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Practical Identity-Based Encryption for Online Social Networks

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Preface

I would like to thank everybody who kept me busy the last year, especially my promotor and my assistants. I would also like to thank the jury for reading the text. My sincere gratitude also goes to my wive and the rest of my family.

Stijn Meul

Contents

Abstract

Nowadays Online Social Networks (OSNs) constitute an important and useful communication channel. At the same time, coarse-grained privacy preferences protect the shared information insufficiently. Cryptographic techniques can provide interesting mechanism to protect privacy of users in OSNs. However, this approach faces several issues, such as, OSN provider acceptance, user adoption, key management and usability. We suggest a practical solution that uses Identity Based Encryption (IBE) to simplify key management and enforce confidentiality of data in OSNs. Moreover, we devise an outsider anonymous broadcast IBE scheme to disseminate information among multiple users, even if they are not using the system. Finally, we demonstrate the viability and tolerable overhead of our solution via an open-source prototype.

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List of Abbreviations

ANO-IBE	Anonymous IBE
ANO-IND-CCA	Anonymity preserving IBE scheme that is indistinguishable under chosen ciphertext attacks
ANO-IND-CPA	Anonymity preserving IBE scheme that is indistinguishable under chosen plaintext attacks
DKG	Distributed Key Generation
IBE	Identity-Based Encryption
IND-CCA	Indistinguishability under Chosen Ciphertext Attack
IND-CPA	Indistinguishability under Chosen Plaintext Attack
OSN	Online Social Network
PKG	Public Key Generator

List of Symbols

λ	Security parameter
l	The number of bits required to realise security level λ
s	Secret
sk_i	Private key corresponding to the public key pk_i or the public verifying key vk_i depending on the application
pk_i	Public key with corresponding private key sk_i
vk_i	Verifying key with corresponding signing key sk_i
$\{0,1\}^l$	Binary bit sequence of length l
$\{0,1\}^*$	Binary bit sequence of variable length
m	Message
c	Ciphertext
v, w	Binary bit sequences
$\{v \parallel w\}$	Concatenated bit sequences
$\texttt{id}_{Alice}$	Identity of Alice
$s_{\texttt{id}_{Alice}}$	IBE private key corresponding to the identifier $\texttt{id}_{Alice}$
k	Generic symmetric session key
$E_k(m)$	Symmetric encryption of the message m under session key k
$D_k(c)$	Symmetric decryption of the ciphertext c under session key k
G	Group $(G, *)$
$S_A(m)$	Signature of entity A on message m
$S_{sk_A}(m)$	Signature generated by the signing key sk_A of entity A on message m
$e: G_1 \times G_2 \to G_T$	Bilinear map
U, P, Q	Points on an elliptic curve
$e(P,Q)$	Bilinear map for the points $P \in G_1, Q \in G_2$ such that $e(P,Q) \in G_T$
$\mathcal{A}(a,b)$	Algorithm $\mathcal{A}$ with parameters a and b
$\langle a,b,c \rangle \leftarrow \mathcal{A}(d,e)$	Algorithm $\mathcal{A}$ with parameters d and e, returns the collection of values a, b, c

Chapter

1 Introduction

The newest internet trend at the dawn of the 21st century certainly is the Online Social Network (OSN). Words like tweeting, sharing, liking, trending and tagging have found common acceptance in the vocabulary of today's internet savvy users while services like Facebook, Google+, LinkedIn and Twitter have become part of everyday life.

The far reaching influence of today's most popular OSNs is best illustrated with the help of some statistics. In May 2013, 72% of all internet users were active on a social network [70]. At the time of writing, Facebook has 1.23 Billion monthly active users which corresponds to 17% of the global population [33, 107]. Furthermore, the average Facebook user spends 15 hours and 33 minutes online per month [101]. These numbers show that social networks no longer represent the latest craze of an internet bubble but are conversely deeply rooted in our daily habits.

1.1 Problem Statement

1.2 Existing Solutions

Several existing solutions have been proposed in literature, all trying to solve most of the earlier mentioned issues in OSNs.

flyByNight [80] is a Facebook application that protects user data by storing it in encrypted form on Facebook. It relies on Facebook servers for its key management and is therefore not secure against active attacks by Facebook itself.

NOYB (None Of Your Business) [65] replaces the details of user A with those of random users B and C thereby making this process only reversible by friends who are allowed to see the profile of user A. However this can not be applied to user messages or status updates that are the most frequently used features in the OSNs considered in this thesis.

FaceCloak [81] stores published Facebook data on its servers in encrypted form and replaces the data on Facebook with random text fetched from Wikipedia. This could be a useful mechanism to prevent OSNs from blocking security aware users because they are scared to see their advertising revenues shrink. However, this approach has the disadvantage that other users could take this data to be genuine user content. Furthermore, FaceCloaks architecture leads to an inefficient key distribution system.

Persona [10] is a scheme that can be used as a Firefox extension to let users of an OSN determine their own privacy by supporting the ability to encrypt messages to a group of earlier defined friends based on *attribute-based encryption (ABE)*[93]. The scheme supports lots of useful use cases such as sending messages to all friends that are related to a certain attribute or even encrypting messages to friends of friends. The major drawback of this system however is that every new friend has to exchange a public key before he is able to interact in the privacy preserving architecture consequently requiring an infrastructure for broadcasting and storing public keys. Furthermore, to support the encryption of messages to friends of friends, user defined groups should be made available publicly thereby making the public key distribution system even more complicated. Finally the proposed ABE encryption scheme is 100 to 1000 times slower than a standard RSA operation [10].

Scramble [17] is a Firefox extension that allows defining groups of friends that are given access to certain social network updates. The tool uses public key encryption based on OpenPGP [34] to broadcast encrypted messages on almost any platform. Furthermore Scramble provides the implementation of a tiny link server such that OSN policies not allowing to post encrypted data are bypassed. However, as indicated by usability studies [105] OpenPGP has a higher usage threshold because an average user does not manage to understand OpenPGP properly. Additionally, Scramble has to rely on the security decisions of the web of thrust. It therefore inherits the unpleasant property of OpenPGP that the user can not be sure that the used PGP key actually belongs to the intended Facebook profile.

The most unattractive property of all the above applications is that they have to rely on a rather complex infrastructure. Persona has to support an extended public key distribution system and Scramble relies on the leap-of-faith OpenPGP web of trust. All proposed solutions require users with no cryptographic background on asymmetric cryptography to make responsible decisions concerning the management of their keys. Furthermore, maintaining such complex key infrastructures gets more and more complex as more users subscribe.

1.3 Goals of this Thesis

The goal of this thesis is to develop an architecture that solves the issues discussed in Section 4.2 thereby taking the challenges and pitfalls from earlier solutions in Section 1.2 into account. Specifically the architecture should have the following properties:

- **User friendly:** An average OSN user should be able to use the resulting architecture, i.e. a user with no knowledge on cryptographic primitives.

- **Applicable:** The original OSN environment should not be altered since some OSN providers are probably not willing to support a more confidential architecture because it could possibly hurt their business model.
- **Immediately ready to use:** No additional registration or subscription to third party key architectures should be required to enable usage of the system. As soon as a user subscribes to the OSN provider he should be able to start receiving confidential messages.

1.4 Structure of this Thesis

Chapter

2 Background

This chapter briefly covers the mathematical knowledge required to understand cryptographic algorithms presented later in this text. The mathematical details of this chapter represent a fundament of a challenging world containing exciting cryptographic concepts like identity-based encryption. If the reader feels he has sufficient background of the concepts covered in this chapter, the chapter can be skipped without loss of comprehension.

Note that this chapter only overviews the cryptographic fundamentals required to understand the remainder of the thesis. Definitions and theorems are always provided without proof. For a more in depth discussion about algebraic topics in this chapter, the reader is referred to [87] and [21]. More information on elliptic curves, Diffie-Hellman assumptions and pairing based cryptography can be found in [3].

For the remainder of this chapter, the notion of negligible functions is introduced, followed by an overview of algebraic structures and their properties. Then, a number of theoretic assumptions fundamental for cryptographic security are presented. The introduction of gap groups and bilinear maps follows naturally by exploring these variants of the Diffie-Hellman assumption. Finally, hash functions are defined as well as their relation to the random oracle assumption.

2.1 Complexity Theory

2.1.1 Assymptotic Notation

2.1.2 Complexity Classes

Polynomial time algorithm (Sub)exponential-time algorithm

2.1.3 Negligible Function

In practice no modern cryptographic algorithm achieves perfect secrecy[1], i.e. with unbounded computational power all practical cryptographic algorithms can be broken.

[1]Note that the one-time pad is not taken into account. Although it is the only proven information secure cryptographic algorithm, it is seldom used in practical cryptographic systems.

Therefore, a more pragmatic definition of security is usually considered, such as security against adversaries that are computationally bound to their finite resources. In this pragmatic view of security an algorithm is considered secure only if the probability of success is smaller than the reciprocal of any polynomial function. The negligible function can be used to exactly describe this notion in a formal way.

Definition 2.1. A **negligible function** in λ is a function $\mu(\lambda) : \mathbb{N} \rightarrow \mathbb{R}$ if for every polynomial $p(\cdot)$ there exists an N such that for all $\lambda > N$ [59]

$$\mu(\lambda) < \frac{1}{p(\lambda)}$$

The negligible function is used along this chapter to formally describe computationally infeasible problems. In such a context λ often represents the security parameter. The larger λ will be chosen, the smaller $\mu(\lambda)$ will be.

2.2 Probability Theory

2.2.1 Random Variables

Definition of perfect randomness here

2.2.2 Indistinguishability

2.3 Abstract Algebra

Abstract algebra is a field of mathematics that studies algebraic structures such as groups, rings and vector spaces. These algebraic structures define a collection of requirements on mathematical sets such as e.g., the natural numbers $\mathbb{N}$ or matrices of dimension 2 x 2 $\mathbb{R}^{2x2}$. If these requirements hold, abstract properties can be derived. Once a mathematical set is then categorised as the correct algebraic structure, properties derived for the algebraic structure will hold for the set as a whole.

In the light of our further discussion, especially additive and multiplicative groups prove to be essential concepts. However, algebraic groups come with a specific vocabulary such as binary operation, group order and cyclic group that are defined in this section as well.

Definition 2.2 (Binary operation). A *binary operation* * on a set S is a mapping $S \times S \rightarrow S$. That is, a binary operation is a rule which assigns to each ordered pair of elements a and b from S a uniquely defined third element $c = a * b$ in the same set S. [21, 87]

Definition 2.3 (Group). A *group* $(G, *)$ consists of a set G with a binary operation $*$ on G satisfying the following three axioms:

1. *Associativity* $\forall a, b, c \in G : a * (b * c) = (a * b) * c$

2. *Identity element* $\forall a \in G, \exists\, e \in G : a * e = e * a = a$ where e denotes the *identity element* of G

3. *Inverse element* $\forall a \in G, \exists\, a^{-1} : a * a^{-1} = a^{-1} * a = 1$ where a^{-1} denotes the *inverse element* of a

Definition 2.4 (Commutative group). A group $(G, *)$ is called a *commutative group* or an *abelian group* if in addition to the properties in Definition 2.3, also commutativity holds.

4. **Commutativity** $\forall a, b \in G : a * b = b * a$

Depending on the group operation $*$, $(G, *)$ is either called a *multiplicative group* or an *additive group.* In Definition 2.3 the multiplicative notation is used. For an additive group the inverse of a is often denoted $-a$ [87].

A group $(G, *)$ is often denoted by the more concise symbol G although groups are always defined with respect to a binary group operation $*$. Despite of a more concise notation, any group G still obeys all axioms from Definition 2.3 with respect to an implicitly known group operation $*$.

A perfect example of a commutative group is the set of integers with the addition operation $(\mathbb{Z}, +)$ since the addition is both associative and commutative in $\mathbb{Z}$. Furthermore, the identity element $e = 0$ and the inverse element $\forall a \in \mathbb{Z}$ is $-a \in \mathbb{Z}$. Note that the set of natural numbers with the addition operation $(\mathbb{N}, +)$ is not a commutative group as not every element of $\mathbb{N}$ has an inverse element.

Definition 2.5 (Cyclic group). A group G is *cyclic* if and only if $\forall b \in G, \exists g \in G, \exists n \in \mathbb{Z} : g^n = b$. Such an element g is called a **generator** of $\mathbb{G}$.

Definition 2.5 implies that in a cyclic group every element can be written as a power of one of the group's generators.

Definition 2.6 (Finite group). A group G is *finite* if the number of elements in G denoted $|G|$ is finite. The number of elements $|G|$ in a finite group is called the *group order.*

The set $\mathbb{Z}_n$ denotes the set of integers modulo n. The set $\mathbb{Z}_5$ with the addition operation is a cyclic finite group of order 5. The set $\mathbb{Z}_5\backslash\{0\}$ with the multiplication operation, often denoted $\mathbb{Z}_5^*$, is a cyclic finite group of order 4 where the neutral element $e = 1$. For example, 2 is a generator in $\mathbb{Z}_5^*$ since every element in $\mathbb{Z}_5^*$ can be written as $\{2^n | n \in \mathbb{Z}\}$.

Definition 2.7 (Order of an element). Let G be a group. The *order of an element* $a \in G$ is defined as the least positive integer t such that $a^t = e$. If there exists no such t, t is defined as ∞.

Theorem 2.8. *If the order of a group G equals a prime p, the group is cyclic and commutative.*

Definition 2.9 (Subgroup). Given a group $(G, *)$, any H that is a non-empty subset $H \subseteq G$ and satisfies the axioms of a group with respect to the group operation $*$ in H, is a *subgroup of* G.

Definition 2.10 (Ring). A *ring* $(R, +, *)$ consists of a set R with two binary operations $+$ and $*$ on R satisfying the following axioms:

1. $(R, +)$ is an abelian group with identity denoted e
2. *Associativity* $\forall a, b, c \in R : a * (b * c) = (a * b) * c$
3. *Multiplicative identity element* $\forall a \in R, \exists 1 \in R : a * 1 = 1 * a = a$ where 1 denotes the *multiplicative identity element* of R
4. *Left distributivity* $\forall a, b, c \in R : a * (b + c) = (a * b) + (a * c)$
5. *Right distributivity* $\forall a, b, c \in R : (b + c) * a = (b * a) + (c * a)$

Definition 2.11 (Commutative ring). A ring $(R, +, *)$ is called a *commutative ring* or an *abelian ring* if in addition to the properties in Definition 2.10, also commutativity holds.

6. **Commutativity** $\forall a, b \in R : a * b = b * a$

Definition 2.12 (Field). A commutative ring $(R, +, *)$is called a *field* if in addition to the properties in Definition 2.11 and Definition 2.10 all elements of R have a multiplicative inverse.

7. *Multiplicative inverse* $\forall a \in R, \exists a^{-1} : a * a^{-1} = a^{-1} * a = 1$ where a^{-1} denotes the *inverse element* of a

Definition 2.13 (Finite field). A *finite field* or a *Galois Field* is a field F with a finite number of elements. The number of elements $|F|$ of a finite field F is called its *order*.

Definition 2.14 (Ring homomorphism). Given rings R and S, a *ring homomorphism* is a function $f : R \to S$ such that the following axioms hold:

1. $\forall a, b \in R : f(a + b) = f(a) + f(b)$
2. $\forall a, b \in R : f(ab) = f(a) f(b)$
3. $f(e_R) = f(e_S)$ where e_S and e_R denote the identity element of respectively S and R

Definition 2.15 (Bijective function). Any function $f : R \to S$ is bijective if it satisfies the following axioms

1. *Injective* Each element in S is the image of at most one element in R. Hence, $\forall a_1, a_2 \in R$ if $(a_1) = f(a_2)$ then $a_1 = a_2$ follows naturally.

2. *Surjective* Each $s \in S$ is the image of at least one $r \in R$.

Definition 2.16 (Ring isomorphism). A ring isomorphism is a bijective homomorphism.

Informally speaking, a ring isomorphism $f : R \rightarrow S$ is a mapping between rings that are structurally the same such that any element of R has exactly one image in S.

Note that $(\mathbb{Z}_n, +, \cdot)$ is a finite field if and only if n is a prime number. Furthermore, if F is a finite field, then F contains p^m elements for some prime p and integer $m \geq 1$. For every prime power order p^m, there is a unique finite field of order p^m. This field is denoted by $\mathbb{F}_{p^m}$ or $GF(p^m)$. The finite field $\mathbb{F}_{p^m}$ is unique up to an isomorphism.

2.4 Number Theoretic Assumptions

This section presents a collection of number theoretic assumptions. The cryptographic security of our future constructions falls or stands on these assumptions [24, 87].

In the definitions that follow $\langle G, n, g \rangle \leftarrow \mathcal{G}\left(1^\lambda\right)$ is defined as the setup algorithm that generates a group G of order n and a generator $g \in G$ on input of the security parameter k.

Definition 2.17 (DL). The *discrete logarithm problem* is defined as follows. Given a finite cyclic group G of order n, a generator $g \in G$ and an element $a \in G$, find the integer $x, 0 \leq x \leq n-1$ such that $g^x = a$.

The *discrete logarithm assumption* holds if for any algorithm $\mathcal{A}(g, g^x)$ trying to solve the DL problem there exists a negligible function $\mu(k)$ such that

$$\Pr\left[\mathcal{A}(g, g^x) = a \mid \langle G, n, g \rangle \leftarrow \mathcal{G}\left(1^\lambda\right)\right] \leq \mu(\lambda)$$

where the probability is over the random choice of n, g in G according to the distribution induced by $\mathcal{G}\left(1^\lambda\right)$, the random choice of a in G and the random bits of the algorithm $\mathcal{A}$.

Definition 2.18 (CDH). The *Computational Diffie-Hellman problem* is defined as follows. Given a finite cyclic group G of order n, a generator $g \in G$ and g^a, g^b with uniformly chosen random independent elements $a, b \in \{1, \ldots, |G|\}$, find the value g^{ab}.

