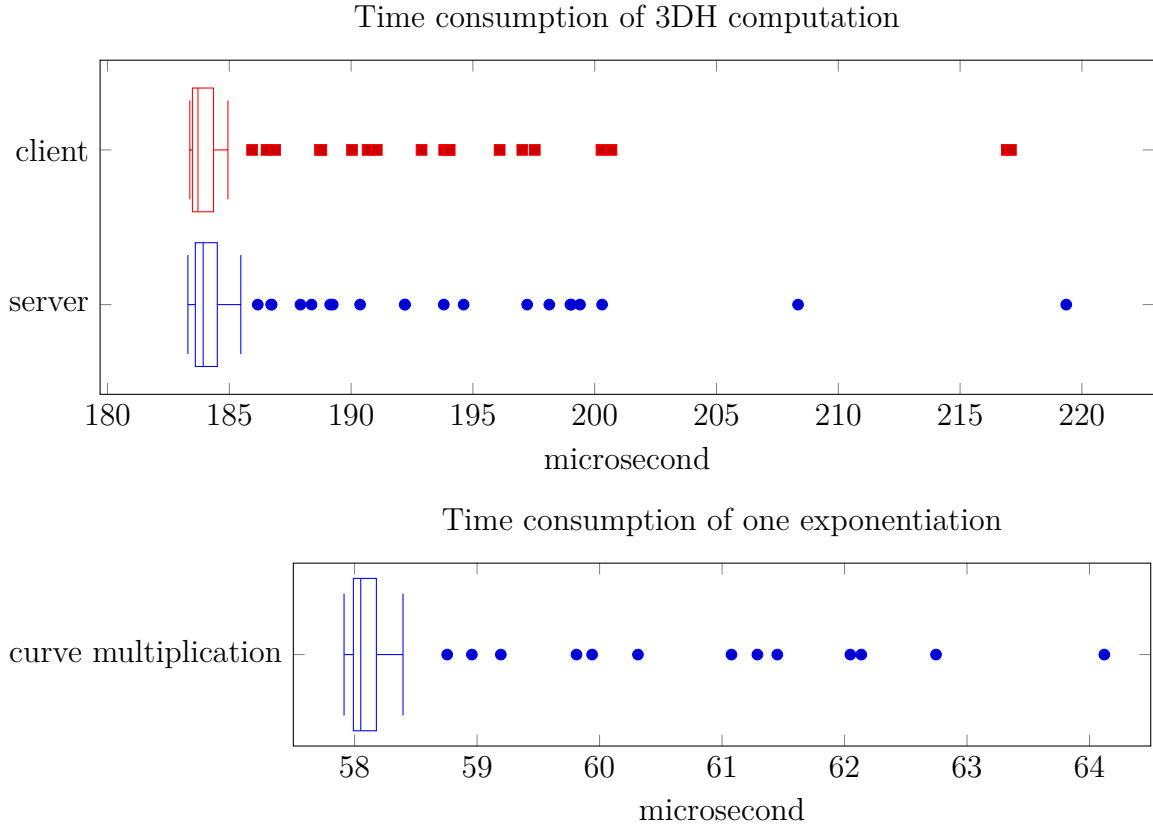
Before diving into the overall performances of KHAPE and its endpoints, it is important to understand what some of the components that take the most time to compute are.

#### 6.2.1 3DH

The 3DH AKE is unsurprisingly the most time-consuming operation to compute. Considering that a curve multiplication takes around 58 us to compute and that 3DH — as its name suggest — compute three of them. Adding the cost of deriving two keys using HKDF, the median time of 3DH computation is around 184 us. Both client and server functions have around the same performances. This is not surprising because they compute the same operations with different party's key.

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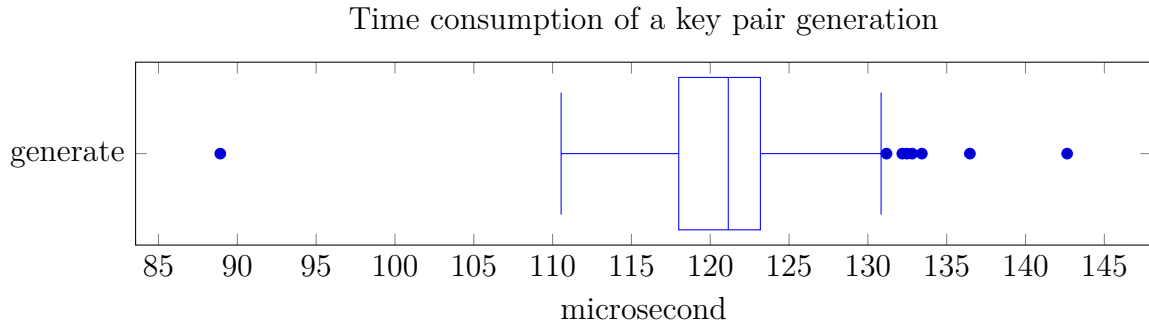
<sup>1</sup>The laptop is plugged to the charging cable during all the benchmarks. This makes a performance gain of around 40% compared to when it runs on batteries.



### 6.2.2 Key generation

Key generation also takes a lot of time with a median of 122 us. Key generation consists of: 1) generating a 32 bytes random value, 2) generating a private key from the random bytes, 3) computing its associated public key — a curve multiplication operation — and then 4) converting the public key to a field element using the `elligator2` map.

For step 2, not all 32 bytes random value can be used to generate a private key and for step 4, not all public key can be mapped to a field element. In this case, the rejection method is used which means that the key generation process is restarted from step 1. This is more secure than trying to modify the value to make it fit but on the other hand, it is more costly in terms of performance as the key generation process can be made multiple time. This is also why the time distribution of this function is more spread out than for other functions.

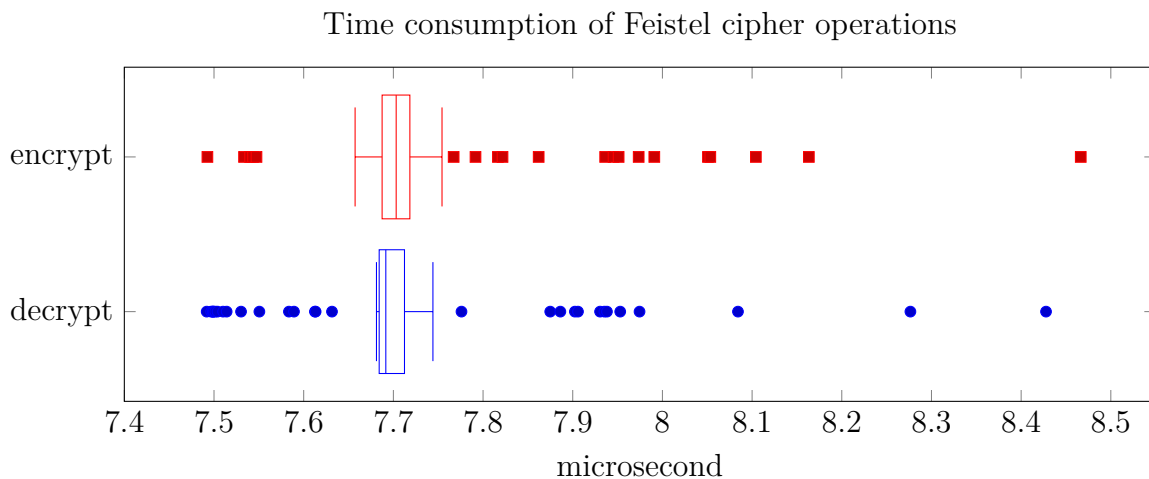


### 6.2.3 Encryption scheme

KHAPE require a Ideal Cipher encryption which has been implemented with a 14-round Feistel cipher.

#### Feistel cipher

The Feistel cipher implemented is not optimal in terms of performance but it is surprising not that much time consuming. It is still around 36 times slower than AES256-CTR (see below) but it does not take much time compared to the group operation above.

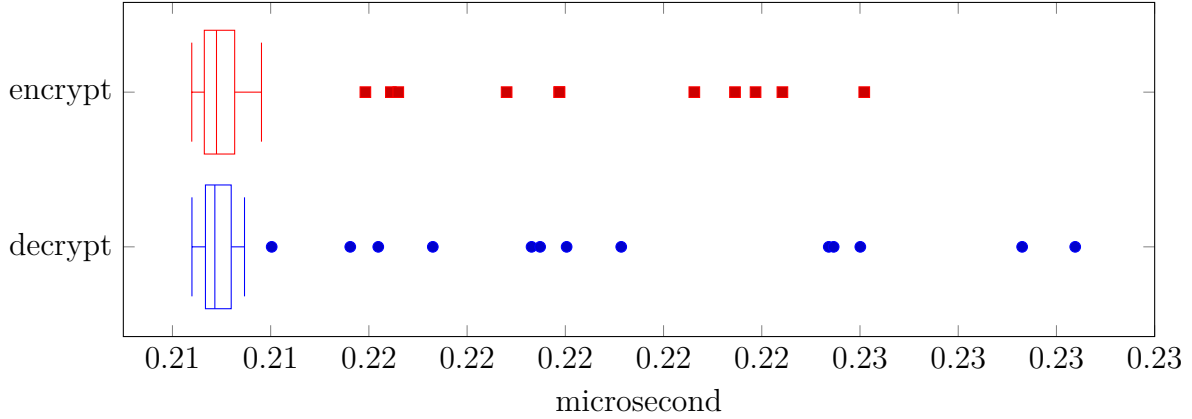


#### AES256-CTR

Even though AES cannot be used for the encryption in KHAPE, it is still interesting to benchmark it with the same context that the Feistel cipher is used for. The

encryption and the decryption take almost exactly the same time in median because with AES-CTR, the decryption is performed with the same function as the encryption.

Time consumption of AES256-CTR operations



## 6.3 KHAPE benchmark

In KHAPE, both registration and authentication process have multiple endpoints — respectively four and five. These endpoints are shared between the client and the server to constitute the protocol.

For this benchmark, each endpoints are tested to measure the time they take to complete and compare them using different parameters. It is interesting to see Section 4.3 to understand what operations are computed on each endpoint and to compare it with the benchmark result. Note that only the time taken for each endpoint to complete is measured. In a real-world scenario, the resulting messages have to be transmitted between the client and the server. The network delay is not very interesting to benchmark as it depends too much on the network infrastructure between the client and the server. Instead, Section 6.6 shows a comparison of message size between multiple configuration of KHAPE and OPAQUE.