The *Computational Diffie-Hellman assumption* holds if for any algorithm $\mathcal{A}\left(g, g^a, g^b\right)$ trying to solve the CDH problem there exists a negligible function $\mu(k)$ such that

$$\Pr\left[\mathcal{A}\left(g, g^a, g^b\right) = g^{ab} \mid \langle G, n, g \rangle \leftarrow \mathcal{G}\left(1^\lambda\right)\right] \leq \mu(\lambda)$$

where the probability is over the random choice of n, g in G according to the distribution induced by $\mathcal{G}\left(1^k\right)$, the random choice of a, b in $\{1, \ldots, |G|\}$ and the random bits of the algorithm $\mathcal{A}$.

Definition 2.19 (DDH). The *Decisional Diffie-Hellman problem* is defined as follows. Given a finite cyclic group G of order n, a generator $g \in G$ and g^a, g^b, g^{ab}, g^c with uniformly chosen random independent elements $a, b, c \in \{1, \ldots, |G|\}$, distinguish $\left\langle g, g^a, g^b, g^{ab} \right\rangle$ from $\left\langle g, g^a, g^b, g^c \right\rangle$.

Define $\mathcal{A}(x)$ as an algorithm returning `true` if $x = \left\langle g, g^a, g^b, g^{ab} \right\rangle$ and `false` if $x = \left\langle g, g^a, g^b, g^c \right\rangle$ for $c \neq ab$. The *Decisional Diffie-Hellman assumption* holds if for any such algorithm $\mathcal{A}(x)$ there exists a negligible function $\mu(k)$ such that

$$|\Pr\left[\mathcal{A}\left(\left\langle g, g^a, g^b, g^{ab} \right\rangle\right) = \texttt{true}\right] - \Pr\left[\mathcal{A}\left(\left\langle g, g^a, g^b, g^c \right\rangle\right) = \texttt{true}\right]| \leq \mu(\lambda)$$

where the probability is over the random choice of n, g in G according to the distribution induced by $\mathcal{G}\left(1^\lambda\right)$, the random choice of a, b, c in $\{1, \ldots, |G|\}$ and the random bits of the algorithm $\mathcal{A}$.

Definition 2.19 states that $\left\langle g, g^a, g^b, g^{ab} \right\rangle$ and $\left\langle g, g^a, g^b, g^c \right\rangle$ are *computationally indistinguishable*. This implies that no efficient algorithm exists that can distinguish both arguments with non-negligible probability. The concept of computational indistinguishability bears close resemblance to statistical indistinguishability. The reader is referred to [60, 61] for a more in depth discussion of the topic. The intuitive interpretation of Definition 2.19 is that g^{ab} looks like any other random element in G.

Someone with the ability to calculate discrete logarithms could trivially solve the CDH problem. That is, if a and b can be derived only from $\left\langle g^a, g^b \right\rangle$, it becomes easy to calculate g^{ab}. Therefore, a group structure where the CDH assumption holds, immediately implies a group where the DL assumption is valid as well. There is no mathematical proof that supports the inverse relation. Thus, a group where the DL problem is hard not necessarily implies the CDH problem. For specific group structures the CDH assumption immediately follows from the DL assumption as shown in [84, 85]. However, their proof can not be generalised to just any group.

There exists a similar relation between the CDH and the DDH problem. If a powerful algorithm could solve CDH, i.e. derive g^{ab} from $\left\langle g, g^a, g^b \right\rangle$ alone, it would become trivial to distinguish $\left\langle g, g^a, g^b, g^{ab} \right\rangle$ from $\left\langle g, g^a, g^b, g^c \right\rangle$. Again, an inverse relation can not be proven. As a matter of fact, concrete examples of groups exist where CDH is hard although DDH is not.

Therefore, the relation between DL, CDH and DDH is often written as follows

$$DDH \Rightarrow CDH \Rightarrow DL$$

The $\Rightarrow$ notation is then translated into "immediately implies". In a group where DDH is hard both CDH and DL will be hard. Contrarily, there exist group structures where the CDH and the DL assumption hold while DDH can be found easily. Such groups are called *Gap Diffie-Hellman Groups.*

Definition 2.20 (GDH). The *Gap Diffie-Hellman problem* is defined as follows. Solve the CDH problem with the help of a DDH oracle. Given a finite cyclic group G of order n, a generator $g \in G$ and g^a, g^b with uniformly chosen random independent elements $a, b \in \{1, \ldots, |G|\}$, find the value g^{ab} with the help of a DDH oracle $\mathcal{DDH}\left(g, g^a, g^b, z\right)$. Where the DDH oracle $\mathcal{DDH}\left(g, g^a, g^b, z\right)$ is defined to return `true` if $z = g^{ab}$ and `false` if $z \neq g^{ab}$.

The *Gap Diffie-Hellman assumption* holds if for any algorithm $\mathcal{A}\left(g, g^a, g^b\right)$ trying to solve the CDH problem with the help of a DDH oracle $\mathcal{DDH}\left(g, g^a, g^b, z\right)$ there exists a negligible function $\mu(k)$ such that

$$\Pr\left[\mathcal{A}\left(g, g^a, g^b\right) = g^{ab} \mid \langle G, n, g\rangle \leftarrow \mathcal{G}\left(1^\lambda\right)\right] \leq \mu(\lambda)$$

where the probability is over the random choice of n, g in G according to the distribution induced by $\mathcal{G}\left(1^\lambda\right)$, the random choice of a, b in $\{1, \ldots, |G|\}$ and the random bits of the algorithm $\mathcal{A}$.

2.5 Bilinear Maps

It can be shown that bilinear pairings are an example of a practical usable DDH oracle [72].

2.5.1 Definition

Definition 2.21 (Admissible bilinear map). Let G_1, G_2 and G_T be three groups of order q for some large prime q. An *admissible bilinear map* $e : G_1 \times G_2 \to G_T$ is defined as a map from the gap groups G_1 and G_2 to the target group G_T that satisfies the following properties:

1. *Bilinearity* $\forall a, b \in \mathbb{Z}, \forall P \in G_1, \forall Q \in G_2 : e(aP, bQ) = e(P, Q)^{ab}$
2. *Non-degeneracy* If P is a generator of G_1 and Q is a generator of G_2, $e(P, Q)$ is a generator of G_T
3. *Computability* There is an efficient algorithm to compute $e(P, Q)$ for all $P \in G_1$ and $Q \in G_2$

In literature, authors distinguish two types of admissible bilinear maps: symmetric and asymmetric bilinear maps. A *symmetric bilinear map* is an admissible bilinear map where the gap groups are the same, i.e. $G_1 = G_2$. Definition 2.21 describes the more general *asymmetric bilinear map* where $G_1 \neq G_2$. Schemes relying on symmetric bilinear maps are easier to construct information theoretic security proofs although asymmetric bilinear maps are more efficient and suitable for implementation thanks to their flexible embedding degree [28, 109].

In practice, bilinear maps are constructed using pairings. The most popular pairings implementing admissible bilinear maps are the Weil pairing [28] and the Tate pairing [54]. Both the Tate and the Weil pairing rely on abelian varieties for their implementation. G_1 is mostly an additive elliptic curve group, G_2 a multiplicative elliptic curve group while G_T is a finite field. For instance, the asymmetric Weil pairing is often implemented with a cyclic subgroup of $E\left(\mathbb{F}_p\right)$ of order q for G_2 and a different cyclic subgroup of $E\left(\mathbb{F}_{p^6}\right)$ of the same order q for G_1 where $E\left(\mathbb{F}_{p^6}\right)$ denotes the group of points on an elliptic curve E over the finite field $\mathbb{F}_{p^6}$. The interested reader is referred to [3] for more information concerning elliptic curves and their use in pairing based cryptography. Details on Elliptic Curve Cryptography fall out of the scope of this thesis as it suffices to make abstraction of these concepts for the remainder of the text.

Recent research [9, 13, 71] has has shown that the discrete logarithm problem is easier in the symmetric setting because symmetric pairings rely on more structured supersingular (hyper)elliptic curves. Therefore, it is discouraged to rely on symmetric pairings in practical implementations [109].

2.5.2 Bilinear Diffie-Hellman Assumption

A bilinear map allows to solve the Decisional Diffie-Hellman problem in G_1 and G_2. The DDH problem in G_1 consists of distinguishing $\langle P, aP, bP, abP\rangle$ from $\langle P, aP, bP, cP\rangle$ where $P \in G_1$, P is a generator of G_1 and a, b, c randomly chosen in $\{1, \ldots, |G_1|\}$. Given a symmetric bilinear map $e : G_1 \times G_1 \to G_T$ a solution to this problem is found by relying on the bilinearity of the pairing as follows:

$$e\left(aP, bP\right) = e\left(P, P\right)^{ab} \overset{?}{=} e\left(P, cP\right) = e\left(P, P\right)^{c}$$

Such that the second equality will hold only if $ab = c$. A similar statement can be made concerning G_2 with the help of the map $e : G_2 \times G_2 \to G_T$. Consequently, G_1 and G_2 are both GDH groups. Since DDH (Definition 2.19) is a stronger assumption than CDH (Definition 2.18), CDH can still be hard in GDH groups [28].

Since DDH in the Gap groups G_1 and G_2 is easy, DDH can not serve as a basis for crypto systems in these groups. Therefore, an alternative to the CDH problem is defined called the Bilinear Diffie-Hellman problem.

In the definition that follows $\mathcal{G}\left(1^\lambda\right)$ is defined to be a BDH parameter generator as in [28], i.e. $\mathcal{G}$ takes as input a security parameter λ, $\mathcal{G}$ runs in polynomial time in λ and $\mathcal{G}$ outputs a prime number q, the description of two groups G_1, G_2 of order q and the description of an admissible bilinear map $e : G_1 \times G_2 \to G_T$.

Definition 2.22 (BDH). The *Bilinear Diffie-Hellman problem* is defined as follows. Given any admissible bilinear pairing $e : G_1 \times G_2 \to G_T$ with random $P, aP, bP \in G_1$ and random $Q, aQ, bQ \in G_2$ with uniformly chosen random independent elements $a, b, c \in \{1, \ldots, |G|\}$, find $e\left(P, Q\right)^{abc}$

The *Bilinear Diffie-Hellman assumption* holds if for any algorithm
$\mathcal{A}\left(P, aP, bP, Q, aQ, bQ\right)$ trying to solve the BDH problem there exists a negligible function $\mu\left(k\right)$ such that

$$\Pr\left[\mathcal{A}\left(P, aP, bP, Q, aQ, bQ\right) = e\left(P, Q\right)^{abc} \mid \langle q, G_1, G_2, e\rangle \leftarrow \mathcal{G}\left(1^\lambda\right)\right] \le \mu\left(\lambda\right)$$

where the probability is over the random choice of q, G_1, G_2, e according to the distribution induced by $\mathcal{G}\left(1^\lambda\right)$, the random choice of a, b in $\{1, \ldots, |G|\}$ and the random bits of the algorithm $\mathcal{A}$.

2.6 Cryptography

Cryptology is the science describing how to hide confidential information. Cryptology consists of two complementary fields that continuously try to outwit each other: cryptography and cryptanalysis. On the one hand, *cryptography* is the practice and study of techniques trying to hide information from undesired third parties. On the other hand, *cryptanalysis* is the domain of cryptology trying to derive information from hidden data.

2.6.1 Symmetric Cryptography

Figure 2.1 shows a typical cryptographic system often shortened to ”cryptosystem”. In a typical cryptosystem one party (often called Alice) tries to send a message m over an insecure channel to another party (often called Bob). The channel is insecure as third parties like Eve can eavesdrop on the channel to read out data that is being sent over.

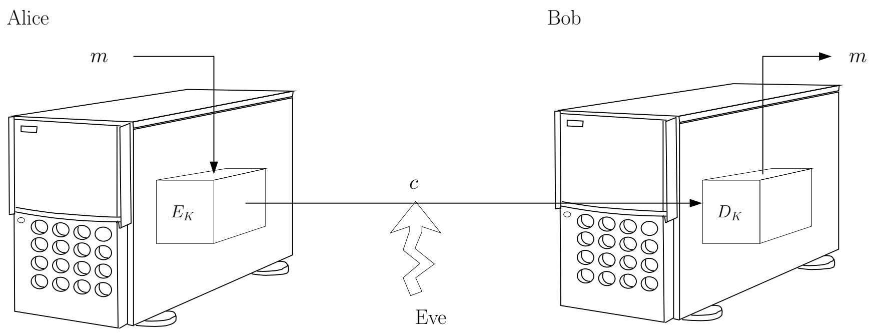


Figure 2.1: A cryptosystem [6]

Confidentiality

Figure 2.1 achieves confidentiality, i.e. the information in m is protected from disclosure to unauthorised parties. To prevent eavesdroppers from reading out the message m, Alice and Bob have agreed on a key k that is unknown to the outside world. Before sending a message m over the insecure channel, Alice encrypts the message m to a ciphertext c under the secret key k using an *encryption algorithm* E_k such that $c = E_k(m)$. Ideally c looks like random gibberish to eavesdroppers like Eve. Bob can then read out the original plaintext message m by applying the decryption algorithm D_k under the same key k. Cryptosystems as the one described in Figure 2.1 are called *symmetric* as both Alice and Bob have to use the same key k for encryption and decryption.

Most cryptosystems that are practically used today satisfy Kerchoff's principle [102]. Kerchoff's principle states that although the encryption and decryption mechanism are known to the outside world, the cryptosystem assures confidentiality as long as the symmetric key k remains secret.

One-time Pad

A simple symmetric encryption algorithm E_k could be to XOR the binary message m with a binary key k such that the ciphertext is equal to $c = m \oplus k$. Decryption D_k would then consist of an XOR operation with the same binary symmetric key k such that $m = c \oplus k = (m \oplus k) \oplus k$. In such a scheme, the key k should be a random binary string with the same length as the plaintext message m. This scheme was originally proposed by Vernam and is therefore often called the *Vernam scheme*.

Further research on the Vernam scheme by Mauborgne showed that the Vernam scheme can be proven information theoretic secure if k is chosen completely random and used only once. Because of these requirements on the key k, the Vernam scheme is more widely known as the *one-time pad*.

Practical Encryption Algorithms

Because the one-time pad is proven information theoretic secure, it can not be broken even if the adversary has access to unlimited computing power. Although this is a desirable property, the one-time pad is not frequently used in modern cryptosystems due to its impractical key management.

Suppose Alice and Bob have a lot of secret information to share. This would require that the a priori agreed key k is long enough to hide all this information. Once the size of the message m becomes larger than the key k, Alice and Bob should agree on new random bits in k to secure the remainder of their conversation. In fact, they have to agree upfront on as much random bits in k as there will be bits in the message m.

Because such large random symmetric keys k are not practical in real-life applications, block cipher modes and stream ciphers are widely used. These are algorithms that accept a fixed size symmetric key but allow to encrypt larger messages m by introducing deterministic pseudo randomness. As already mentioned in Section 2.4, these algorithms require a more pragmatic view on cryptography because they only ensure that disclosure of information is computationally difficult but not impossible. Common examples of block ciphers are AES and DES. They can be used in CFB, CTR or CFB mode to name a few. Stream ciphers include Trivium and RC4. For more information on block ciphers, stream ciphers and modes of operation the reader is referred to [87].

Authenticated Encryption

An authenticated encryption scheme consists of two generic probabilistic polynomial time algorithms:

`AE.Encrypt(`m, k`)`: Encrypt is a secure symmetric encryption scheme that takes as input a plaintext m, an additional binary sequence a and a symmetric key k. As a result `AE.Encrypt` generates ciphertext c and authentication tag t as output. Symbolically this is often denoted as $\langle c, t\rangle \leftarrow \mathtt{E}_k(m, a)$

`AE.Decrypt(`c, k`)`: Decrypt is a secure symmetric decryption scheme that takes as input a ciphertext c, an additional binary sequence a and a symmetric key k. As a result `AE.Decrypt` generates the original plaintext m and an authentication tag t as output. Symbolically this is often denoted as $\langle m, t\rangle \leftarrow \mathtt{D}_k(c, a)$

The properties of a secure authenticated encryption scheme are such that it is hard to change the plaintext message m, the additional binary sequence a, the symmetric key k or the ciphertext c without altering the returned authentication tag t. Therefore, a recipient of a ciphertext c and an authentication tag t_1 should only compare the returned authentication tag t_2 from $\langle m, t_2\rangle \leftarrow \mathtt{D}_k(c, a)$ with the received tag t_1 to be convinced that the ciphertext c was generate on input of the same symmetric key k, plaintext message m an binary sequence a. Since it is hard to alter the binary sequence a without changing the authentication tag t, a is often called the *authenticated data*, i.e. data that is authenticated by the encryption scheme but not encrypted.

2.6.2 Asymmetric Cryptography

The concept behind asymmetric cryptography is to use a different key for encryption than decryption, thereby making secure communication easier between parties who have never met before. A background on the basic concepts of traditional asymmetric cryptography allows to put the conclusions of this chapter into context.

Definition

In a *Public Key Infrastructure* (PKI) each entity A has a key pair $\langle pk_A, sk_A\rangle$ where pk_A and sk_A denote the public and the private key of entity A respectively. The public key is publicly available, while the private key often remains secret and only known by A. The domain of cryptography describing the concept of these key pairs is often called *asymmetric cryptography.*

In asymmetric cryptography, key pair generation is a two step process. In the first step, the private key sk is chosen uniformly random. In the second step, the public key pk is derived by applying a one-way function to sk. The one-way property of the applied function implies that it is computationally hard to derive the public key from the private key, e.g. in the ElGamal encryption scheme [55] the public key is calculated as $pk = g^{sk}$ in a group $\mathbb{Z}_p$ for some large prime p. As long as the DL assumption from Definition 2.17 holds it is infeasible to derive sk from pk.

The concept of two different keys enables a wide plethora of useful applications. Once all public keys of a PKI system are known, two entities who never met before can immediately setup secure communication by encrypting under the correct public keys. Asymmetric cryptography also enables these entities to authenticate their messages by relying on signature schemes. Authenticity of signatures then immediately follows from the privacy of sk.