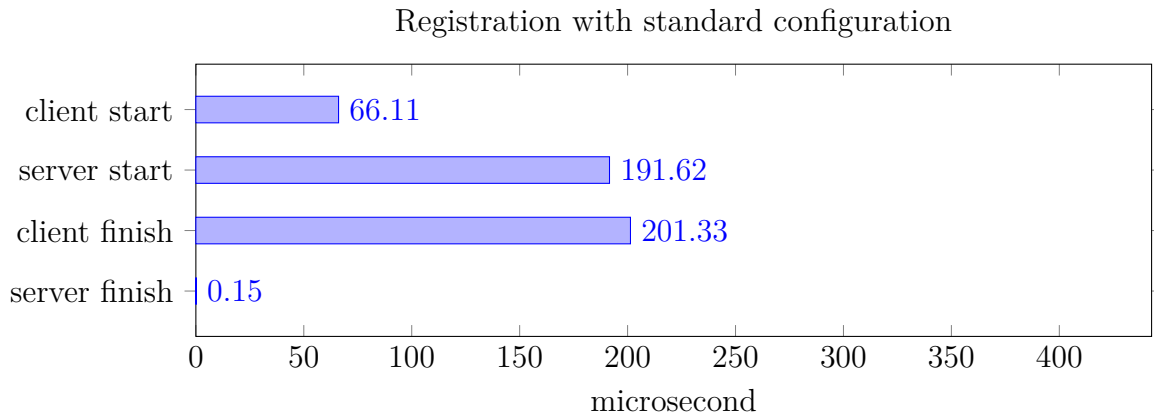
### 6.3.1 Standard configuration

KHAPE's default and most secure configuration is by using both OPRF and SlowHash. But since SlowHash functions are designed to be slow, it does not make sense to add it to the baseline benchmark because it does not show the real performances of the protocol. So for these benchmarks, the standard baseline configuration is KHAPE with OPRF and without SlowHash.



## Registration

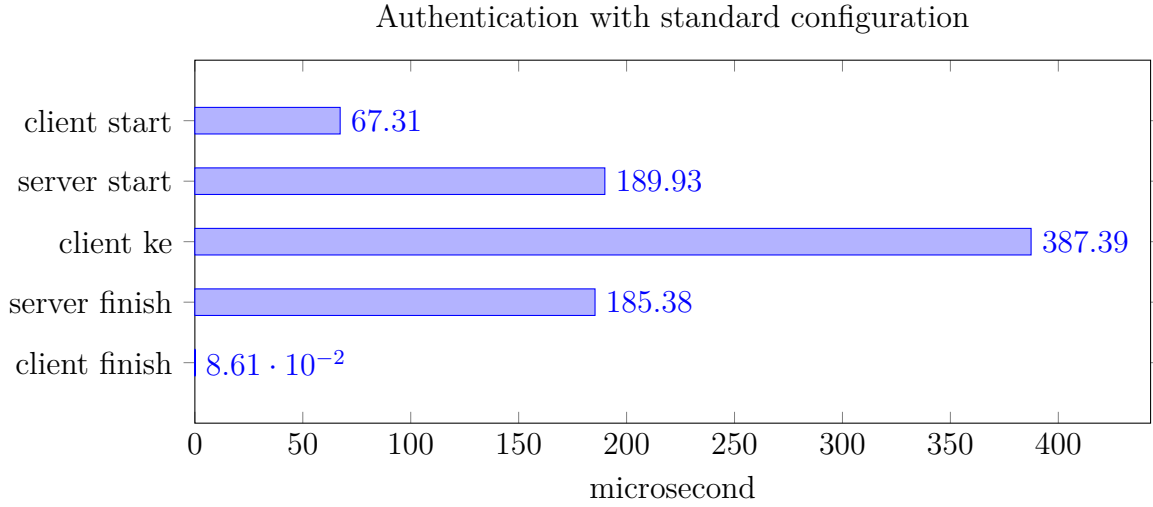
For the registration, we can see that both `server start` and `client finish` endpoints take the most time at around 200 us. It is not surprising as it is where each party generate his own key pair, which take around 122 us. The `server finish` endpoint take almost no time since it only builds a storable structure with the value received.



## Authentication

It is important to note that the endpoints for the registration and authentication are obviously different. For readability reason, it is not specified on the label of the charts but in the chart's title, which could make it look like authentication and registration share the same function.

We can see that `client ke` endpoint takes the most time. This is because a lot of things are computed in this endpoint including the generation of an ephemeral key pair (122 us) and the computation of the 3DH (184 us). We also notice that both `client start` and `server start` take about the same time as their homonym endpoints in registration. This is because these two functions are relatively similar between registration and authentication.

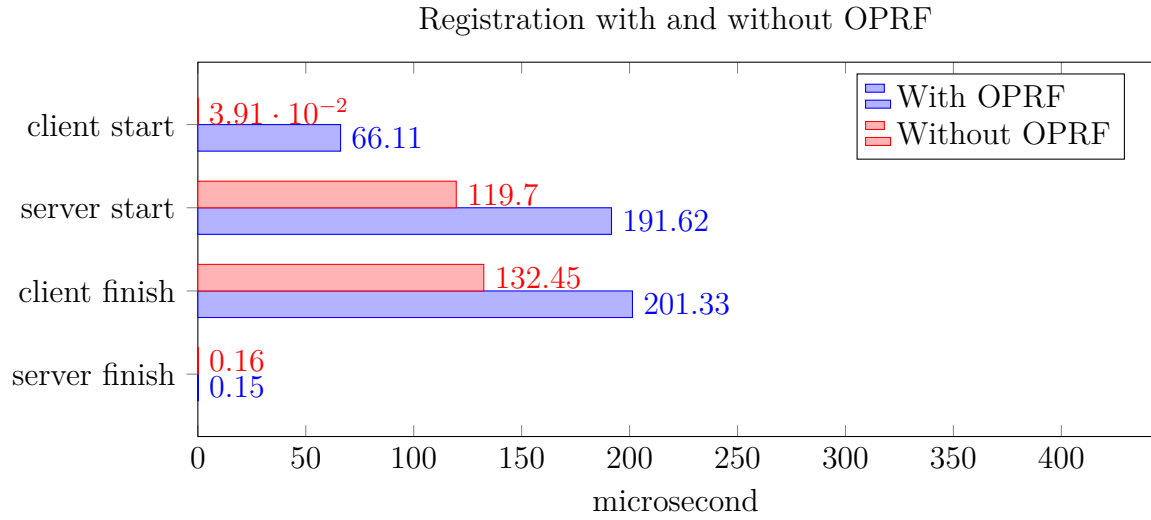


### 6.3.2 With OPRF vs. without OPRF

OPRF largely increase KHAPE security guarantees (see Section 3.3.5) but it remains optional. If used, OPRF is computed for both registration and authentication. It requires to compute two hashes and three exponentiations (curve multiplication) for each run. The exponentiation is computed on the first three endpoints of registration and authentication. In this section, we compare the performance of KHAPE with and without OPRF to see how much it impact the overall performances of the protocol.

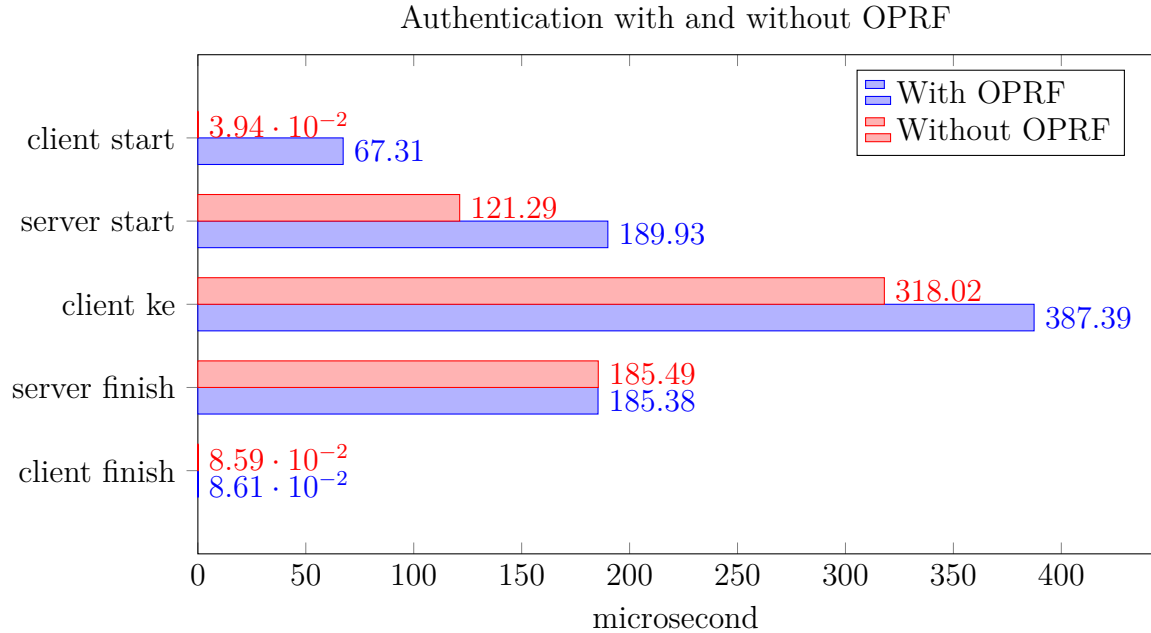
#### Registration

Each OPRF concerned endpoints take between 66 and 72 us more to compute when using OPRF. In total, the registration will take around 207 us more than without an OPRF.



## Authentication

For the authentication, it is similar. The first three endpoints take between 67 and 69 us more to compute and the total time addition for the authentication is around 205 us more than without OPRF.



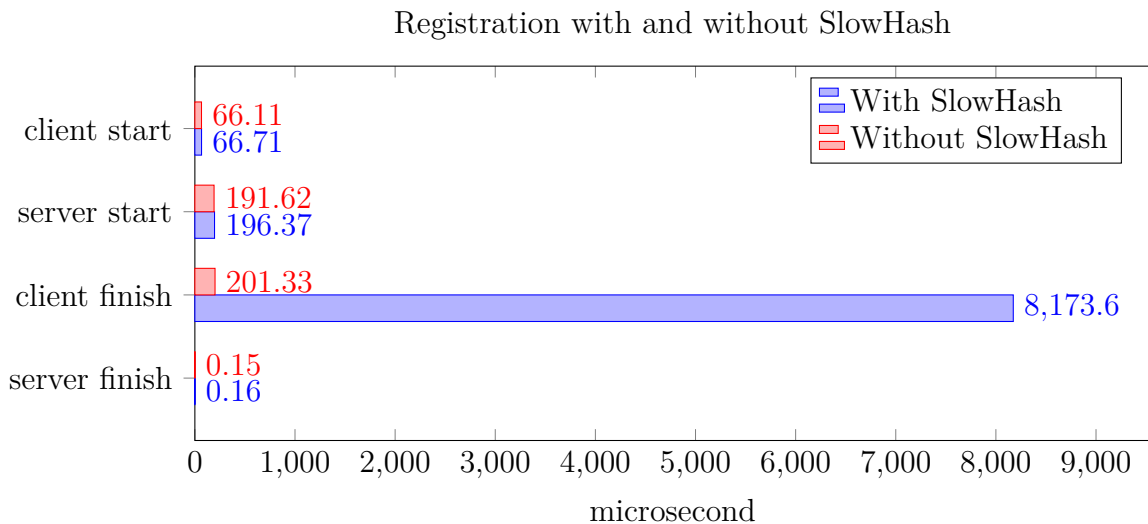
### 6.3.3 With SlowHash vs. without SlowHash

Using a memory-hard hashing function also increases the level of security of the protocol (see section 3.3.6).