Signature Schemes

A digital signature resembles a handwritten signature in that it proofs a particular person has approved a particular message. However, a digital signature is harder to forge than its handwritten counterpart due to the computational hardness assumptions digital signatures rely on. More specifically, a signature is a construction such that it can be checked with a public verifying key vk_A whether the signature was generated by the corresponding private signing key sk_A.

Definition 2.23 (Digital signature). A digital signature $S_A(m)$ associates a message m with a known sender A in such a way that a recipient B is ensured about the following properties:

1. *Authentication:* B can be certain that A is the sender of the message.
2. *Non-repudiation:* A can not deny having sent the message m.
3. *Integrity:* B can be certain that the message m is delivered consistently, i.e. unaltered from how A originally drafted the message m.

Algorithm 1 explains how a generic signature scheme is often constructed. Note that a signature scheme only shifts the authentication problem. Verification of a signature $S_A(m)$ only ensures the message m originated from the owner of the key pair $\langle sk_A, vk_A \rangle$.

Algorithm 1 Generic Signature Scheme

In a digital signature scheme each entity A has a publicly known verifying key vk_A and a corresponding private signing key sk_A. A generic signature scheme consists of two algorithms:

1. `Sign(`sk_A, m`)`: Entity A signs the message m using its private signing key sk_A resulting in a signature $S_{sk_A}(m)$
2. `Verify(`$pk_A, S_{sk_A}(m), m$`)`: Entity B verifies the signature $S_{sk_A}(m)$ with the public verifying key vk_A of A. The `Verify` step returns `true` or `false` depending on the validity of the signature.

Commitment Schemes

A commitment scheme is an asymmetric cryptographic scheme that allows to commit to a certain value while keeping the exact value private. The value can be revealed later giving anyone who received the commitment the possibility to check whether the value was changed between the commitment phase and the revealing of the value.

More formally, a generic commitment scheme is composed of three probabilistic polynomial time algorithms:

`CS.Setup`(1^λ): On input of a security parameter λ, generates the public parameters *params* of the system

`CS.Commit`$(params, m, r)$: Returns a commitment $c_{m,r}$ to a message m and a random binary sequence r.

`CS.Open`$(params, c_{m,r}, m', r')$: On input of public parameters *params*, a commitment $c_{m,r}$, a message m and a random binary sequence r it returns `true` if $c_{m,r} \leftarrow$`CS.Commit`$(params, m, r)$ with $m = m'$ and $r = r'$ and `false` otherwise.

For a more elaborate discussion on commitment schemes the reader is referred to the original paper from Brassard et al. [32].

2.6.3 Hash Functions

The concept of hash functions is required to further explain random oracles. Random oracles are a useful construction in proving certain cryptographic algorithms.

Definition

A *hash function* is a computationally efficient deterministic function mapping binary strings of arbitrary length to binary strings of some fixed length, called *hash-values*.

Cryptographic hash functions have the following desirable properties:

- *Computability:* Given a binary string m, the hash value h can be calculated efficiently $h = \texttt{hash}\,(m)$
- *Pre-image resistance:* Given a hash value h, it is infeasible to calculate a corresponding binary string m such that $h = \texttt{hash}\,(m)$
- *Second pre-image resistance:* Given a binary string m_1, it is hard to find a different binary string m_2 such that $\texttt{hash}\,(m_1) = \texttt{hash}\,(m_2)$
- *Strong collision resistance:* Given a `hash` function `hash(.)`, it is hard to find two different binary strings m_1 and m_2 such that $\texttt{hash}\,(m_1) = \texttt{hash}\,(m_2)$

Hash functions are useful for a wide variety of practical applications. For instance, hash functions serve as one way functions in password databases to relax sensitivity of the stored content. In addition, hash functions represent a valuable tool for data authentication and integrity checking. Another use of hash functions is in protocols involving a priori commitments. If the reader is new to the concept of hash functions, he is referred to [87] for an in depth discussion on the topic.

Random Oracles

A *random oracle* is a theoretical black box that returns for each unique query a uniformly random chosen result from its output domain. A random oracle is deterministic, i.e. given a particular input it will always produce the same output.

In a perfect world hash functions can be considered random oracles. That is, if hash functions were perfect, their output would look like perfect random bit sequences. Therefore, hash functions are often considered random oracles in security proofs. Such security proofs are said to be *proven secure in the random oracle model.* Proofs in the random oracle model first show that an algorithm is secure if a theoretical random oracle would be used. A next step of these security proofs is replacing the random oracle accesses by the computation of an appropriately chosen (hash) function h [19]. Algorithms that do not require such a construction in their security proof are said to be *proven secure in the standard model.*

Although theoretical definitions of random oracles and hash functions are quite similar, some practical implementations of hash functions do not behave like random oracles at all. Canetti at al. [35] show that there exist signature and encryption schemes that are secure in the Random Oracle Model, although any implementation of the random oracle results in insecure schemes [35]. Coron et al. counter these findings with indifferentiability, i.e. if a hash function is indifferentiable from a random oracle the random oracle can be replaced by the hash function while maintaining a valid security proof [42]. Therefore, it is a common belief that proofs in the random oracle model provide some evidence that a system is secure. Although research results from Coron et al. are debated in [51] and [92]. In fact, indifferentiability from random oracles certainly contributed to the victory of Keccak in the NIST hash function competition for a new SHA-3 hashing standard as all final round hashing algorithms supported this property [16].

2.7 Summary

Now the reader has knowledge of the mathematic fundaments, more advanced cryptographic constructions like identity-based encryption, broadcast encryption and distributed key generation are revealed in Chapter 3.

The first part of this chapter introduced the concepts of a negligible function as well as algebraic structures such as groups and finite fields. These basic notions were used further on to define number theoretic hard problems that serve as a basis for security. From the discrete logarithm assumption, several variants of the Diffie-Hellman problem were introduced, eventually leading to the Gap Diffie-Hellman assumption. The notion of the Gap Diffie-Hellman assumption allowed to uncover gap groups and their use in admissible bilinear maps. The Bilinear Diffie-Hellman assumption was defined as a computationally infeasible problem for the construction of cryptographic protocols relying on bilinear maps. Finally, this chapter concluded with differences between security under random oracle assumptions and security in the standard model.

Chapter

3 Literature Review

This chapter overviews cryptographic building blocks used to construct an encryption mechanism for online social networks. Thereby, a profound background of the existing literature, makes it easier to design the perfect encryption tool.

This chapter is organised as follows. An introduction is given to public key infrastructures and their drawbacks. In a next section, identity-based encryption (IBE) is proposed as a possible alternative to the existing public key infrastructures. An introduction is given to the basic concept of identity-based encryption, its drawbacks and advantages, the different security definitions and the evolution of IBE in literature. This is followed by an elaborate discussion on broadcast encryption (BE) and secret sharing. Finally, distributed key generation is described as a possible solution to the inherent key escrow problem of IBE.

3.1 Public Key Infrastructures

Section 2.6.2 already introduced the concept of a Public Key Infrastructure (PKI). However, PKI systems only shift the problem from trusting the users to trusting their keys. For example, if Eve could make the PKI system believe that her own public key pk_{Eve} actually represents the public key of Alice pk_{Alice}, Eve would be able to read all Alice's confidential communication as she obviously has the private key sk_{Eve} corresponding to pk_{Eve}. Therefore, it is important that public key systems rely on an architecture that authenticates whether keypairs belong to the claimed owner. In practice this is mostly achieved with the help of certification authorities or a web of trust.

3.1.1 Certification Authorities

In a traditional PKI system, all entities in the system trust a central party called the *Certification Authority* (CA). It is the CA that guarantees public keys belong to the claimed owner.

Suppose Alice wants to start using a key pair $\langle pk_A, sk_A \rangle$. She has to authenticate herself with the CA by correctly following a protocol that confirms Alice's identity. Once Alice is authenticated with the CA, Alice sends the public key pk_A to the CA along with a proof showing that Alice also owns the corresponding private key sk_A. This ”proof of correct possession” often takes the form of a signature $S_{sk_A}(pk_A)$ generated by the private key sk_A on the public key pk_A.

Once the CA is convinced of the authenticity of Alice’s public key, it distributes a certificate approving that pk_A effectively belongs to Alice. To avoid forged certificates, the CA signs Alice’s certificate with its private key sk_{CA}. Anyone doubting the authenticity of the public key pk_A can get convinced pk_A effectively belongs to Alice by checking the signature of the CA with the CA’s public key pk_{CA}.

In practice, CAs often approve the trustworthiness of other CAs by issuing certificates on their signing keys. In this way, often highly complex hierarchical architectures are achieved that boil down to the trust in one signing key of the highest authority. This puts heavy requirements on the CA’s infrastructure as a compromised CA signing key can break the system completely. Indeed, a compromised signing key would allow to sign certificates of unauthenticated public keys or even certificates of public keys that belong to malicious entities.

If an entity’s private key is lost or leaked to a third party, it can be revoked by the CA. CAs achieve this by periodic publication of *revocation lists*. These revocation lists contain all compromised public keys. Consequently, users relying on a PKI should always verify these continuously growing lists before trusting a keypair. Thereby, revocation lists not only make the system less transparent, they also impose high demands on the infrastructure of entities relying on the PKI.

To partially get around the issue of revocation lists, certificates contain an expiration date. After expiration, a certificate should no longer be trusted. However, this requires keypair owners to contact CAs more frequently to sign new certificates each time the previous one has expired. Clearly, this puts a high computational demand on the authentication procedure of the CAs as well.

3.1.2 OpenPGP and Web of Trust

An alternative to the traditional PKI setting relying on CAs is a *web of trust*. In a web of trust any entity can rate the trustworthiness of a public key. For example, if Bob receives Alice’s public key personally during a date, the public key can be considered more trustworthy than when Bob receives Alice’s key via e-mail. Web of trust systems allow users to vet for the authenticity other users’ keys in the system. A standardised web of trust system is OpenPGP [34].

The major advantage of a web of trust is that there no longer needs to be a CA with highly secure infrastructure as the publication of certificates now becomes a shared responsibility.

The system also has its drawbacks. Usability studies already have shown that non tech-savvy users have problems using PGP systems [105]. Furthermore, users are now required to judge for themselves whether they can trust a public key or not. This gives more responsibility to users than most of them can handle without proper knowledge of the consequences to their actions.

3.2 Identity-Based Encryption

Although architectures relying on CAs or webs of trust are common practice, they seem to have their drawbacks. However, recent research has uncovered a new paradigm with promising features called identity-based encryption.

Shamir [98] already proposed a first concept of identity-based cryptography in 1984. In identity-based cryptography any string can be a valid public key for encryption or signature schemes thereby eliminating the need for digital certificates. Identity-based cryptography proves to be particularly elegant if the public key is related to an attribute that uniquely identifies the identity of the user like an e-mail address, an IP address or a telephone number. Consequently, identity-based cryptography reduces system complexity and the cost for establishing and managing the Public Key Infrastructure (PKI) [11].

3.2.1 Definition

A generic Identity-Based Encryption (IBE) scheme is composed of four probabilistic polynomial time algorithms [28]:

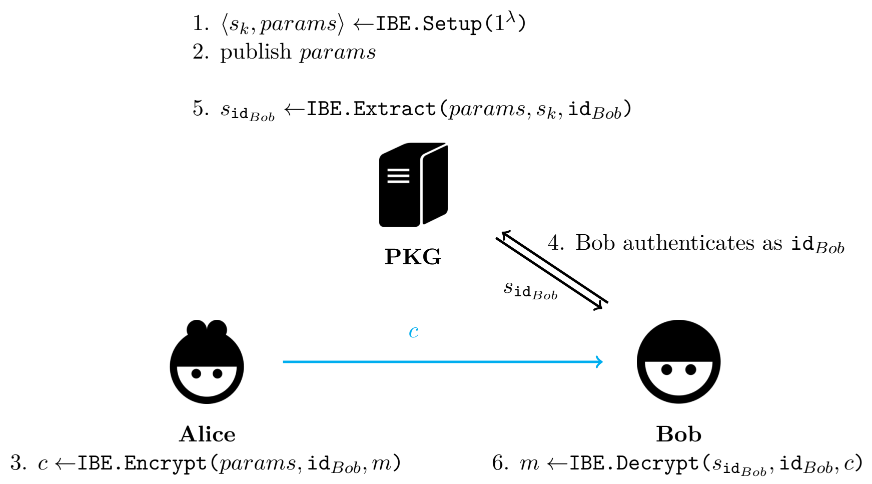
IBE.Setup(1^λ) On input of a security parameter λ, outputs a master secret s_k and public parameters *params*.

IBE.Extract($params, s_k, \mathtt{id}$)**:** Takes public parameters *params*, the master secret s_k, and an `id` as input and returns the private key $s_{\mathtt{id}}$ corresponding to the identity `id`.

IBE.Encrypt($params, \mathtt{id}, m$)**:** Returns the encryption c of the message m on the input of the public parameters *params*, the `id`, and the arbitrary length message m.

IBE.Decrypt($s_{\mathtt{id}}, c$)**:** Decrypts the ciphertext $c = \mathtt{IBE.Encrypt}(params, \mathtt{id}, m)$ back to the message m on input of the private key $s_{\mathtt{id}}$ corresponding to the receiving identity `id`.

Figure 3.1 illustrates these generic algorithms. A trusted Public Key Generator (PKG) generates a master private key s_k and public parameters *params* on input of the security parameter λ. Next, the PKG publishes the public parameters *params* while storing s_k preferably in encrypted format on a local disk. If Alice wants to send a message m to Bob, it suffices for her to know the public parameters *params* and the id $\mathtt{id}_{Bob}$, uniquely identifying Bob. Then, Alice encrypts the message to a ciphertext c that is sent over an insecure channel to Bob. On receipt of the ciphertext, Bob authenticates to the PKG over a secure channel to request his private key $s_{\mathtt{id}_{Bob}}$. Subsequently, the PKG generates the private key $s_{\mathtt{id}_{Bob}}$ corresponding to Bob's identity $\mathtt{id}_{Bob}$ on input of the master private key s_k, Bob's id $\mathtt{id}_{Bob}$ and public parameters *params*. Subsequently, the PKG sends $s_{\mathtt{id}_{Bob}}$ back again over a secure channel. Bob has now all the required information to decrypt the ciphertext c to its original plaintext message m.



1. $\langle s_k, params\rangle \leftarrow \texttt{IBE.Setup}(1^\lambda)$
2. publish $params$
5. $s_{\texttt{id}_{Bob}} \leftarrow \texttt{IBE.Extract}(params, s_k, \texttt{id}_{Bob})$
PKG
4. Bob authenticates as $\texttt{id}_{Bob}$
$s_{\texttt{id}_{Bob}}$
c
Alice
3. $c \leftarrow \texttt{IBE.Encrypt}(params, \texttt{id}_{Bob}, m)$
Bob
6. $m \leftarrow \texttt{IBE.Decrypt}(s_{\texttt{id}_{Bob}}, \texttt{id}_{Bob}, c)$

Figure 3.1: Generic identity-based encryption scheme. The blue arrow denotes an insecure channel that can be eavesdropped.

3.2.2 Pros and Cons of IBE

Note that it is important that the PKG can be fully trusted as it generates all the private keys $s_{\texttt{id}}$ in the system. A malicious PKG server could use this information to start eavesdropping on the insecure channel between Alice and Bob (the orange arrow in Figure 3.1) while decrypting all ciphertexts that are being sent over. The undesired property that private keys have to be shared with a trusted third party is often called *key escrow* in literature [8].

Another problem from the generic scheme shown in Figure 3.1 is that keys can not be revoked in the system. However, Bob's private key $s_{\texttt{id}_{Bob}}$ can still get compromised if he is careless with its storage. In fact, the research community has been focused on the revocation of IBE keys extensively [23, 27, 67, 79]. Key revocation often requires additional infrastructure that complicates the elegancy of the currently proposed IBE scheme. As a matter of fact, the major drawback of revoking Bobs key is that Bob can no longer receive encrypted messages because his public key is part of his identity. Therefore, a pragmatic solution to this issue could be to append expiration dates to the public keys. Consequently, public keys will only be valid for a limited amount of time thereby restricting the damage that could be done with a compromised private key [28].

IBE schemes have some desired properties as well. For starters, only one PKG suffices to realise the system, which relaxes expensive infrastructure requirements on the PKI. Furthermore, once the PKG has successfully delivered all the private keys in the system, it can go offline as the scheme does not require any future interactions between the PKG and the users in the system.

Another useful property of an IBE scheme is that Bob does not need to subscribe to a hierarchy of CAs neither a web of trust before Alice can start sending him messages. In this way, the possibility to send encrypted messages becomes inherently part of any system in which the users are assigned unique identifiers. This is particularly useful in systems where the majority of the users has no knowledge about cryptographic primitives. Users do no longer need to generate a key pair neither subscribe to a third party infrastructure. It suffices to recall how their connections can be uniquely identified in the system to know their public keys.

3.2.3 Security of IBE

Definitions of security are often subtle as different levels of security can be defined. In IBE *indistinguishability under chosen plaintext attack* (IND-CPA) and *indistinguishability under chosen ciphertext attack* (IND-CCA) are considered. Anonymity of the encryption scheme is an additional property of the scheme that is often desired [18].

Note that both the notion of IND-CPA, IND-CCA and anonymity are only introduced in an informal way in this section to give a basic understanding of these concepts to the reader. For a more formal description of IND-CPA and IND-CCA, the reader is referred to [28], whereas for a more formal description of ciphertext anonymity the reader is referred to [7].

Indistinguishability Under Chosen Plaintext Attack

Indistinguishability under chosen plaintext attack (IND-CPA) is described by the negligible advantage an adversary has in trying to distinguish which of both given plaintext messages m_0 and m_1 generated a ciphertext c. It captures the notion of *semantic security*, i.e. that any ciphertext c should not give more information about the original plaintext m than any other random binary string of the same length.

IND-CPA is best defined with the help of a game that challenges the adversary. If the adversary has negligible advantage trying to win the IND-CPA game in Game 2, the IBE system is said to be IND-CPA secure.