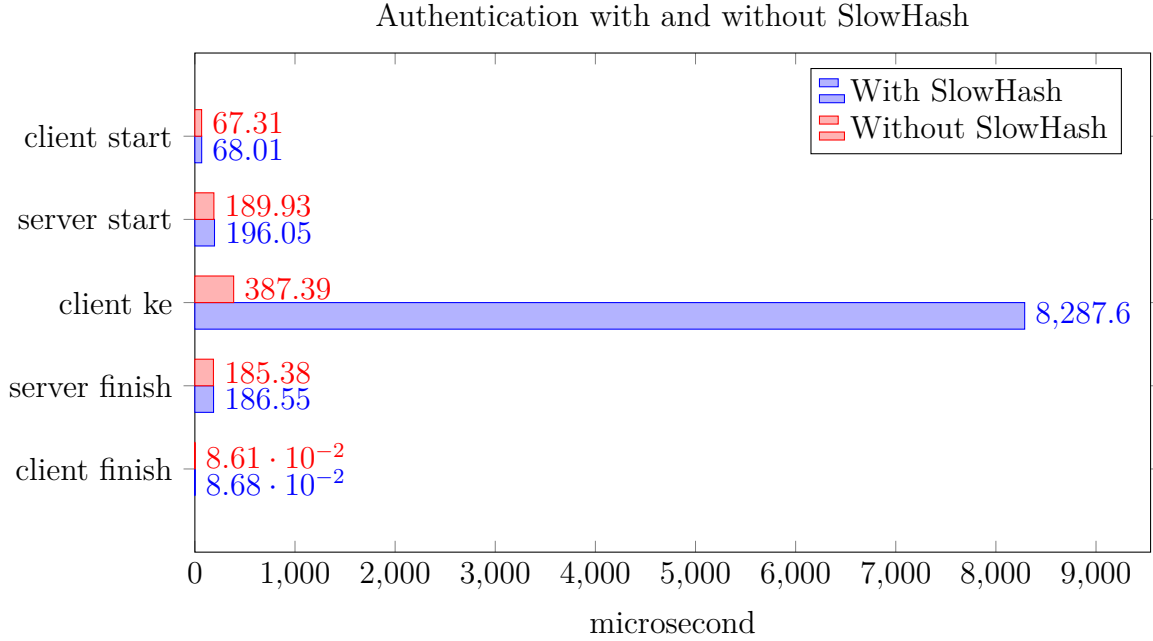
This benchmark is not very meaningful since these functions are designed to be slow and the performance only depends on the parameters used. But it is still interesting to see the performance degradation attached to the use of these functions and the scale of it compared to the rest of the protocol. It also makes it easier to understand how these functions slow down attackers that build hashing table. Since we replace a simple and efficient hashing function that would not even take 0.5 us to compute by a slow and expensive hashing function that takes around 8,000 us to compute. That makes it 16,000 times slower to compute and so the attackers can compute 16,000 times less hash in the same time frame.

This benchmark is using the rust library Argon2's default parameters. The default parameters of the KHAPE library are more resource intensive and time consuming since we believe that final user can wait a little bit more than 8 ms to register/authenticate to a secure system.

## Registration



## Authentication



## 6.4 OPAQUE benchmark

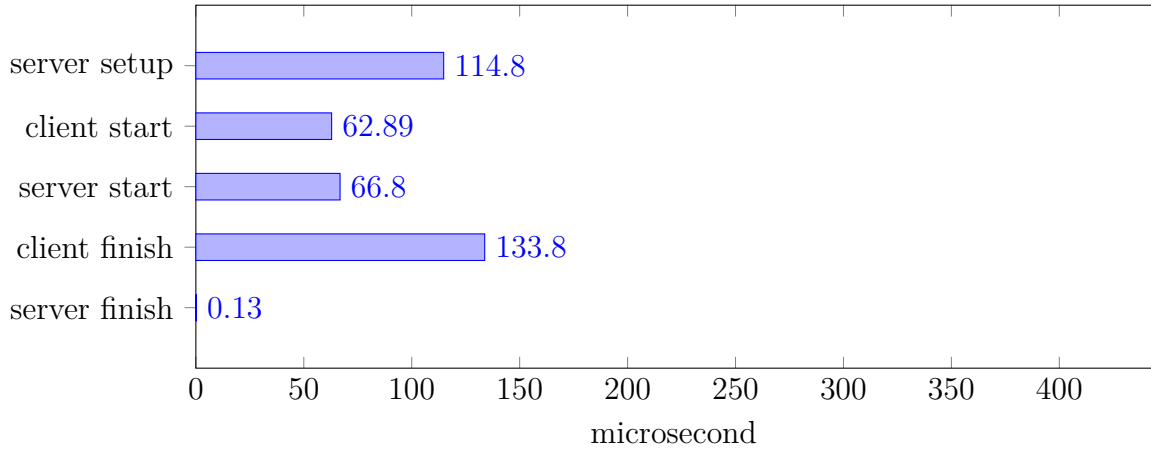
KHAPE and OPAQUE designs share lots of similarities. This makes OPAQUE a perfect candidate for performance comparison. But before that, we need to understand the difference to be able to compare them fairly.

The benchmark is computed with a cipher suite that is close to the primitive used for KHAPE : ristretto255 curve for the OPRF group, Montgomery curve for the KE group, 3DH for the AKE and SHA3 for hashing. Note that the default cipher suite for OPAQUE use SHA2 instead of SHA3 and ristretto255 curve for both OPRF group and KE group but the performance obtained between the two cipher suites are relatively similar.

### Registration

For the registration, OPAQUE has an additional endpoint `server setup` that generates the server's key pair. In KHAPE, this operation is done in the `server start` endpoint.

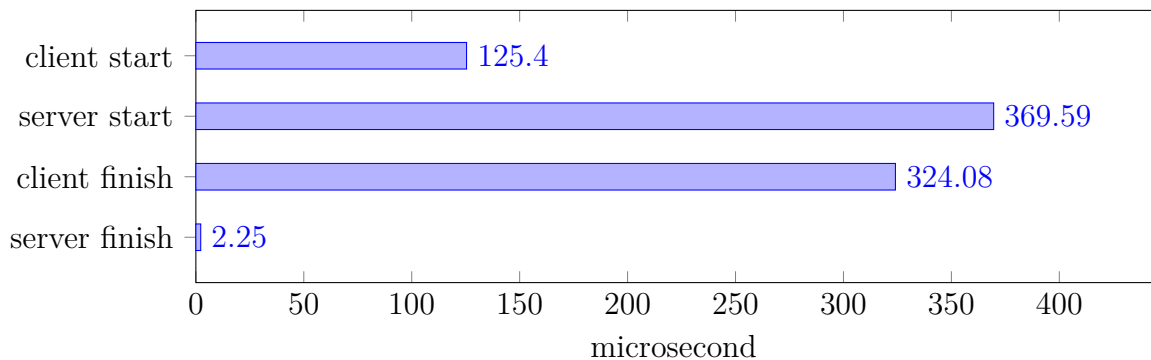
OPAQUE's registration with similar configuration than KHAPE



## Authentication

For the authentication, OPAQUE has only four endpoints since the server initialize the key verification. The `server start` endpoint is the most time consuming with a median time of around 369 us. It is responsible for generating an ephemeral key pair, compute the OPRF evaluation, computing the key exchange and deriving the output key and key verification tag. In KHAPE, all these operations are spread between `server start` and `server finish` endpoints.

OPAQUE's authentication with similar configuration than KHAPE



## 6.5 OPAQUE vs. KHAPE

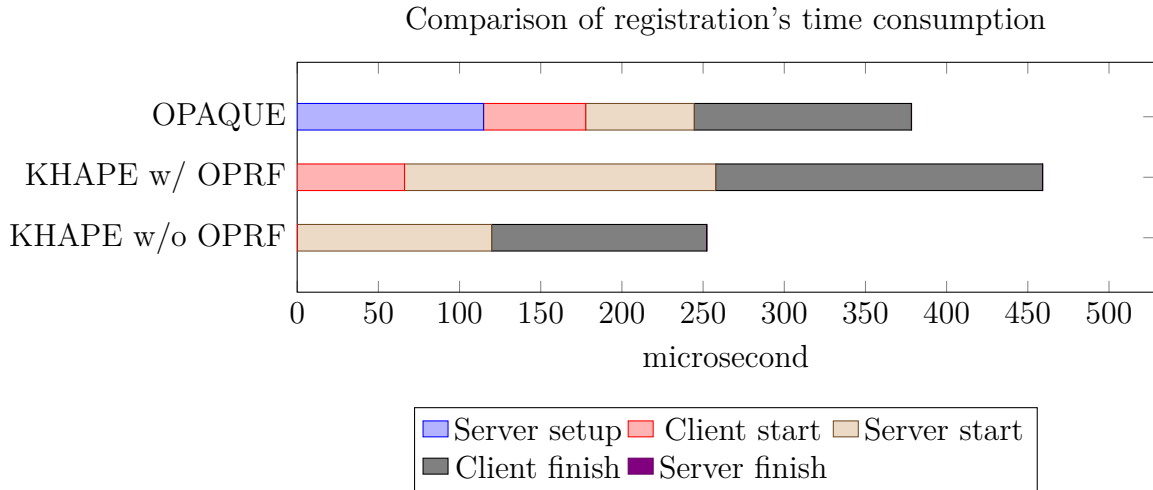
In this section, we compare the performances of the KHAPE protocol — with and without OPRF — with the performances of the OPAQUE protocol.

## Registration

Firstly, we will compare OPAQUE and KHAPE with OPRF. For the registration, KHAPE with OPRF lose around 81 us to OPAQUE in the median. The `client start` endpoint takes about the same time. KHAPE's `server start` operations are split between `server setup` and `server start` for OPAQUE, which make it more flexible since it can be called before a request comes. In detail, it is the random key pair generation that is computed in the `server setup` endpoint. The two endpoints combined take about the same time as KHAPE's `server start` endpoint.

Majority of KHAPE time lose is on the `client finish` endpoint. This is probable due to the fact that KHAPE generate a key pair using the rejection method and then encrypt the private key and server's public key in an encrypted envelope. We saw earlier that encryption is not very time consuming (7.7 us) but key generation is (122 us). OPAQUE neither generate a key pair, nor use the rejection method nor encrypt the envelope. Instead of using the OPRF output to derive an encryption key to decrypt the encrypted private key, OPAQUE directly derive the private key (and the resulting public key) from the OPRF output. This solution allows OPAQUE to get rid of encryption altogether and to avoid computing a random key generation which makes it much faster. Also note that this method is only for the client side. The server still needs to generate a random key pair which is done in the `server setup` endpoint. This is why we cannot see a similar performance gain in the server-side registration and that the first three endpoints are relatively similar in terms of time consumption.