Indistinguishability Under Chosen Ciphertext Attack

Indistinguishability under chosen ciphertext (IND-CCA) is a more demanding level of security. Therefore, an algorithm that is IND-CCA secure is considered more secure than an IND-CPA secure algorithm. IND-CCA security means that an adversary has no advantage in trying to distinguish which of both given plaintext messages m_0 and m_1 generated a ciphertext c even if the adversary has access to a list of (plaintext, ciphertext)-tuples.

IND-CCA is defined with the help of a game that challenges an adversary similar to the IND-CPA game. Compared to the IND-CPA game, the IND-CCA game contains two additional steps in which the adversary gets access to another oracle. If the adversary has negligible advantage trying to win the IND-CCA game from Game 3, the IBE system is said to be IND-CCA secure.

In literature a distinction is often made between a *non-adaptive* case (IND-CCA1) and an *adaptive* case (IND-CCA2) of IND-CCA. In the non-adaptive case, step 6 from Game 3 is not allowed. More precisely, an IBE scheme that satisfies Game 3 is said to be IND-CCA2 secure.

Game 2 Generic IBE-IND-CPA Game [5]

Goal: An adversary is challenged by a game to check the IND-CPA security of an IBE scheme.

Result: This IBE-IND-CPA Game helps to define the concept of IND-CPA security for IBE schemes.

1. The challenger runs $\langle s_k, params \rangle \leftarrow \texttt{IBE.Setup(}1^\lambda\texttt{)}$ and returns $params$ to the adversary.
2. The adversary can start querying an oracle $O_{Extract}\,(\texttt{id}_i)$ that returns a private key $s_{\texttt{id}_i} \leftarrow \texttt{IBE.Extract(}params, s_k, \texttt{id)}$ corresponding to an adversary defined identity $\texttt{id}_i$.
3. The adversary picks two equal length plaintext messages m_0 and m_1 and an identity $\texttt{id}_{encrypt}$. The adversary honestly passes $\langle m_0, m_1, \texttt{id}_{encrypt} \rangle$ to the challenger.
4. The challenger picks a random bit b and executes $c \leftarrow \texttt{IBE.Encrypt(}params, \texttt{id}_{encrypt}, m_b\texttt{)}$. The challenger gives c to the adversary.
5. The adversary continues querying the oracle $O_{Extract}\,(\texttt{id}_i)$ adaptively.
6. The adversary outputs a bit b' based on the ciphertext c. If $b = b'$ the adversary wins the game. If $b \neq b'$ or if the adversary queried the oracle $O_{Extract}\,(\texttt{id}_i)$ with $\texttt{id}_i = \texttt{id}_{encrypt}$ during step 2 or step 5, the adversary loses the game.

Anonymous Identity-Based Encryption

An IBE scheme is called anonymous (ANO-IBE) when the ciphertext does not leak the identity of the recipient. In the overview illustrated in Figure 3.1, this implies that no eavesdropper on the insecure channel between Alice and Bob could derive that Bob is the recipient based on the information in the ciphertext c alone [31].

ANO-IBE is defined with the help of a game that challenges an adversary similar to the IND-CPA game. If the adversary has negligible advantage trying to win the ANO-IBE game in Game 4, the IBE system is said to be anonymous.

Gentry [57] presents the first scheme which combines the notions of IND-CPA and IND-CCA with ANO-IBE. Therefore, system is then said to be IND-ANO-CPA secure or IND-ANO-CCA secure if it satisfies a modified version of the game in Game 4. For a more detailed discussion on the topic the reader is referred to the original paper [57].

Game 3 Generic IBE-IND-CCA Game [5]

Goal: An adversary is challenged by a game to check the IND-CCA security of an IBE scheme.

Result: This IBE-IND-CCA Game helps to define the concept of IND-CPA security for IBE schemes.

1. The challenger runs $\langle s_k, params\rangle \leftarrow \texttt{IBE.Setup}(1^\lambda)$ and returns $params$ to the adversary.
2. The adversary can start querying an oracle $O_{Extract}(\texttt{id}_i)$ that returns a private key $s_{\texttt{id}_i} \leftarrow \texttt{IBE.Extract}(params, s_k, \texttt{id})$ corresponding to an adversary defined identity $\texttt{id}_i$.
3. The adversary can start querying another oracle $O_{Decrypt}(s_{\texttt{id}_i}, c_j)$ that returns a plaintext $m_j \leftarrow \texttt{IBE.Decrypt}(s_{\texttt{id}_i}, c_j)$ corresponding to an adversary defined ciphertext c_j and identity $\texttt{id}_i$.
4. The adversary picks two equal length plaintext messages m_0 and m_1 and an identity $\texttt{id}_{encrypt}$. The adversary honestly passes $\langle m_0, m_1, \texttt{id}_{encrypt}\rangle$ to the challenger.
5. The challenger picks a random bit b and executes $c \leftarrow \texttt{IBE.Encrypt}(params, \texttt{id}, m_b)$. The challenger gives c to the adversary.
6. The adversary continues querying the oracle $O_{Extract}(\texttt{id}_i)$ adaptively.
7. The adversary continues querying the oracle $O_{Decrypt}(s_{\texttt{id}_i}, c_j)$ adaptively.
8. The adversary outputs a bit b' based on the ciphertext c. If $b = b'$ the adversary wins the game. Otherwise, the adversary loses the game. If the adversary queried the oracle $O_{Extract}(\texttt{id}_i)$ with $\texttt{id}_i = \texttt{id}_{encrypt}$ during step 2 or step 6 or if the adversary queried the oracle $O_{Decrypt}(s_{\texttt{id}_i}, c_j)$ with $c_j = c$ during step 3 or step 7, the adversary loses the game as well.

Game 4 Generic ANO-IBE Game [5]

Goal: An adversary is challenged by a game to check the ANO-IBE security of an IBE scheme.

Result: This ANO-IBE Game helps to define the concept of ANO-IBE security for IBE schemes.

1. The challenger runs $\langle s_k, params\rangle \leftarrow \texttt{IBE.Setup(}1^\lambda\texttt{)}$ and returns $params$ to the adversary.
2. The adversary can start querying an oracle $O_{Extract}\,(\texttt{id}_i)$ that returns a private key $s_{\texttt{id}_i} \leftarrow \texttt{IBE.Extract(}params, s_k, \texttt{id}_i\texttt{)}$ corresponding to an adversary defined identity $\texttt{id}_i$.
3. The adversary picks a plaintext message m and an identity $\texttt{id}_{encrypt}$. The adversary honestly passes $\langle m, \texttt{id}_{encrypt}\rangle$ to the challenger.
4. The challenger picks a random bit b and computes $c \leftarrow \texttt{IBE.Encrypt(}params, \texttt{id}_{encrypt}, m\texttt{)}$ if $b = 0$. If $b = 1$, the challenger computes $c \leftarrow \texttt{IBE.Encrypt(}params, \texttt{id}_{encrypt}, r\texttt{)}$ where r is a random bit sequence with the same length as the message m. The challenger gives c to the adversary.
5. The adversary continues querying the oracle $O_{Extract}\,(\texttt{id}_i)$ adaptively.
6. The adversary outputs a bit b' based on the ciphertext c. If $b = b'$ the adversary wins the game. If $b \neq b'$ or if the adversary queried the oracle $O_{Extract}\,(\texttt{id}_i)$ with $\texttt{id}_i = \texttt{id}_{encrypt}$ during step 2 or step 5, the adversary loses the game.

3.2.4 Historical Overview on IBE

Although Shamir [98] easily constructed an identity-based signature scheme based on RSA in 1984, the use case of IBE remained an open problem until the introduction of bilinear maps. Boneh and Franklin [28] proposed the first practically usable IBE scheme based on the Weil pairing, however, the security proof still relies on the random oracle assumption. At the same time, Sakai and Kasahara [90] proposed a different IBE scheme independently from Boneh and Franklin. The scheme from Sakai and Kasahara initially received less attention though, because the original presentation is in Japanese and lacking a security proof. Subsequently, Sakai and Kasahara [95] proposed an extended version of their original scheme which is proven to be IND-CCA secure in the random oracle model by Chen et al. [39]

Canetti et al. [36] introduced the first secure IBE scheme without relying on the random oracle model. Nevertheless, the attacker model in [36] requires the adversary to declare upfront which identity `id` is targeted during step 5 of the CCA Game (Algorithm 3) and step 4 of the CPA Game. Therefore, the scheme by Boneh and Franklin [28] is considered more secure as attackers can adaptively choose the targeted identity. Later, Boneh and Boyen [25] presented a variant to [36] which also realises only selective ID security.

Waters [103] is the first to present a scheme that is IND-CCA secure in the standard model. Drawback of the scheme from Waters [103] is that it requires large public parameters. Gentry [57] proposes a more efficient alternative to this scheme in the standard model while achieving shorter public parameters. However, the scheme from Gentry relies on a complicated hardness assumption called q-BDHE. It is only after the introduction of the Dual System paradigm by Waters [104] in 2009 that IND-CCA security can be achieved in the standard model based on reasonable assumptions. De Caro et al. [38] are the first to define an IND-ANO-CCA secure IBE scheme on the Dual System construction of Waters [104].

Although all these contributions were a step forward in the evolution of IBE, not all of these schemes are ANO-IBE. Most IBE systems in the random oracle model can be proven anonymous. Therefore, the IBE scheme from Boneh and Franklin [28] is IND-ANO-CCA secure. In the standard model, it appeared to be harder to construct ANO-IBE schemes at first sight, e.g. it can be proven that the scheme from Boneh and Boyen [25] is not anonymous in its original form. The scheme from Gentry [57] was the first anonymous IBE scheme in the standard model. Boyen and Waters [31] published almost synchronously another IBE scheme in the standard model that is also IND-ANO-CCA secure. In 2010, Ducas [47] showed that even schemes that were first considered not anonymous like the one from Boneh and Boyen [25] but also [26, 103] can be proven anonymous when relying on asymmetric pairings thereby making anonymity a more common property in IBE schemes.

3.2.5 Most Attractive IBE Schemes

In the standard model mainly the anonymous IBE constructions from Gentry [57] and De Caro et al. [38] have the most satisfying properties. However, IBE constructions in the standard model often come at the cost of higher computational requirements [30]. Certainly the scheme from De Caro demands a higher amount of computational resources since it relies on composite order groups. Although methods [52, 76] have been developed to convert IBE schemes from composite order groups to single order prime groups, these methods do not apply to the scheme from De Caro et al. [75]

From all schemes discussed in Section 3.2.4 the ones initially developed by Boneh and Franklin [28] and Sakai and Kasahara [95] are the most attractive ones in the random oracle model because of their anonymity and non-selective security. Consequently, it is not a coincidence that both schemes have found description in an informational RFC document. Sakai and Kasahara IBE is described in RFC 6508 [64] and RFC 6509 [63]. Boneh and Franklin IBE can be found in RFC 5409 [82].

Because the ANO-IND-CPA secure scheme and the ANO-IND-CCA secure scheme from Boneh an Franklin [28] are important for the remainder of this text, they are both included in Algorithm 5 and Algorithm 6 respectively.

Algorithm 5 IND-ANO-CPA Boneh and Franklin IBE [28]

Goal: Alice wants to send an IBE encrypted message to Bob.

Result: Alice sends an IBE encrypted ciphertext c that is successfully decrypted by Bob.

1. `Setup`(1^λ): Let λ be the security parameter for a security level of l bits.
   a) Execute setup algorithm $\langle q, G_1, G_2, e : G_1 \times G_2 \to G_T, P \in G_1 \rangle \leftarrow \mathcal{G}\left(1^\lambda\right)$ to generate the parameters
      i. A large prime q
      ii. Gap groups G_1 and G_2 of order q
      iii. An admissible bilinear map $e : G_1 \times G_2 \to G_T$
      iv. A random generator $P \in G_1$
   b) Choose a uniformly random $s_k \in \mathbb{Z}_q^*$ and calculate
   $$P_{pub} = s_k P$$
   c) Choose cryptographic hash functions
      i. $H_1 : \{0,1\}^* \to G_1$
      ii. $H_2 : G_2 \to \{0,1\}^l$
2. `Extract`$(params, s_k, \texttt{id})$:
   a) Compute $Q_{\texttt{id}} = H_1(\texttt{id}) \in G_1$
   b) Set the private key of `id` to $s_{\texttt{id}} = s_k Q_{\texttt{id}}$
3. `Encrypt`$(params, \texttt{id}, m)$:
   a) Compute $Q_{\texttt{id}} = H_1(\texttt{id})$
   b) Choose a random $r \in Z_q$
   c) Encrypt the plaintext message m to the ciphertext c as
   $$c = \left\langle rP, m \oplus H_2\left(g_{\texttt{id}^r}\right)\right\rangle = \langle U, v \rangle \quad \text{with} \quad g_{\texttt{id}} = e\left(Q_{\texttt{id}}, P_{pub}\right) \in G_T$$
4. `Decrypt`$(s_{\texttt{id}}, c)$: Decrypt the ciphertext c back to the plaintext message m as
$$m = v \oplus H_2\left(e\left(s_{\texttt{id}}, U\right)\right)$$

Algorithm 6 IND-ANO-CCA Boneh and Franklin IBE [28]

Goal: Alice wants to send an IBE encrypted message to Bob.

Result: Alice sends an IBE encrypted ciphertext c that is successfully decrypted by Bob.

1. `Setup(`1^λ`)`:
    a) As in the BasicIndent scheme
    b) As in the BasicIndent scheme
    c) Choose cryptographic hash functions
        i. $H_1 : \{0,1\}^* \to G_1$
        ii. $H_2 : G_2 \to \{0,1\}^l$
        iii. $H_3 : \{0,1\}^l \to (0,1)^l$
2. `Extract(`$params, s_k,$ `id`$)$: As in the BasicIndent scheme
3. `Encrypt(`$params,$ `id`$, m$`)`:
    a) Compute $Q_{\texttt{id}} = H_1\{\texttt{id}\}$
    b) Choose a random $sigma \in (0,1)^l$
    c) Compute $r = H_3\{sigma, m\}$
    d) Encrypt the plaintext message m to the ciphertext c as

$$c = \langle rP, sigma \oplus H_2\left(g_{\texttt{id}}^r\right), m \oplus H_3\left(sigma\right)\rangle = \langle U, v, w\rangle$$
$$\text{with } g_{\texttt{id}} = e\left(Q_{\texttt{id}}, P_pub\right) \in G_T$$

4. `Decrypt(`$s_{\texttt{id}}, c$`)`: Decrypt the ciphertext c back to the plaintext message m as follows
    a) Compute $sigma = v \oplus H_2\left(e\left(s_{\texttt{id}}, U\right)\right)$
    b) Compute $m = w \oplus H_3\left(sigma\right)$
    c) Set $r = H_3\left(sigma, m\right)$. Test that $U = rP$. If not, reject the ciphertext.
    d) Output m as the decryption of c

3.3 Broadcast Encryption

Another relevant aspect of encryption in OSNs is how one encrypted message can be securely broadcasted to multiple users. Broadcast encryption (BE) was introduced by Fiat and Naor [50], as a public-key generalisation to a multi user setting. A BE scheme allows a user to encrypt a message m to a subset $\mathcal{S}$ of users in a public key system, such that, only users in the set $\mathcal{S}$ are able to decrypt the message. The computational overhead of BE is generally bound to the ciphertext and the number of recipients.

3.3.1 Definition

A generic Broadcast Encryption (BE) scheme is composed of four probabilistic polynomial time algorithms:

BE.Setup(1^λ) : On input of a security parameter λ, generates the public parameters $params$ of the system.

BE.KeyGen$(params)$: Returns the public and private key (pk_i, sk_i) for each user i while taking the public parameters $params$ into account.

BE.Encrypt$(m, \mathcal{S})$: Takes a set of public key values $\mathcal{S} = \{pk_i \dots pk_{|\mathcal{S}|}\}$ corresponding to users i in the system along with a plaintext message m to generate a corresponding ciphertext c.

BE.Decrypt(c, sk_i)**:** Reconstructs m from c using the private key sk_i if the corresponding public key $pk_i \in \mathcal{S}$. Otherwise, return $\perp$.

Note that this definition is stated generically enough to allow all kinds of public keys to be used. Therefore, not only traditional PKIs can benefit from BE schemes, but also IBE schemes in which a public identifier $\texttt{id}_i$ serves as a public key pk_i.

3.3.2 Historical Overview on Broadcast Encryption

The problem of BE has been widely studied in literature since its first introduction by Fiat and Naor [50]. This section highlights the most important evolutions of BE in literature. The summary that follows is far from complete as it only considers publications that are relevant to our final goal: achieving user-friendly broadcast encryption for OSNs.

Broadcast Encryption

The implementation from Fiat and Naor [50] requires a ciphertext of size $O\left(t \log^2 t \log n\right)$ to be secure against t colluding users. The first fully collusion resistant scheme was proposed in [88] by Naor et al. thereby making the ciphertext size independent of the number of colluding users. A collusion resistant BE scheme refers to a broadcast encryption scheme that is secure even if all users that are not in the recipient set

$\mathcal{S}$ would collaborate. Halevy and Shamir further reduce the required ciphertext length for collusion resistant schemes in [66]. It is the first paper in a series of many [46, 62, 77] that achieves ciphertext sizes only dependent on the number of revoked users $O(r)$. Boneh, Gentry and Waters [26] are the first to consider utilisation of bilinear maps to realise constant size ciphertexts and $O(n)$ public keys.

Identity-Based Broadcast Encryption

Sakai and Furukawa are the first to define a collusion resistant identity based broadcast encryption (IBBE) scheme in [94]. Independently from [94] Delerablée realises a similar IBBE scheme and claims to be the first as well in [44]. The size of the public key in both [94] and [44] is proportional to the maximum size of the intended set of recipients while realising short ciphertexts and private keys.

Baek et al. [11] define an IBBE scheme that requires only one pairing computation. The scheme in [11] is proven secure under the random oracle assumption where the attacker ties himself to a selective-ID attack. Gentry and Waters achieve identity based broadcast encryption with sublinear ciphertexts in [58]. Their scheme is proven secure against a stronger notion of adaptive security where the attacker can adaptively alter its queries depending on earlier received information. Barbosa and Farshim [12] proposed an identity-based key encapsulation scheme for multiple parties which is an extension of *mKEM* as considered by Smart [100] to the identity-based setting. An mKEM is a Key Encapsulation Mechanism which takes multiple public keys as input. An encrypted message under mKEM consists of an encapsulated session key k and a symmetric encryption $E_k(m)$ of the plaintext message m under k. However, the scheme from Smart [100] is only proven secure under the random oracle assumption.

Anonymous Broadcast Encryption

All earlier mentioned references describing BE require the intended set of recipients to be published to realise higher efficiency. Barth, Boneh and Waters [15] are the first to design a BE scheme that takes the anonymity of the recipient into account. The proposed anonymous broadcast encryption (ANOBE) scheme imposes a linear dependency of the ciphertext on the number of recipients and can only be proven secure in the random oracle model. In [78] Libert et al., propose an alternative ANOBE scheme that is proven secure in the standard model. Both [15] and [78] propose a tag based system that allows efficient decryption at the cost of making the public master key linear dependent on the total number of users. Krzywiekci et al. [74] propose a scheme that is proportional to the number of revoked users, although the security proof is rather informal. In [108], Yu et al. design an architecture that even hides the number of users in the recipient set using Attribute Based Encryption (ABE) [93]. [48]

However, ABE requires that all users are assigned attributes such that all users who have sufficient attributes in common can decrypt the message. In networks where the total number of users is large it can be a work intensive task to label each user with the correct attributes.

Outsider-Anonymous Broadcast Encryption

Fazio and Perera introduce the notion of outsider anonymous broadcast encryption in [48]. The scheme relies on IBE to encode where a recipient is positioned in a publicly published tree to achieve sublinear ciphertexts. It is remarkable that sublinear ciphertexts are achieved while attaining recipient anonymity to all users that are outside the intended set of receivers. However, the scheme has the drawback of immediately fixing the total number of users that are allowed in the system. Furthermore, an additional architecture is required to maintain the tree of subscribed users. Finally, although IBE is used, the scheme does not allow to represent public keys of users by their public identifiers because the public key needs to be the position of a user in the tree structure of the external architecture. In this way, most of the desirable properties of IBE cancel out.

Although the scheme from Fazio and Perera does not fit the requirements for user-friendly broadcast-encryption in OSNs, it is useful to remember their definition of outsider-anonymity.

Definition 3.1 (Outsider Anonymity). A BE scheme is called *outsider anonymous* if the identities of the recipients are known to the other identities in the recipient set $\mathcal{S}$ while remaining secret to other parties of the BE scheme.

3.3.3 Most Attractive BE Schemes

From all schemes discussed in Section 3.2.4 mainly the scheme from Libert et al. [79] has the most attractive properties as it is proven secure in the standard model at almost no reduced computational efficiency. The scheme supports anonymity in both identity-based BE as well as traditional asymmetric cryptosystems.

If anonymity is not an issue, different BE schemes have to be considered depending on the goals of the target application. The scheme from Libert et al. [78] will certainly not have the most desirable properties in non-anonymous BE environments since it can not benefit from higher efficiency due to the recipient being publicly known.

3.4 Secret Sharing

In earlier paragraphs of this chapter, identity-based encryption was already explored as a possible alternative to traditional public key infrastructures. IBE mainly profits from a less complex architecture and increased ease of usability. Nevertheless, the major drawback of IBE seems to be the inherent key escrow property. In order to get around this issue, distributed key generation seems a promising solution. However, before diving into distributed key generation protocols, some knowledge on secret sharing is appropriate.

3.4.1 Definition

Definition 3.2 (Secret Sharing Scheme). A *Secret Sharing Scheme* is a cryptographic scheme that divides a secret S into n pieces of data $S_1, \ldots, S_n$ called *shares.*

Shares are distributed over n different parties called *shareholders* such that only specific subsets of the distributed shares allow reconstruction of the original secret S.

Definition 3.3 (Threshold scheme). A (t,n) *threshold scheme* $(t \leq n)$ is a secret sharing scheme by which a trusted party securely distributes n different shares S_i to n different parties P_i for $1 \leq i \leq n$ such that any subset of t or more different shares S_i easily allows to reconstruct the original secret S. Knowledge of $t-1$ or less shares is insufficient to reconstruct the original secret S.

Definition 3.4 (Perfect threshold scheme). A (t,n) threshold scheme is said to be *perfect* if no subset of fewer than t shareholders can derive any partial information in the information theoretic sense about the original secret S even with infinite computational resources.

3.4.2 Shamir Secret Sharing

In 1979, both Shamir [97] and Blakley [22] independently proposed an algorithm achieving perfect threshold secret sharing. Shamir's solution was based on polynomial interpolation while Blakley's algorithm relied on finite geometries. Blakley secret sharing uses more bits than necessary as it describes multidimensional planes. In contrast, Shamir secret sharing requires as many bits for each share as the length of the original secret. Therefore Shamir secret sharing has gained more popularity in both research communities and in practical implementations.

The idea behind Shamir secret sharing is elegant in its simplicity. Any polynomial $f(x)$ of degree $t-1$ is uniquely defined by t points lying on the polynomial. For example, it is possible to draw only one straight line between 2 different coordinates, a quadratic is fully defined by 3 different coordinates and so on. If the trusted party randomly generates a polynomial of degree $t-1$ it suffices to securely distribute one of n different coordinates on the curve to each party $P_i, 0 \leq i \leq n$. A subset of at least t different shareholders has to collaborate in order to reconstruct the original polynomial by interpolation. For security reasons the polynomial $f(x)$ is calculated in a finite field modulo a large prime number p. The complete mechanism of Shamir's threshold scheme can be found in Algorithm 7. The mechanism behind reconstruction in Algorithm 7 is explained because the coefficients of an unknown polynomial $f(x)$ of degree less than t, defined by points $(x_i, y_i), 1 \leq i \leq t$ are given by the Lagrange interpolation formula

$$f(x) = \sum_{i=1}^{t} y_i b_i \quad \text{with} \quad b_i = \prod_{1 \leq j \leq t, j \neq i} \frac{x - x_j}{x_i - x_j}$$

A proof of this formula is omitted but can be found in [106].

3.4.3 Verifiable Secret Sharing

Verifiable secret sharing [41] tries to ensure the participating parties that their received shares are consistent by providing a verification mechanism. This verification

Algorithm 7 Shamir's (t, n) threshold scheme [87]

Goal: A dealer D distributes shares of a secret s to n parties.

Result: If a subset of at least t out of n shareholders collaborates, they can reconstruct the original secret s.

1. *Setup* A dealer D begins with a secret integer $s \geq 0$ it wishes to distribute among n parties
   a) D chooses a prime $p > \max(s, n)$ and defines $a_0 = s$
   b) D selects $t-1$ random, independent coefficients $a_1, \ldots, a_{t-1}, 0 \leq a_j \leq p-1$ defining the random polynomial over $\mathbb{Z}_p$, $f(x) = \sum_{j=0}^{t-1} a_j x^j$
   c) D computes $\sigma_i = f(i) \bmod p, 1 \leq i \leq n$ and securely transfers the share σ_i to shareholder P_i, along with a public index i.
2. *Reconstruction* Any group of t or more shareholders pool their shares. Their shares provide t distinct points $(x, y) = (i, \sigma_i)$ allowing computation of the coefficients $a_j, 1 \leq j \leq t-1$ of $f(x)$ by Lagrange interpolation. The secret is recovered by calculating

$$f(0) = \sum_{i=1}^{t} y_i b_i = s \quad \text{with} \quad b_i = \prod_{1 \leq j \leq t, j \neq i} \frac{j}{j-i}$$

mechanism can either detect an unfair dealer during setup or participants submitting incorrect shares during the reconstruction phase. The first verifiable secret sharing schemes were *interactive*, i.e. interaction between shareholders and the trusted party was required to verify their shares. In *non-interactive verifiable secret sharing* only the trusted party is allowed to send messages to the future shareholders. Shareholders can not communicate with each other neither can they send messages back to the trusted party. Non-interactive verifiable secret sharing is preferred over interactive alternatives as their is no chance of shareholders accidentally leaking too much information.

Popular verifiable secret sharing schemes are Feldman's scheme [49] and Benaloh's scheme [20]. No further details are given as a basic notion of verifiable secret sharing suffices for the remainder of this text.

3.5 Distributed Key Generation

Distributed key generation is inspired on secret sharing. The idea behind distributed key generation is that a secret s can be shared among n shareholders without the requirement for a centralised dealer D as in Algorithm 7. In this way, a secret can be negotiated between all shareholders without any of the shareholders explicitly computing the secret. The major advantage of such a scheme is that no party in the scheme requires a higher level of trust since no party explicitly knows the secret. Similarly to the Shamir secret sharing scheme a group of t or more shareholders will need to pool their shares in order to reconstruct the secret s.

3.5.1 Definition

Definition 3.5 (Distributed key generation scheme). A *distributed key generation scheme* is a (t, n) perfect threshold scheme ($t \leq n$) that requires no trusted party. That is, a distributed key generation scheme is a cryptographic scheme that negotiates a secret s with n different parties $P_1, \ldots, P_n$ by letting each party P_i distribute shares s_{ij} of its own private secret s_i with all other parties P_i where $1 \leq i \leq n, 1 \leq j \leq n$. At least t out of n parties will need to collude in order to compute the original secret s explicitly.

3.5.2 Pedersen Distributed Key Generation

The first usable distributed key generation protocol was defined by Pedersen [89]. A later publication from Gennaro et al. [56] proves the Pedersen scheme to be insecure in its original form in the presence of malicious key generation centers.

Although the Pedersen scheme [89] is proven insecure, it is most instructive to describe the protocol in its original form as later schemes like the one from Gennaro [56] extensively rely on the same concepts. Therefore, the original Pedersen protocol is shown in Algorithm 8. TODO for Algorithm 8: Complete it after fully understanding it

Algorithm 8 Pedersen's distributed key generation [89]

Goal: A secret s is negotiated with n uniquely numbered parties $\{P_1, \ldots, P_n\}$ without any of the parties explicitly computing the secret s.

Result: If a subset of at least t out of n parties colludes, they can reconstruct the original secret s.

1. *Setup* At initialisation, a setup algorithm $\langle p, g \rangle \leftarrow \mathcal{G}\left(1^{\lambda}\right)$ is executed that returns a large prime number p and a generator g of $\mathbb{Z}_p$ on input of a security parameter λ. After execution of $\mathcal{G}\left(1^{\lambda}\right)$ each party $P_i, 1 \leq i \leq n$ should do the following:

    a) P_i generates a random private key $s_i \in \mathbb{Z}_p$ and publishes the corresponding public key $pk_i = g^{s_i}$

    b) P_i chooses $t-1$ random independent coefficients $a_{i,1}, \ldots, a_{i,t-1}, 0 \leq a_{i,j} \leq p-1$ defining a random polynomial $f_i(x)$ over $\mathbb{Z}_p$, $f_i(x) = \sum_{b=0}^{t-1} a_{i,j} x^b$.

    c) P_i commits to the coefficients $a_{i,1}, \ldots, a_{i,t-1}, 0 \leq a_{i,j} \leq p-1$ by broadcasting $A_{ib} = g^{a_{i,b}} \bmod p$ for $b = 1, \ldots, t$ to all other parties.

    d) P_i computes the share $\sigma_{ij} = f_i(j) \bmod p$ and securely transfers the share σ_{ij} to party P_j along with a signature $S_{P_i}(\sigma_{ij})$ authenticating the share. P_i keeps σ_{ii} to itself.

    e) P_i verifies for each share σ_{ji} received from P_j whether it is consistent by verifying that

    $$g^{\sigma_{ji}} = \prod_{b=0}^{n-1} (A_{jb})^{i^k} \bmod p$$

    If the check fails for an index j, P_i broadcasts a complaint against P_j along with the received share σ_{ij} and its signature $S_{P_j}(\sigma_{ij})$. If a party receives t complaints, he is excluded from the set of participating parties $\mathcal{Q}$.

2. *Reconstruction* Any group of t or more shareholders pool their shares. Their shares provide t distinct points $(x, y) = (i, s_i)$ allowing computation of the coefficients $a_j, 1 \leq j \leq t-1$ of $f(x)$ by Lagrange interpolation. The secret is recovered by calculating

$$f(0) = \sum_{i=1}^{t} y_i \prod_{1 \leq j \leq t, j \neq i} \frac{x_j}{x_j - x_i} = s$$

Chapter

4 Design of a Practical Encryption Scheme for Online Social Networks

4.1 Online Social Network

OSNs are getting more and more aware of the rising privacy concerns among their users. Therefore, most OSN services like Google+ and Facebook try to offer preferences that allow the user to determine their privacy up to a certain extent. In practice, most OSNs realise this by offering user specified groups of friends that can be selected when broadcasting a message. The OSN provider then ensures that the broadcasted message is only available to members inside the user specified group. However, these methods are insufficient for most privacy aware users.

4.1.1 Definition

The most commonly accepted definition of an *Online Social Network* (OSN) in literature is from Boyd et al. [29]. However, since this definition is still too generic for the remainder of this text a slightly modified version is presented here.

Definition 4.1 (Online Social Network [29]). An *online social network* (OSN) is a web-based service that allows individuals to:

1. Construct a public or semi-public profile within a bounded system
2. Articulate a list of other users with whom they share a connection.
3. View and traverse their list of connections and those made by others within the system
4. Distribute messages to anyone visiting the system, any user of the system or subsets thereof

4.1.2 Model of Current OSN Situation

Definition 4.2 (OSN user). An *OSN user* U is any entity that has a profile on the OSN and thus identifiable by a unique identifier $\texttt{id}_U$. The set containing all users of an OSN is denoted $\mathcal{U}$.

An OSN user can perform different activities within the infrastructure of the OSN. Depending on the performed activity, the user is labeled as one of three different roles: a sender, a friend or a recipient.

Definition 4.3 (Sender). A *sender* A is an OSN user who broadcasts a message m over the OSN infrastructure to varying subsets of OSN users, called the *intended recipient set* $\mathcal{S}$ such that $\mathcal{S} \subseteq \mathcal{U}$.

Definition 4.4 (Intended recipient). An *intended recipient* of a message m is an OSN user who is explicitly designated by a sender A to be part of the intended recipient set $\mathcal{S}$ of that message m. The intended recipient set $\mathcal{S}$ takes the form of a list of `id`'s uniquely identifying other users' profiles in the OSN infrastructure.

Definition 4.5 (Friend). An OSN user who shares a connection with another OSN user U in the OSN infrastructure, is called a *friend of the user* U. The set of all friends associated to a user U is denoted $\mathcal{F}_U$ such that $\mathcal{F}_U \subseteq \mathcal{U}$.

Currently, other entities than OSN users $U \in \mathcal{U}$ associated with a profile $\texttt{id}_U$, can access the OSN services as well. If abstraction is made of entities with access to specific content, it suffices to define a set of *viewers*.

Definition 4.6 (Viewer). Any entity that is given access to the OSN belongs to the set of viewers $\mathcal{V}$. All viewers with access to non-public content of a profile $\texttt{id}_U$ of a user U are in the set $\mathcal{V}_U \subseteq \mathcal{V}$.

Many different entities can be part of the set $\mathcal{V}$, i.e. OSN users, advertising companies, system administrators of the OSN, software applications specifically developed for the OSN, ... Usually, the OSN determines who is part of $\mathcal{V}$. Therefore, a user U often has no control in who is a member of $\mathcal{V}_U$.

Following the example illustrated by Figure 4.1, Sender A wants to broadcast a message m over the OSN infrastructure to the intended recipient set $\mathcal{S}$. As A only wants to share the message with a specific group of friends, A defines the intended recipient set such that $\mathcal{S} \subset \mathcal{F}_B$. Next, A sends m to the OSN's distribution server along with the intended recipient set $\mathcal{S}$. The OSN Server further distributes the message to all users in $\mathcal{S}$. Also a subset of third party applications and advertisers get access to the distributed message if they are inside the viewers group $\mathcal{V}_B$. Every entity who has access to the message is coloured blue in Figure 4.1.

Figure 4.1 illustrates previous definitions applied to an OSN as it is often encountered on the internet. The different sets in Figure 4.1 are defined as follows:

- The intended recipient set,

$$\mathcal{S} = \{\text{Recipient 1}, \text{Recipient 2}\}$$

- The set of friends of user B,

$$\mathcal{F}_B = \{\mathcal{S}, \text{Friend 1}, \text{Friend 2}\}$$

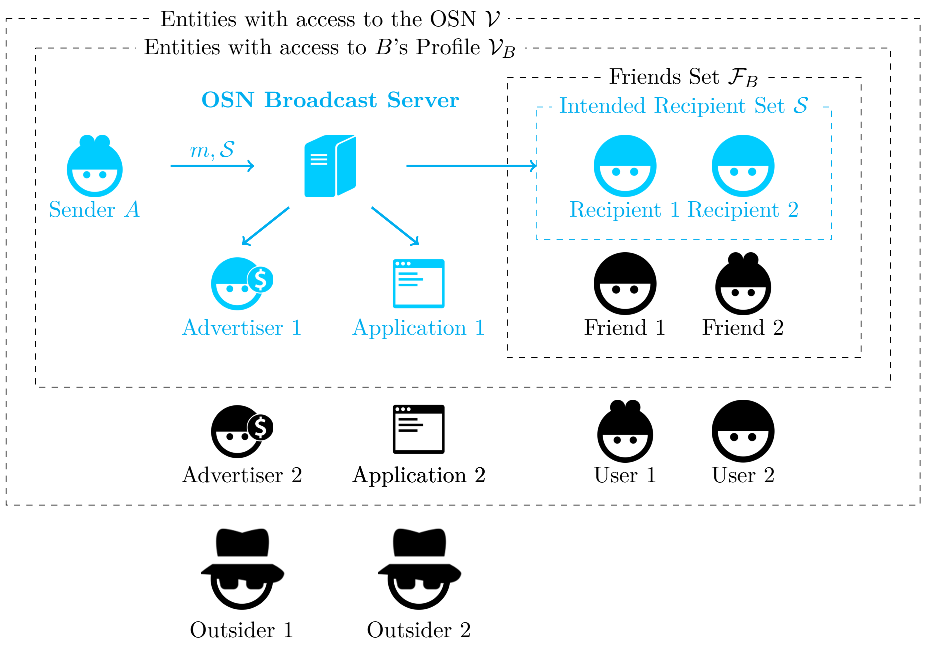


Figure 4.1: Model of the current OSN situation. Entities with access to the message m are coloured blue.