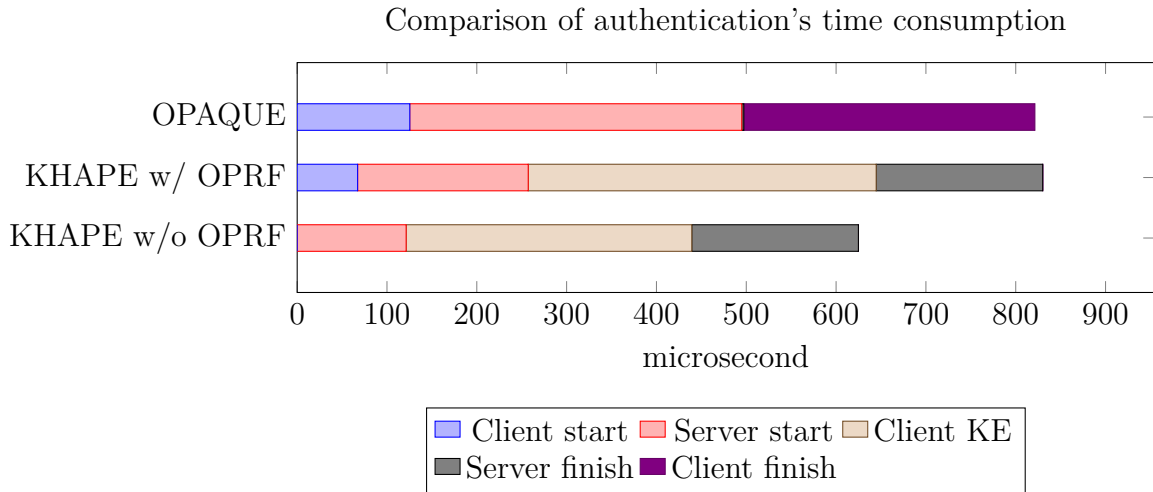
Finally, KHAPE without OPRF is around 207 us faster than KHAPE with OPRF — the equivalent of about three exponentiations — and 126 us faster than OPAQUE, which makes it the fastest protocol.



## Authentication

For the authentication, OPAQUE and KHAPE with OPRF have rather different endpoint performances but the overall performance of each protocol is almost equal with a difference of around 7 us. This is because a lot of similar operations are computed on both protocol but they are executed in different endpoints.

Similar to the registration, KHAPE without OPRF is the fastest protocol. It is faster by 197 us on OPAQUE and by 205 us on KHAPE with OPRF. Even if it is the fastest in both registration and authentication, we believe that the security sacrifice is not worth the performance gain and therefore we recommend using OPAQUE or KHAPE with OPRF which is secure against pre-computation attacks (see Section 3.3.5).



## 6.6 Message size

All the above benchmarks are only comparing computational performances by measuring the time consumption. In a real-world scenario, network delay during transmissions of messages between the client and the server also has to be considered. Network delay benchmark is difficult to evaluate and not very meaningful because it depends too much on the network infrastructure between the two parties. Nevertheless, this section compares the message size and message number for multiple OPAQUE and KHAPE configurations. OPAQUE results are taken from the standard draft test vector and verified with the OPAQUE rust library [25]. In these tests vector, the user identifier is 4 bytes long. The same length will be used for KHAPE's user id. It is interesting to note that in OPAQUE, the user id is not transmitted with the protocol's messages. It is the responsibility of the application to handle it. In KHAPE, the user id is included with the protocol's messages and accessible to the application.



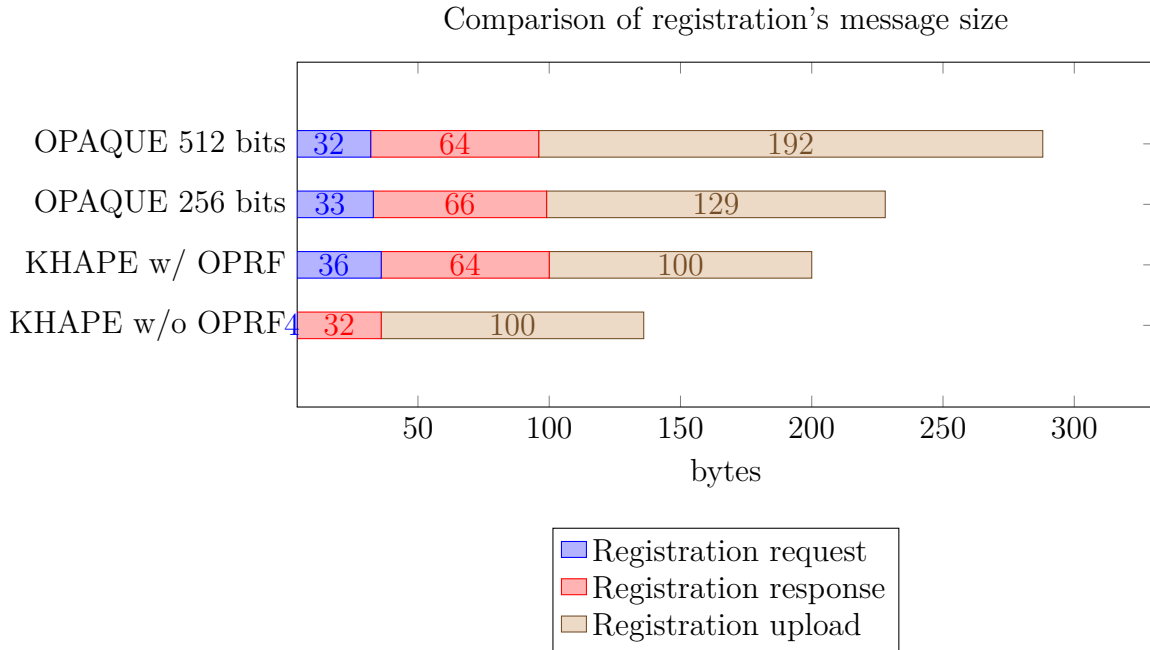
For OPAQUE, the message size depends on the primitives used (cipher suite). In particular, the choice of the hashing function, MAC and KDF has a considerable impact since they can produce output of different length depending on the primitive used. For the benchmark, we will use a cipher suite with 256-bit output for hashing function, MAC and KDF because KHAPE also use this output size for these functions. A comparison is also made with a 512-bit output cipher suite. Note that the 256-bit cipher suites use a P256 curve where the points are represented on 33 bytes. The 512-bit cipher suite use Ristretto255 which is represented on 32 bytes.