- The set of viewers who have access to the profile of user B,

$$\mathcal{V}_B = \{\mathcal{F}_B, \text{Sender } A, \text{Advertiser 1}, \text{Application 1}\}$$

- The set of entities with access to the OSN,

$$\mathcal{V} = \{\mathcal{V}_B, \text{User 1}, \text{User 2}, \text{Advertiser 2}, \text{Application 2}\}$$

- The set of all users in the OSN,

$$\mathcal{U} = \{\mathcal{F}_B, \text{Sender} A, \text{User 1}, \text{User 2}\}$$

The OSN's infrastructure stores almost everything within the viewer set $\mathcal{V}$. The profiles of all users within the friends set $\mathcal{F}_B$, the list of `id`'s within the intended recipient set $\mathcal{S}$, access rights of applications and advertisers that are part of $\mathcal{V}_B$ and access rights of entities within the set $\mathcal{V}$ are all explicitly stored somewhere on the servers of the OSN.

Note that not all OSNs support the functionality to define intended recipient sets $\mathcal{S}$ on a per message basis. In OSNs like Twitter the standard privacy settings are such that message are always published publicly. Therefore, the model from Figure 4.1 only holds for a specific subset of OSNs like Facebook or Google+. More public OSNs like Twitter would require less sets of entities to model their behaviour.

It requires almost no additional effort to transform the model from Figure 4.1 such that it also takes the sharing of other media than messages into account. The model could then adopted for use on SNSs like Youtube or Instagram as well. However, this falls out of the scope of this thesis.

4.2 Issues with Current OSN Situation

There are several issues with the current OSN situation as modelled in Figure 4.1.

First, there is a clear mismatch between the expectations of Sender B and the functionality of the OSN. When a privacy-aware user like sender B takes the effort to define an intended recipient set $\mathcal{S}$, she expects to have full control on who has access to her messages m. In reality, sender B only has partial control since the OSN determines all other entities in $\mathcal{V}_B$ that are not part of sender B's friend list $\mathcal{F}_B$. In some OSNs a user first has to give permission to third party applications before access is granted to the user's content. Note that this gives more control to OSN users on determining who is inside the viewers set $\mathcal{V}_B$. Nevertheless, in practice it is still hard to get a concise overview from the OSN on everyone inside $\mathcal{V}_B$.

Second, any user broadcasting messages over the OSN infrastructure has to trust the OSN that it effectively operates as claimed. If the OSN broadcast server in Figure 4.1 would accidentally broadcast messages publicly despite of the sender's privacy settings, it would be hard for the Sender to find out.

Furthermore, the users of the OSN have to rely on the security of the OSN's infrastructure. If one of the outsiders in Figure 4.1 would succeed in hacking the OSN's digital infrastructure, he would have immediate access to all sensible information stored on the OSN's servers. Similarly, governments can subpoena the OSN to disclose sensible information on certain users with the argument of national security.

Another significant point is that the OSN fully determines which access policies are supported. As already mentioned in Section 4.1.2, not all OSNs offer the definition of an intended recipient set on a per message basis. Even OSNs currently supporting this functionality can suddenly stop offering the service. Moreover, nothing prevents OSN providers from changing their privacy policy on a regular basis, thereby complicating users to define the access policy of their choice.

Besides the earlier mentioned issues, the OSN often operates with a corporate mentality. The OSN has no initiative to stop adding advertisers and applications to the set of entities with access to a user's profile $\mathcal{V}_B$. The more information advertising companies receive from the OSN provider, the better they can tailor advertisements to the user. The more third party applications rely on the OSNs infrastructure, the more appealing the OSN business model looks like. Therefore, OSNs have often no initiative to offer stricter access control policies to their users.

4.3 Cryptographic Goals

Section 1.3 already defined a set of abstract goals for an architecture trying to solve the current privacy issues in OSNs. These goals said that a solution should be user friendly, applicable and immediately ready to use. Besides from these general design goals, it is now possible to define specific cryptographic requirements as well. A well-designed encryption scheme should be able to achieve the following cryptographic goals when publishing a message m to a set of intended recipients $\mathcal{S}$ on an OSN with the help of an encryption scheme:

- **Confidentiality:** The message is protected from disclosure to unauthorised parties, i.e. all entities that are not explicitly in the recipient set $\mathcal{S}$.
- **Outsider recipient anonymity:** The intended recipients of a broadcasted message should be anonymous to anyone not included in the intended recipient set $\mathcal{S}$. This implies that neither the OSN has to know who the recipients are. (Definition 3.1 gives a more formal definition of outsider-anonymity).
- **No redundancy:** The message should be published only once to reach every recipient in the intended recipient set $\mathcal{S}$.
- **Authenticity:** The recipients of the message have reasonable assurances of the message's origin.
- **Integrity:** The recipients are assured the message is distributed in its original form as posted by the sender.
- **No key escrow:** Private keys are only disclosed to the owners of the public key. No other entity should be able to have more information on one's secret key in the information theoretic sense.
- **Key validation:** All users of the system should be able to verify the correctness of their private keys.
- **Limited key validity:** Private keys of users should only be valid for a limited period of time to limit the damage of potentially lost private keys.

4.4 Design Decisions

4.4.1 Confidentiality

Confidentiality can be achieved by applying an encryption scheme before broadcasting a message. Current solutions like Scramble [17] and Persona [10] rely on rather classic public key infrastructures thereby requiring the OSN user to subscribe to a third party key infrastructure. These key infrastructures are required to authenticate and store the public keys of all security aware users. However, this does not correspond to the general design goals from Section 1.3 stating that the proposed solution should be both user friendly and immediately ready to use.

	Security Proof		
IBE Scheme	IND-ANO-CCA	Standard model	Assumption
Boneh and Franklin	✓	✗	BDH
Sakai and Kasahara	✓	✗	BDHI
Gentry	✓	✓	q-BDHE

Table 4.1: Security comparison of considered IBE schemes

	Execution time (ms)			
IBE Scheme	IBE.Setup	IBE.Extract	IBE.Encrypt	IBE.Decrypt
Boneh and Franklin	368.10	13.84	271.90	252.82
Sakai and Kasahara	1257.72	20.49	319.83	259.17
Gentry	24.49	37.46	1136.65	911.32

Table 4.2: Performance comparison of considered IBE schemes in MIRACL

Identity-based encryption (IBE) can be used to achieve both confidentiality and the general design goals from Section 1.3. During the design of our scheme, three IBE schemes were considered as a potential candidate: Boneh and Franklin IBE [28], Sakai and Kasahara IBE [95] and Gentry IBE [57]. For a more elaborate discussion on why only these schemes were considered, the reader is referred to Section 3.3.2.

Table 4.1 lists the different security properties of all schemes. Merely based on Table 4.1, one would prefer the Gentry IBE scheme as it is the only scheme proven secure in the standard model. In the random oracle model, Boneh and Franklin IBE is preferred over Sakai and Kasahara IBE since it relies on the BDH assumption which is more widely accepted than the stronger BDHI assumption.

The execution times of all considered IBE schemes are illustrated in Table 4.2. Experiments were conducted on an Intel Core 2.4 GHz i5 processor with 8 Gb of 1600 MHz DDR3L onboard memory. Pairing computations were implemented using the multi-precision MIRACL library [96]. The Gentry IBE scheme was first transformed to the asymmetric setting to give a fair basis of comparison. The exact transformed Gentry IBE scheme is depicted in Appendix A.

Table 4.2 clearly illustrates the price there is to pay for security in the standard model. Therefore, Boneh and Franklin IBE was chosen as the preferred IBE scheme.

Another important design decision is which profile attribute to use as a public key string uniquely identifying the user's OSN profile. The desired properties for such an IBE public key `id` are the following:

1. The public key should uniquely identify the user
2. The public key should be mandatory for every user of the social network
3. The public key should not change frequently over time

4. The public key should be an inherent part of the infrastructure of the social network thereby meaning that the previous three properties are already ensured by the provider of the social network.

Note that the decision of which string to use as a public key, is highly dependent on the targeted social network. That is, every OSN will have other profile attributes satisfying the earlier mentioned requirements.

4.4.2 Outsider Recipient Anonymity

The outsider anonymity requirement from Section 4.3 is imposed on the recipient set since our solution is developed in the context of OSNs where user interaction plays an important role. Therefore, it is useful that members of the intended recipient set $\mathcal{S}$ know each other. For example, suppose that Alice broadcasts an encrypted message intended to Bob and Dylan using a scheme that fully hides the identity of the recipients. This implies that $\mathtt{id}_{Bob}, \mathtt{id}_{Dylan} \in \mathcal{S}$. As a reaction to Alice's message, Bob wants to write a reply to start a discussion. However, as Bob does not know which other users are allowed to see Alice's message, he can now only encrypt his reply to Alice thereby preventing Dylan from joining the discussion. Nevertheless, this discussion could have been useful to Dylan as well because otherwise Alice would not have included Dylan as a recipient in $\mathcal{S}$ in the first place.

From the outsider-anonymity requirement, it immediately follows that users not necessarily need to be friends to receive each other's messages. In the specific example of Alice, Bob and Dylan, it could be that Bob and Dylan both have Alice as a common friend while no immediate friend connection exists between Bob and Dylan. This should be taken into consideration when determining the identifiers of Bob's and Dylan's profiles, $\mathtt{id}_{Bob}$ and $\mathtt{id}_{Dylan}$ respectively.

As discussed in Section 3.3.2, broadcast encryption schemes can be made more efficient if the recipient set $\mathcal{S}$ is public. So if user interaction is really that important, why not make the intended recipient set public? Consider the example in which Bob's girlfriend celebrates her birthday in a few weeks. When Bob's girlfriend notices that Bob broadcasted an encrypted message to all her friends without including her as a recipient, she will probably know Bob is up to something. This is just one example of possible many that illustrates the negative impact on security, broadcasting of the recipient set $\mathcal{S}$ can have on real life situations. Depending on the context, information can be deduced about the message without decrypting it to plain text.

4.4.3 No redundancy

From the no redundancy requirement it immediately follows that a broadcast encryption scheme should be used, preferably one that hides the anonymity of recipients in the intended recipient set $\mathcal{S}$ to the outside world. However, apart from the outsider-anonymous broadcast encryption scheme from Fazio and Perera [48], no efficient schemes of this kind are described in literature. Since the BE scheme from Fazio and Perera does not fully benefit from the advantages of IBE, the ANOBE scheme from Libert et al. [78] is preferred for further implementation.

Since recipients still have to know who the other recipients within the intended recipient set $\mathcal{S}$ are, the list of `ids` within the recipient set is concatenated to the plaintext message before encryption.

The scheme from Libert et al. also offers non-repudiation by using signature schemes. Note however, that a trusted authority authorising and publishing the public keys is required for the implementation of signature schemes. Because the general design goals were applicability and user friendliness, no third party PKI can be supported. Therefore, the implemented scheme does not rely on signatures like in [78].

If the security parameter is chosen to be λ, the IBE scheme in Algorithm 6 can only encrypt messages with a maximum length of l bits. This can be seen since in the last step of `IBE.Encrypt` the message m is encrypted by an XOR operation with the result of a hash function $H_3 : \{0,1\}^l \to \{0,1\}^l$. Because asymmetric IBE schemes can only encrypt these fixed length messages, the scheme from Libert et al. [78] is altered such that the ciphertext in the original proposal contains a with IBE encrypted symmetric session key k that is the same for each user in the recipient set $\mathcal{S}$ on a per message basis. The actual plaintext is then encrypted with a symmetric encryption scheme based on a mode of operation to support longer message lengths.

4.4.4 Authenticity and Integrity

Authenticity and integrity can be achieved at the same time by relying on an authenticated encryption scheme (Section 2.6.1). The integrity of the message is then as strong as the security guarantees of the authenticated encryption scheme.

Note however, that the authentication mechanism still relies on the security guarantees of the OSN. Since no third party PKI mechanism is used, there is no trusted party verifying the identity corresponding to a public key. In OSNs this is not an issue if IBE is used with unique profile identifiers as a public key. Consequently, such an IBE scheme ensures that messages encrypted under a public identifier can only be seen by the owner of the corresponding OSN profile. Verifying whoever owns the OSN profile remains the responsibility of the OSN and the judgement of the OSN profile's connections. However, if the authentication mechanism of the OSN is inadequate, anyone could login to a user's profile to impersonate the actual owner of the profile. Therefore, our proposed solution can not be more secure than the authentication mechanism of the OSN.

In more traditional communication schemes, authenticated encryption is done with a symmetric key as agreed during an authenticated key agreement protocol like the Station-to-Station protocol [45]. Authenticity of ciphertexts generated by the authenticated encryption scheme than immediately follows from the usage of the same symmetric session key k as earlier agreed during the protocol. However, since in the proposed solution every OSN user should be able to immediately broadcast confidential messages to other users of the OSN, no key agreement protocols will be used. With the publication of only one broadcast ciphertext, every user in the intended recipient set $\mathcal{S}$ should be immediately able to decrypt it to the original plaintext message m. Therefore, there is no real authenticity in the value of the tag t generated by the authenticated encryption scheme because anyone with access to the user's profile could have chosen a random symmetric session key k and have used it as an input to the authenticated encryption scheme. Unless, the only one with access to the user's profile is the actual owner of the profile. Therefore, the authenticity guaranteed by the authenticated encryption scheme boils down to the security of the authentication mechanism as powered by the OSN.

4.4.5 No Key Escrow and Key Validation

One of the major drawbacks of IBE schemes is that they inherently imply key escrow (Section 3.2.2). To circumvent the key escrow property of IBE schemes, multiple PKGs can be used implementing a distributed key generation (DKG) mechanism for IBE. Users can then verify their private keys by relying on the basics of commitment schemes (Section 2.6.2).

For the exact details on how a commitment scheme can achieve this verification mechanism, the reader is immediately referred to the exact proposed scheme in Section 4.7.

4.4.6 Limited Key Validity

As discussed in Section 3.2.2 IBE schemes do not allow revocation of public keys. A solution to circumvent this drawback is by concatenating an expiration date to all public identifiers `id`. However, these expiration dates should be publicly available to all OSN users since they are part of the public IBE key. To avoid the management of a third party infrastructure keeping track of expiration dates of all users, a special type of function could be used mapping identifiers `id` to dates. An example of such a function is shown in Algorithm 9.

Algorithm 9 is constructed such that step 1 to 4 only need to be executed once. The sender then stores values d_1, h_1, m_1 locally and only repeats step 5 for each recipient of the message. The exact implementation details could be hidden from the user in software. Different variants of Algorithm 9 could be applied as well. The most important aspect is that everyone in the system uses the same function to map strings to expiration dates.

4.5 Security Model

To achieve the design decisions from Section 4.4, the model from Figure 4.1 changes significantly. Therefore, a group of PKGs is introduced in the original model with their own responsibilities.

4.5.1 Model

Distributed key generators (DKGs) were already discussed in depth in Section 3.5. However, for the sake of completeness it is useful to introduce a DKG as an additional entity in the current OSN model to the ones already described in Section 4.1.2.

Algorithm 9 A function mapping strings to dates

Goal: Avoid a third party infrastructure that keeps track of expiration dates of key pairs in an IBE system

Result: On input of a public identifier `id` the algorithm returns an expiration date in the form `d/M/y h:m`.

1. Choose a hash function $H : \{0,1\}^* \rightarrow \{0,1\}^l$ mapping binary strings of arbitrary length to binary strings of a fixed length l.
2. Calculate $r = H(\texttt{id})$ and interpret the result r as an integer.
3. Calculate $tot_m = r \bmod 40320 = r \bmod (60 \cdot 24 \cdot 28)$, where tot_m denotes the expiration time in minutes within a certain month.
4. Calculate three integers d_1, h_1, m_1 denoting an expiration day, hour and minute respectively with $1 \leq d_1 \leq 28$, $0 \leq h_1 \leq 23, 0 \leq m_1 \leq 59$ as follows
   a) The expiration minute is calculated as $m_1 = tot_m \bmod 60$
   b) The expiration hour is calculated as $h_1 = \frac{tot_m}{60} \bmod 24$
   c) The expiration day is calculated as $d_1 = \frac{tot_m}{60 \cdot 24}$

   It can be shown that d_1, h_1, m_1 are chosen uniformly random within their boundaries if the random oracle assumption holds for the hash function $H(\cdot)$.
5. Let `nowIsEarlierThan(`d_1`,`h_1`,`m_1`)` be a function that returns `true` if the current time `d/M/y h:m` is before d_1`/M/y` h_1`:`m_1 and `false` otherwise. Output the expiration date as
   a) If `nowIsEarlierThan(`d_1`,`h_1`,`m_1`)` = `true`, return d_1`/M/y` h_1`:`m_1.
   b) If `nowIsEarlierThan(`d_1`,`h_1`,`m_1`)` = `false` and `M`+1 ≤ 12, return d_1`/M/y` h_1`:`m_1.
   c) Else return d_1`/1/(y+1)` h_1`:`m_1

Definition 4.7 (PKG in our security model). A *Public Key Generator* (PKG) is an entity in the security model that ideally never collaborates with any other entity in the model since its prime motivation is to improve the current security situation in OSNs.