## Registration

Firstly, comparing KHAPE with and without OPRF, we see that the first two messages contains 32 more bytes with OPRF. This is simply the size of the representation of a curve point used for OPRF. This difference is exactly the same for the authentication.

Comparing KHAPE and OPAQUE 256-bit cipher suite, we notice that the last message is larger with OPAQUE. This is because OPAQUE encrypt the envelope before transmission with a one-time pad key. This key is derived from a static shared secret which is included in this registration upload message (see Section 2.2.3). The difference of size is due to this additional key sent with OPAQUE.

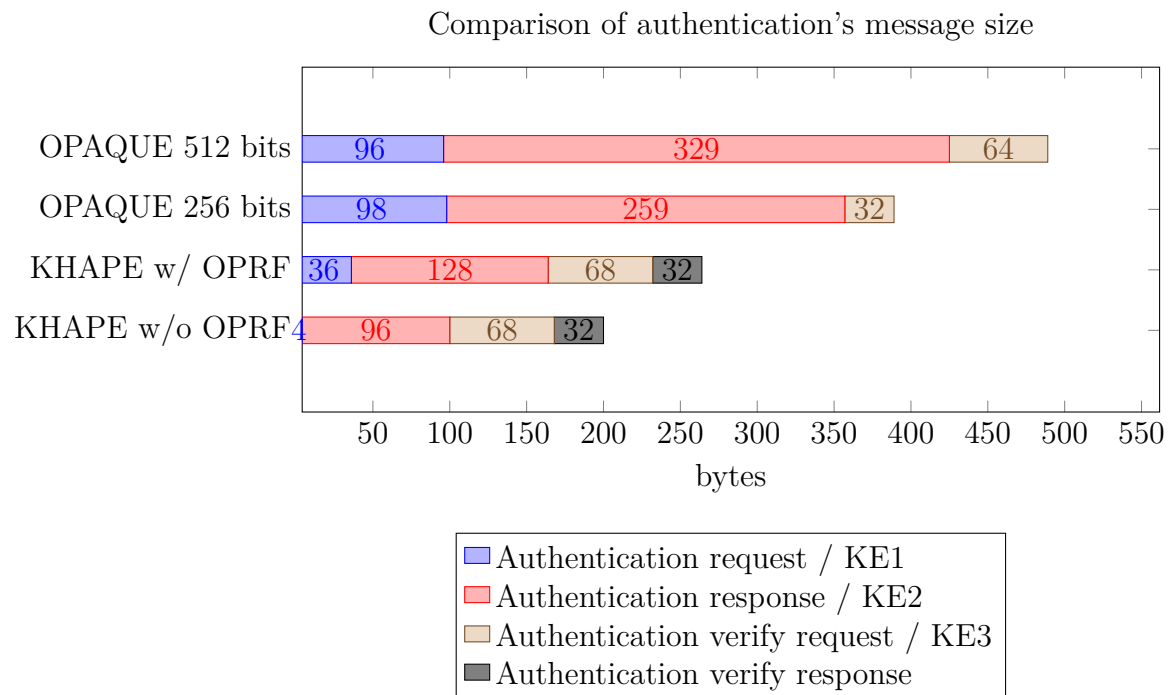
Comparison between the two OPAQUE's cipher suites, since there are two hashing function derived result Comparing the two OPAQUE's cipher suites, we see that the first two messages contain curve points since the 256-bit cipher suite represents curve points on 33 bytes instead of 32. The last message contains two hash-derived output. Their size is doubled with the 512-bit cipher suites.



## Authentication

For the registration, we can see a relatively large difference between KHAPE and OPAQUE 256-bit cipher suites in particular in the second message. The first message already is about three times longer with OPAQUE. This is because in addition to sending the OPRF blinded element like KHAPE do, OPAQUE also send the client's ephemeral public key and a nonce. KHAPE sends the client's ephemeral public key in the third message. In contrary to the server nonce that is used as a context in key derivation, the client nonce has no use in the OPAQUE's internet standard draft. For the second message, both OPAQUE and KHAPE sends the encrypted envelope, the OPRF evaluation result and the server's ephemeral public key. Due to its different envelope encryption (see Section 2.2.3), OPAQUE also sends a masking nonce and the server's public key (which is not included in the envelope in contrary to KHAPE). OPAQUE also sends a server nonce used in key derivation and the first verification tag. For the third message, OPAQUE sends the last verification tag where KHAPE only sends the first verification tag with the server ephemeral key. Only KHAPE sends a fifth message containing the last verification tag. Even though KHAPE's overall message size is smaller, the fact that it has one more message KHAPE's overall message size is smaller but it has one more message than OPAQUE. Having more message is generally more time consuming than having larger messages with all the overhead of a single message.

Similar to the authentication, KHAPE without OPRF has 32 bytes less for the first two messages than KHAPE with OPRF.





## **7 | Conclusion**

**7.1 Final result**

**7.2 Difficulties**

**7.3 Future work**

**7.4 Personal conclusion**



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