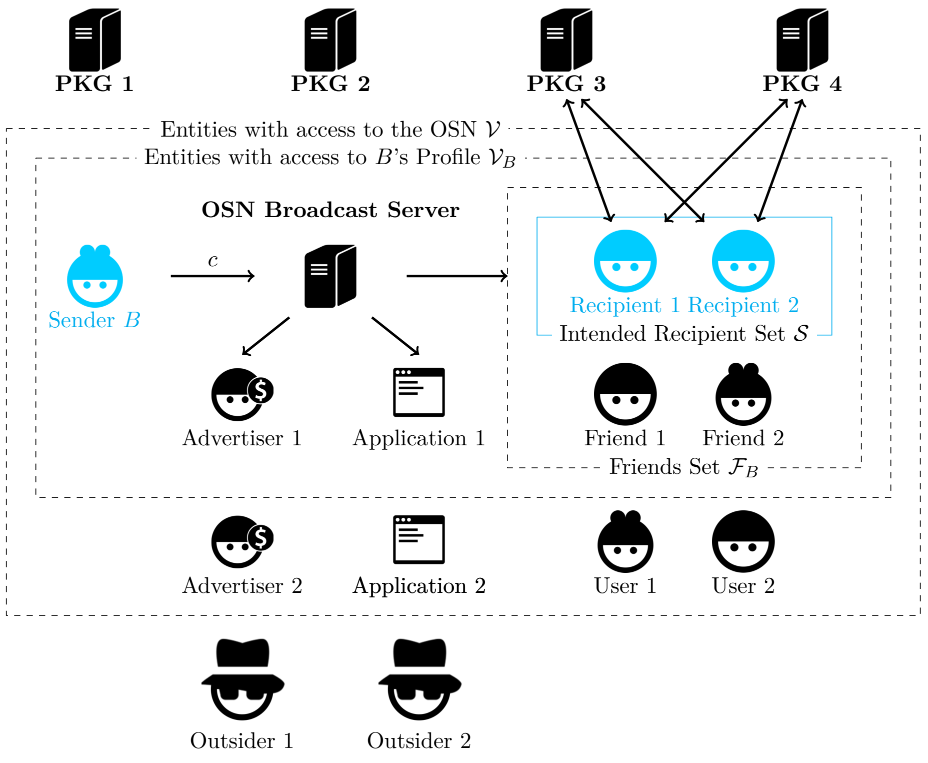


Figure 4.2: Model of the new OSN situation

Figure 4.2 illustrates a variation on the original model of the OSN situation in Figure 4.1. At the top of Figure 4.2 four PKGs are introduced implementing a (t, n) DKG protcol (Section 3.5) with $t = 2$ and $n = 4$. Double arrows represent the secure communication process in which the recipients communicate with the PKG to receive a share of their secret key. In Figure 3.1 this communication was illustrated by two separate single arrows between the PKG and Bob. However, abstraction is made of the exact communication protocol between the recipients and the PKG.

Apart from the newly introduced PKGs, there are some other rather subtile changes in Figure 4.2 when compared to Figure 4.1. Sender B no longer specifies the set of intended recipients $\mathcal{S}$ to the OSN broadcast server. Therefore, the OSN broadcast server delivers the message to all entities with access to B's profile $\mathcal{V}_B$. Note that even Friend 1 and 2 are able to see the broadcasted message which was not the case in Figure 4.1. However, since the broadcasted message is actually a ciphertext c of the original message m, only the entities in blue will be able to read the confidential content of the original plaintext message m.

4.6 Threat Model

4.6.1 Adversary Definition

We consider an adversary in the model illustrated in Figure 4.2, to be any computationally bounded entity trying to violate one or several of the following properties:

1. **Confidentiality:** The entity tries to violate the confidentiality of encrypted messages, i.e. uncovering information within a broadcasted ciphertext. This can either be the intended recipient set $\mathcal{S}$ or the actual content of the plaintext message m.

2. **Integrity:** The entity tries to violate the integrity of encrypted messages, i.e. changing the ciphertext c or the plaintext m such that it differs from the way it was originally drafted by the sender.

3. **Availability:** Any entity apart from the original sender, tries to prevent messages from being broadcasted by bringing down parts of the architecture or the OSN.

4.6.2 Assumptions on the PKG

This thesis focusses mainly on the adoption of user friendly broadcast encryption in OSNs. Therefore, PKGs are considered to always behave as described in the DKG protocol. Note that this is a simplification of a PKG as it is often encountered in real-world applications. However, considering PKGs as malicious requires far more complex distributed key generation algorithms which are out of the scope of this thesis. For DKG protocols that can be used in more hostile PKG environments as encountered in practice, the reader is referred to Kate et al. [73].

4.6.3 Assumptions on the OSN

OSNs are assumed not to violate integrity neither availability. Nothing can be done to prevent the OSN from actively altering its own resources to bring down the proposed IBE architecture. It can not be prevented that a user of IBE on the OSN infrastructure gets blocked by the OSN provider. Neither can it be prevented that OSNs delete messages because they are encrypted. OSNs can also easily impersonate the owner of a profile in their infrastructure. Therefore, from this moment onwards, OSNs are assumed to not act as an active adversary. It is assumed that as soon as privacy aware users notice this kind of OSN behaviour, they will adopt to more reliable OSN alternatives. However, our assumptions do not prevent the OSN from trying to passively break confidentiality as they have every motivation for it in the context of their current business model.

Another assumption on the OSNs infrastructure is that the authentication mechanism of the OSN is secure. This is primarily important for reasons as discussed in Section 4.4.4.

These assumptions on the OSN are ideal assumptions that will probably hold as long as only the minority of the OSN users applies encryption mechanisms to their network. It is still unknown how OSNs will react if variations to the proposed encryption mechanism find common acceptance in their wide user base.

4.6.4 Assumptions on the User

In order to achieve a strong encryption mechanism, users are unlimited in their abilities to behave as an adversary. However, one subtle assumption is made on users that are part of $\mathcal{S}$. Users in the intended recipient set are assumed not to break their social contract. That is, if a sender broadcasts a confidential message to a selected set of recipients, the recipients are assumed not to decrypt the encrypted message and rebroadcast the confidential content to any entity not in the original recipient set. In fact, no existing encryption mechanism provides protection against such misbehaviour, although traitor tracing schemes [40] discourage users from treating by indicating who broke his social contract. However, for the remainder of this text intended recipients are assumed trustworthy in that they not break the social contract.

4.7 Proposed Scheme

Based on the design decisions from Section 4.4, Algorithm 10 achieves all general design goals mentioned in Section 1.3 as well as the cryptographic design goals from Section 4.3.

The proposed scheme achieves confidentiality as in [28, 78], because a session key k can only be obtained if the recipient holds the corresponding secret key $s_{\mathtt{id}_i}$ to an identifier $\mathtt{id}_i$ that is included in the intended set of recipients $\mathcal{S}$. Confidentiality of the session keys k is thus guaranteed by ANO-IND-CCA secure Boneh and Franklin IBE [28].

The broadcasting mechanism is inspired by the BE scheme from Libert et al. [78]. The BE scheme is applied to broadcast the symmetric session keys k. In terms of efficiency, users are required to decrypt w_i on average $O(\eta/2)$ before obtaining the symmetric key k. Both Barth et al. [15] and Libert et al. [78] propose using a tag based system to hint users where they can find their symmetric key. However, it was deliberately decided to not implement such property in the scheme as it introduces dependency of the public parameters linear in the total number of users in the system.

Integrity and authenticity are guaranteed by the authenticated symmetric encryption scheme and the authentication mechanism of the OSN. If the assumptions on the OSN hold, only the owner of an OSN profile should be able to actively broadcast messages in name of the corresponding profile identifier $\mathtt{id}_i$.

The proposed solution can be used in any OSN that assigns unique public identifiers, such as usernames. Since the public keys are represented as strings, users are not required to upload keys to an additional third party server. Distributed key generation solves the key escrow issues that come with IBE solutions.

For the sake of clarity, concatenation of expiration dates with public keys is not explicitly included in Algorithm 10. However, with the help of Algorithm 9 this should be trivial since only the interpretation of the identifier symol $\mathtt{id}_i$ changes from a permanent identifier of a user to only a temporary identifier when concatenated with an expiration date.

The last check of the `KeyGen` step of Algorithm 10, does not ensure security against malicious PKGs. It only allows a user to check whether he received correct shares. Nevertheless, since the Pedersen scheme [89] is insecure, malicious PKGs can still affect the outcome of certain bits of the shared master secret key *msk* with non-negligible advantage. To circumvent these issues, the DKG scheme from Gennaro et al. [56] should be implemented. However, since the scheme is developed in a threat model where PKGs are assumed trustworthy, this concern falls out of the scope of this thesis. Implementation of the scheme from Gennaro et al. [56] occurs similar to the scheme from Pedersen [89] since it relies on the same mathematical concepts. Therefore, adapting Algorithm 10 to a more hostile DKG environment should be straightforward.

4.8 Summary

Algorithm 10 An outsider recipient anonymous identity-based broadcast encryption scheme

`Setup`(λ, t, n)**:** Outputs the public *params* of the system with respect to the security parameter λ, the number of PKGs n and the threshold t.

1. On input of security parameter λ generate a prime q, two groups G_1, G_2 of order q, and an admissible bilinear map $e : G_1 \times G_2 \rightarrow G_T$. Choose random generators $P \in G_1$ and $Q \in G_2$.
2. Choose cryptographic hash functions $H_1 : \{0,1\}^* \rightarrow G_1$, $H_2 : G_T \rightarrow \{0,1\}^l$ and $H_3 : \{0,1\}^l \rightarrow \{0,1\}^l$ such that, H_1, H_2 can be modelled as random oracles.
3. Each PKG j generates $n-1$ shares σ_{jv} of a Pedersen VSS scheme by executing `DKG.Setup`, and redistributing the $n-1$ shares σ_{jv} with the other v PKGs.
4. Each PKG j publishes $P_{pub}^{(j)} = s_j P$, s.t., $s_j = \sum_{v=1}^{n} \sigma_{jv}$.

The master secret key $msk = \sum_{j\in\Lambda} b_j s_j$ for $b_j = \prod_{z\in\Lambda} \frac{z}{z-j}$ cannot be retrieved unless Λ is a subset of size t different PKG servers. The following parameters are published publicly:

$$params = \{q, G_1, G_2, e, P, Q, H_1, H_2, H_3, t, n, P_{pub}^{(0)}, \ldots, P_{pub}^{(n)}\}$$

`KeyGen({PKG`$_0, \ldots,$`PKG`$_t\}$, `id`$_i$`):` On input of a user `id`$_i$ the subset Λ of size t of PKG servers, generates a valid private key for `id`$_i$.

1. User with identifier `id`$_i$, authenticates to Λ or all PKGs and sends `id`$_i$.
2. Each PKG computes $Q_{\mathtt{id}_i} = H_1(\mathtt{id}_i)$, and $Q_{priv,\mathtt{id}_i}^{(j)} = s_j Q_{\mathtt{id}_i}$, where s_j is the secret share from PKG j.
3. The user `id`$_i$ computes the shared public parameter P using the Lagrange coefficients b_j as follows:

$$P = \sum_{j\in\Lambda} b_j P_{pub}^{(j)} \quad \text{for} \quad b_j = \prod_{z\in\Lambda} \frac{z}{z-j}$$

4. All PKGs in Λ return $Q_{priv,\mathtt{id}_i}^{(j)}$ to the corresponding user `id`$_i$ over a secure channel.
5. Each user verifies for each $Q_{priv,\mathtt{id}_i}^{(j)}$ value whether,

$$e\left(Q_{priv,\mathtt{id}_i}^{(j)}, P\right) \overset{?}{=} e\left(Q_{\mathtt{id}_i}, P_{pub}^{(j)}\right)$$

   Next, `id`$_i$ calculates the private key $s_{\mathtt{id}_i}$ using the Lagrange coefficients b_j as follows:

$$s_{\mathtt{id}_i} = \sum_{j\in\Lambda} b_j Q_{priv,\mathtt{id}_i}^{(j)} \quad \text{for} \quad b_j = \prod_{z\in\Lambda} \frac{z}{z-j}$$

In this way, no user or PKG learns the master key *msk* of the system. This algorithm combines `DKG.Reconstruct`, `IBE.Extract` and `BE.KeyGen` algorithms.

`Publish(`$params, \mathcal{S}, m$`):` Takes the message m, the subset $\mathcal{S}$ of size η and the public parameters $params$, output a broadcast message $\mathcal{B}$.

1. Generate a random symmetric session key $k \leftarrow \{0,1\}^l$.
2. Choose a random value $\rho \in \{0,1\}^l$ and compute r as a hash of concatenated values $r = H_3(\{\rho \parallel k\})$
3. For each recipient $\mathtt{id}_i \in \mathcal{S}$, compute the ciphertext, running the `IBE.Encrypt` algorithm, as follows.

$$w_i = \rho \oplus H_2\left(g^r_{\mathtt{id}_i}\right) \quad \text{where} \quad g_{\mathtt{id}_i} = e\left(Q_{\mathtt{id}_i}, P_{pub}\right) \in G_T$$

4. Let w be a randomised concatenation, then the authenticated data $\mathcal{A}$ is computed as

$$\begin{aligned} \mathcal{A} &= \{\eta \parallel rP \parallel k \oplus H_3(\rho) \parallel w_1 \parallel w_2 \parallel \ldots \parallel w_\eta\} \\ &= \{\eta \parallel U \parallel v \parallel w\} \quad \text{for} \quad w = \{w_1 \parallel w_2 \parallel \ldots \parallel w_\eta\} \end{aligned}$$

   And $\mathcal{M}$ a concatenation of the intended recipient set $\mathcal{S}$ and the plaintext message m, such that $\mathcal{M} = \{m \parallel \mathcal{S}\}$. (`BE.Encrypt`)

5. Apply authenticated symmetric encryption

$$\langle c, t\rangle \leftarrow \mathtt{E}_k(\mathcal{M}, \mathcal{A})$$

6. The following message is then published in the OSN

$$\mathcal{B} = \{\mathcal{A} \parallel t \parallel c\}$$

`Retrieve(`$params, s_{\mathtt{id}_i}, \mathcal{B}$`):` on input of the broadcast message $\mathcal{B}$ and the private key $s_{\mathtt{id}_i}$ of user $\mathtt{id}_i$, reconstruct the plaintext message m. This algorithm comprises the `{IBE,BE}.Decrypt` algorithms. For each $i \in \{\}$

1. Compute $w_i \oplus H_2\left(e\left(s_{\mathtt{id}_i}, U\right)\right) = \rho$ for $s_{\mathtt{id}_i}$, and $v \oplus H_3\{\rho\} = k$
2. Set $r = H_3(\rho, k)$.
3. Retrieve $\langle \mathcal{M}, t'\rangle \leftarrow \mathtt{D}_k(c, \mathcal{A})$
4. Verify whether $t' \overset{?}{=} t \in \mathcal{B}$, and return m. Otherwise return $\perp$.

Chapter

5 Implementation

5.1 Software Architecture

There is still a long way to go from Algorithm 10 towards a practical implementation for OSNs. As a proof of concept, Algorithm 10 is applied to Facebook, the largest online social network at the time of writing. Recall that one of the more general goals of this thesis is to develop a solution that is applicable, i.e. a solution that does not require the OSN environment to be altered. Until so far this goal is successfully met since Algorithm 10 could be designed completely based on a more general model of an OSN. The resulting algorithm is a solution that can be applied to virtually any OSN that allows to uniquely distinguish users based on unique public identifiers, a requirement that discriminates almost no existing OSNs.

5.1.1 Software Environment

Despite the avoidance of complex third party infrastructures, some software is needed that effectively implements Algorithm 10 in a user-friendly way. Ideally, this is an easy-to-install piece of software that runs as an additional layer on top of the current infrastructure of the OSN user. Therefore, it was chosen to implement Algorithm 10 in the form of a browser extension.

Since Scramble [17] already has a user friendly interface that supports all required use cases to implement encryption on OSNs, it is natural to integrate our IBE scheme into Scramble. Besides from Scramble being open source and lightweight, the most important trigger to modify the existing Scramble code is that it is developed at KU Leuven.

5.1.2 Existing Environment

Recall from Section 1.2 that Scramble [17] is a Firefox extension that currently relies on OpenPGP [34] for key management. Due to the dependency on OpenPGP, Scramble is independent of any OSN. In fact, Scramble only functions as an encryption and decryption tool that can be used on any website offering users to submit content. However, users who want to be part of the recipient set of the uploaded messages

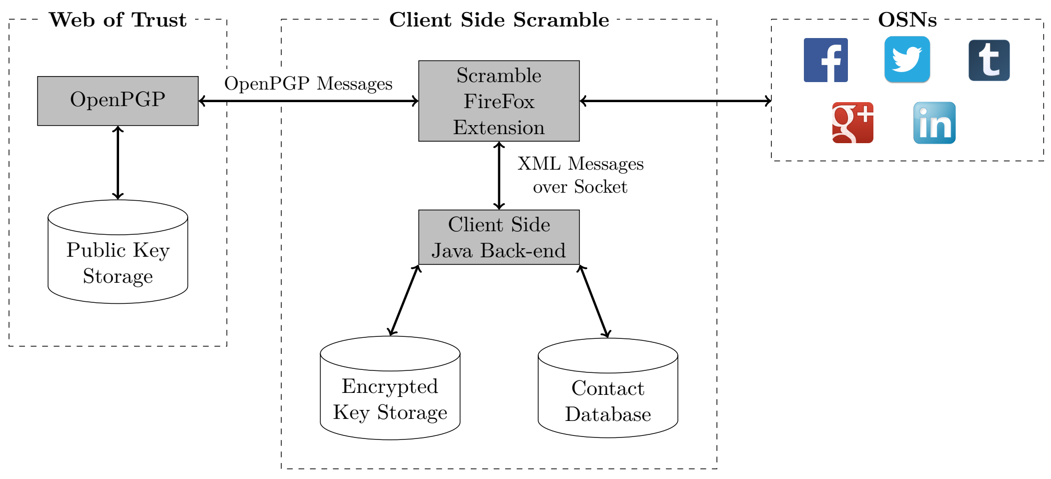


Figure 5.1: Original Scramble Architecture

need to have uploaded a public key to the OpenPGP network beforehand. The existing Scramble environment is shown in Figure 5.1.

Since Scramble is a FireFox extension, the user interface (UI) is implemented in Javascript. Although Javascript is ideal for synchronous UIs, it is not the desired programming language for computational demanding tasks such as encryption and decryption. Therefore, the Scramble library communicates with a back-end in Java that implements all cryptographic operations. Every time a user selects a computation intensive task in the Javascript UI, Javascript sends an XML message requesting the result from the client side Java back-end. The Java back-end processes the request and immediately sends the result in another XML message back to the UI. Sending and receiving of XML messages between FireFox extension and Java back-end, takes place synchronously over a socket listening on an internal port.

As already discussed in Section 1.2, Scramble relies on OpenPGP for key management. Therefore, the FireFox extension communicates with a web of trust (Section 3.1.2) storing all public keys of users who subscribed to the OpenPGP network. Because the OpenPGP network stores more keys than a Scramble user needs, Scramble offers the functionality to store public keys from the OpenPGP network locally in a contact database via the client side Java back-end. Furthermore, the client-side Java back-end has access to an encrypted list of the user's secret keys corresponding to public keys that are already in the OpenPGP network. With the help of a passphrase the Java back-end has access to these private keys to allow encryption of received messages.

5.1.3 Changes to the Existing Environment

The altered Scramble architecture is schematically illustrated in Figure 5.2. Scramble still offers the original functionality as an alternative to our IBE implementation.

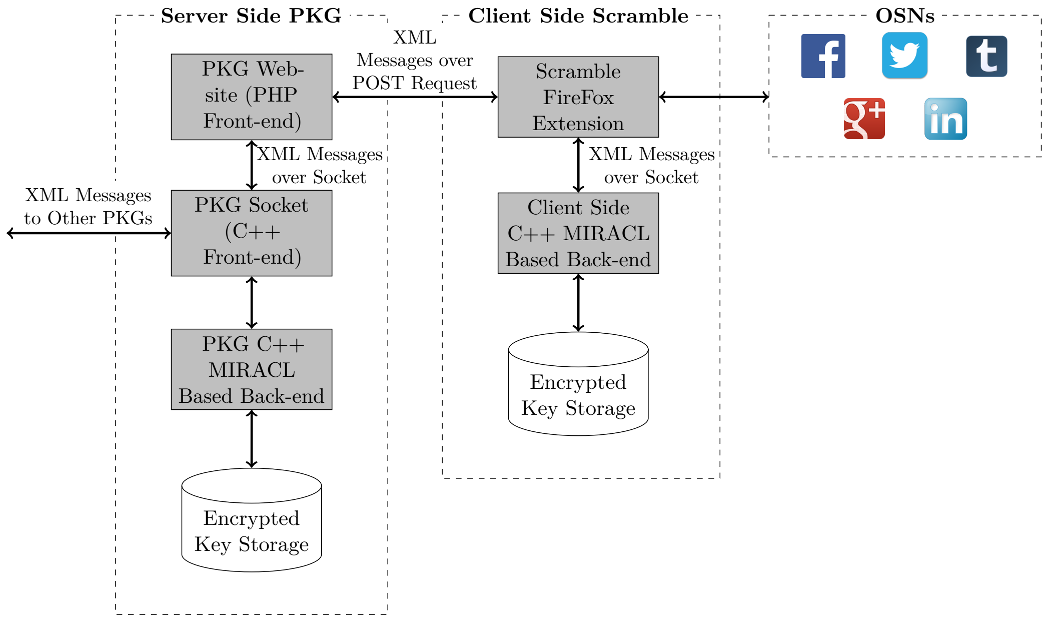

Server Side PKG
Client Side Scramble
OSNs
XML Messages over POST Request
PKG Website (PHP Front-end)
XML Messages over Socket
XML Messages to Other PKGs
PKG Socket (C++ Front-end)
PKG C++ MIRACL Based Back-end
Encrypted Key Storage
Scramble FireFox Extension
XML Messages over Socket
Client Side C++ MIRACL Based Back-end
Encrypted Key Storage

Figure 5.2: New Scramble Architecture

However, for reasons of conciseness Figure 5.2 omits the original OpenPGP implementation although it is not removed in the new implementation.

The new client side Scramble architecture implements a C++ based back-end instead of the earlier Java back-end because most efficient pairing-based multi precision libraries are written in C. In fact only two pairing-based libraries are widely accepted in practical implementations: MIRACL [96] and PBC [4]. MIRACL was preferred over PBC since it is generally faster in its pairing computations. All core algorithms of MIRACL are implemented in C while a C++ wrapper allows object-oriented programming.

The contact database is removed from the original Scramble implementation as illustrated in Figure 5.1 since public keys no longer have to be explicitly stored in the architecture. More specifically, since Scramble can rely on IBE, the public keys are inherently part of the supported OSN. Therefore, the FireFox extension falls back on a number of calls to supported OSN APIs in order to get all public keys of one's connections.

Figure 5.2 exchanges the web of trust from Figure 5.1 for a DKG infrastructure in order to support IBE without key escrow. For clarity, only one PKG is shown since all PKGs will have the same structure. The PKG supports two front-ends: a C++ based front-end and a PHP based front-end.

The C++ based front-end of the PKG only serves as a front-end during execution of the DKG protocol. Negotiation of the shares is implemented over synchronous sockets. At the startup of the PKG socket, the administrator is asked for a secret passphrase. Then, the sockets start listening on a predetermined port until all shares are correctly negotiated. Once all PKGs have exchanged their shares, the PKG calculates its public parameters and finishes the `Setup` step from Algorithm 10. The coefficients of the secret polynomial are encrypted with the earlier specified passphrase along with the negotiated secret share. After storage of these secret parameters, the C++ socket starts listening on another port to handle requests from the PHP front-end. Handling of private key extraction requests is multithreaded to handle requests of multiple clients at the same time.

The PHP based front-end receives private key extraction queries from the Scramble FireFox extension in the form of POST requests. The PKG communicates the requested `id` to the listening C++ socket in the form of an XML message. After the required MIRACL based pairing computations, the PKG socket sends the response back to the PHP webpage which publishes the response as an XML message over HTTPS [91].

Note that the new architecture from Figure 5.2 can be applied to virtually any OSN that identifies its users with publicly available identifiers. However, the scramble plugin can be made more user friendly by implementing OSN specific API calls. Currently, an implementation for Facebook serves as a proof-of-concept.

5.2 Practical Design Decisions

The implementation of Algorithm 10 still requires some practical design decisions that are further discussed in this section.

5.2.1 Type of Elliptic Curve

The MIRACL library supports 5 different curves and 6 different security levels. However, the Barreto-Lynn-Scott (BLS) curve [14] is preferred since it provides the highest level of security in MIRACL. BLS curves rely on Ate pairings [68] with an embedding degree of 24. Consequently, BLS curves are considered suitable for a security level of 256 bits.

5.2.2 Authenticated Encryption Scheme

An AES-GCM [86] implementation is used for the authenticated encryption scheme in Algorithm 10 since it is one of the more efficient authenticated encryption schemes unencumbered by patents. The AES-GCM implementation as provided by MIRACL is used with authentication tags of 128 bits. Apart from a symmetric key of 128, 192 or 256 bits, AES-GCM also requires an Initialisation Vector (IV). The recommended length of the IV is 96 bits because it can be handled more efficiently [69].

5.2.3 Key Lengths

Since the maximum level of security in MIRACL is determined by the BLS curve, all implemented key lengths in Algorithm 10 follow from the 256 bits security level ($l = 256$). Note that in Step 1 of `Retrieve` the decryption of a recipient's session key is calculated as:

$$w_i \oplus H_2\left(e\left(s_{\mathtt{id}_i}, U\right)\right) = \rho$$

followed by

$$v \oplus H_3\{\rho\} = k$$

with

$$H_2 : G_T \rightarrow \{0,1\}^l$$

Since $l = 256$, w_i and ρ are binary sequences of 256 bits. Hence, ρ only contains sufficient randomness to securely encrypt a session key k of the same length. The full 256 bit k is not completely used for symmetric encryption as the AES-GCM scheme still requires an IV as well. Since the randomness and key freshness of the IV is at least as important as the secrecy of k [1], it was deliberately chosen not to apply key derivation functions to derive a separate symmetric encryption key and IV from the same value k. Therefore, the first 128 bits of k are used as the symmetric key of AES-GCM, while the second 96 bits function as an IV. According to NIST, this should ensure confidentiality at least until 2030. However, if a higher level of security should be required, key derivation on k could be considered.

5.2.4 Hash Functions

The hash function $H_1 : \{0,1\}^* \rightarrow G_1$ is implemented using the MIRACL function call `hash_to_group`. Hash function $H_2 : G_T \rightarrow \{0,1\}^l$ relies on the `hash_to_aes_key` function. Both H_1 and H_2 internally fall back on SHA-256 [2]. Also $H_3 : \{0,1\}^l \rightarrow \{0,1\}^l$ is implemented with the MIRACL provided SHA-256 implementation.

5.2.5 Generating Random Numbers

Random numbers are generated using the MIRACL build-in strong random number generator. The strong random generator is initialised with a time-of-day value and a binary array of 1024 bits read from `/dev/urandom`. These values are then used as a seed for the generation of random numbers. The practical implementation of the MIRACL strong random generator is based on an advice published by RSA Laboratories in [83].

5.3 Implemented Scheme

5.3.1 Client-Side Implementation

5.3.2 Server-Side Implementation

5.4 Performance Analysis

5.5 Shortcomings of Current Implementation

The algorithm as it is currently implemented only serves as a proof-of-concept since it lacks a number of requirements needed for secure use in practice. These aspects were

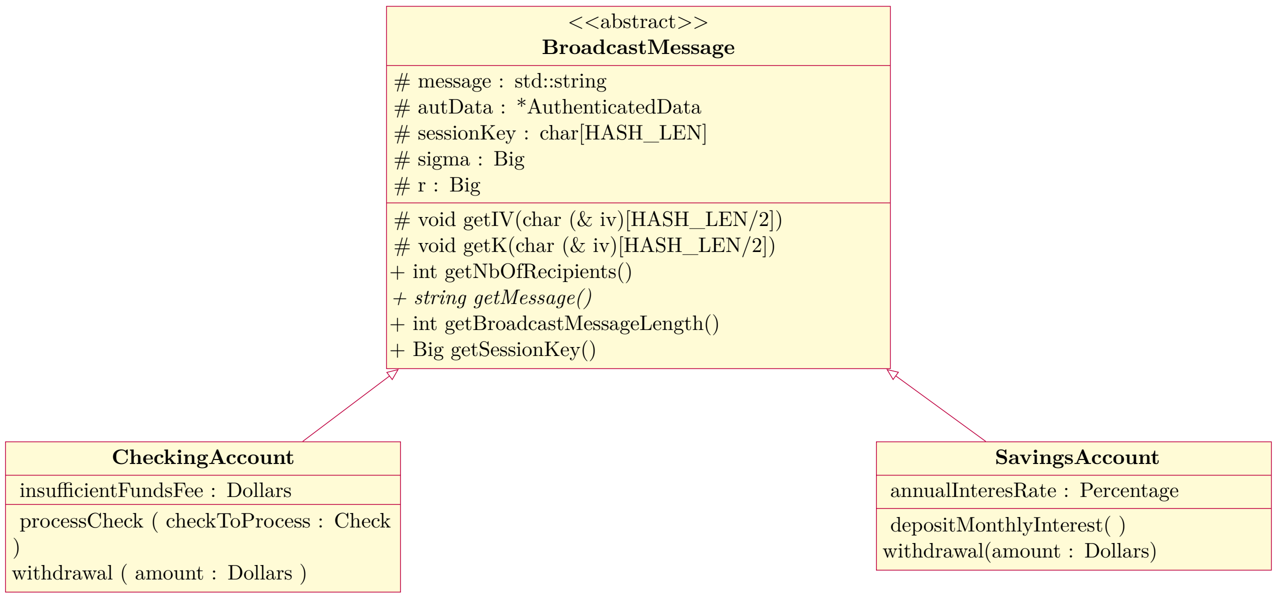

<<abstract>>
BroadcastMessage
# message : std::string
# autData : *AuthenticatedData
# sessionKey : char[HASH_LEN]
# sigma : Big
# r : Big
# void getIV(char (& iv)[HASH_LEN/2])
# void getK(char (& iv)[HASH_LEN/2])
+ int getNbOfRecipients()
+ string getMessage()
+ int getBroadcastMessageLength()
+ Big getSessionKey()
CheckingAccount
insufficientFundsFee : Dollars
processCheck (checkToProcess : Check)
withdrawal (amount : Dollars)
SavingsAccount
annualInteresRate : Percentage
depositMonthlyInterest( )
withdrawal(amount : Dollars)

Figure 5.3: Class Diagram of C++ MIRACL Based Back-end

not implemented due to the limited time available. Although all core requirements for the protocol in Algorithm 10 were implemented, only the aspects for practical usage in more hostile environments are missing. However, including these aspects should be straightforward and is only a matter of implementation instead of hard design decisions.

5.5.1 Client Side

Since the IBE scheme is integrated in the existing Scramble UI, not many adaptions should be made to the client side implementation. The major drawback of our IBE proposal is that it makes the Scramble plugin more dependent on the underlying OSN. Consequently, every OSN should be separately integrated into the Scramble plugin since each OSN offers its own API calls for reading out friend connections. More OSNs than Facebook should be actively supported by the IBE Scramble tool to motivate the use of the plugin.

5.5.2 Server Side

In its present form, the PKG is only simulated in a local environment. Therefore, it suffices to rely on synchronous communication over C++ sockets each listening on a different port. However, before adaption to a world-wide DKG network is possible, the protocol should take more asynchronous aspects into account such as connection-loss, DOS-attacks or undelivered packets. Kate et al. [73] propose a more advanced DKG protocol in the asynchronous setting that could be adapted for our IBE setting.

Since the DKG protocol is currently always simulated in a local environment, all PKG sockets communicate their XML messages in plain text. More secure socket protocols should be considered such as SSL [53] for adoption to a more hostile distributed setting.

Furthermore, the current assumptions on the PKGs (Section 4.6.2) are too severe for practical environments. In practice the current Pedersen DKG scheme [89] is insecure and is better replaced by the one from Gennaro et al. [56]. If all mentioned updates on the current server side scheme are effectively achieved, more relaxed assumptions on the PKG are in place. With less stringent PKG assumptions, the DKG network could even be partially supported by the OSN providers to show their good intensions of making their networks more private.

5.5.3 Shortcomings Effecting Both Client and Server

Currently, private key extraction takes the form of a POST request over HTTPS [91]. Although the PKGs publish the response in plain text to their PHP website, the communication is encrypted by a self-signed SSL certificate. Ideally, this certificate is signed by a world-wide trusted CA such that the client-side implementation can effectively verify whether it is communicating with a valid PKG.

Although web communication between the client side Scramble tool and the server side PKG is already encrypted, a client can request the private key parameters for every `id` since there is no authentication mechanism checking the user's identity. However, Facebook provides third party authentication in its API. If a Facebook login dialogue is integrated in the Scramble UI, the returned Facebook authentication token serves as a proof to the PKG that the requester of the private key resembles the owner of the corresponding Facebook profile.

5.6 Summary

Chapter

6 Conclusion

The final chapter contains the overall conclusion. It also contains suggestions for future work and industrial applications.

Appendices

Appendix

A Gentry's IBE Scheme

TODO for this Appendix: change the notation such that it corresponds to all other pairing based computations in this thesis Gentry [57] proposed the first IND-ANO-CCA secure scheme in the random oracle model. The original proposed scheme from Gentry relies on symmetric pairings. A transformed version of the algorithm to the asymmetric setting can be found in Algorithm 11.

The correctness of the transformed scheme in Algorithm 11 can be proven as follows.

$$
\begin{aligned}
&e\left(u, h_{\mathrm{ID},2}h_{\mathrm{ID},3}^{\beta}\right) v^{r_{\mathrm{ID},2}+r_{\mathrm{ID},3}\beta} \\
&\qquad = e\left(p_1^{s(\alpha-\mathrm{ID})}, \left(h_2h_3^{\beta}\right)^{\frac{1}{\alpha-\mathrm{ID}}} q_2^{\frac{-\left(r_{\mathrm{ID},2}+r_{\mathrm{ID},3}\beta\right)}{\alpha-\mathrm{ID}}}\right) e\left(p_1, q_2\right)^{s\left(r_{\mathrm{ID},2}+r_{\mathrm{ID},3}\beta\right)} \\
&\qquad = e\left(p_1^{s(\alpha-\mathrm{ID})}, \left(h_2h_3^{\beta}\right)^{\frac{1}{\alpha-\mathrm{ID}}}\right) = e\left(p_1, h_2\right)^{s} e\left(p_1, h_3\right)^{s\beta}
\end{aligned}
$$

Thus, the check passes. Moreover, as in the ANO-IND-CPA scheme,

$$
e\left(u, h_{\mathrm{ID}}\right) v^{r_{\mathrm{ID},1}} = e\left(p_1^{s(\alpha-\mathrm{ID})}, h^{\frac{1}{\alpha-\mathrm{ID}}} q_2^{\frac{-r_{\mathrm{ID},1}}{\alpha-\mathrm{ID}}}\right) e\left(p_1, q_2\right)^{s r_{\mathrm{ID},1}} = e\left(p_1, h\right)^{s},
$$

as required.

Algorithm 11 Gentry's asymmetric IBE Scheme [57]

Let G_1, G_2 and G_T be groups of order p and let $e : G_1 \times G_2 \to G_T$ be the bilinear map. The IBE system works as follows.

Setup: The PKG picks random generators $p_1, g_1 \in G_1$, generators $q_2, h_1, h_2, h_3 \in G_2$ and a random $\alpha \in \mathbb{Z}_p$. It sets $g_1 = p_1^\alpha \in G_1$. It chooses a hash function H_1 and $H_2 : \{0,1\}^* \to \{0,1\}^n$ from a family of universal one-way hash functions. The public *params* and private *masterkey* are given by

$$\mathit{params} = (p_1, q_2, h_1, h_2, h_3, H_1, H_2) \qquad \mathit{masterkey} = \alpha$$

KeyGen: To generate a private key for identity ID $\in \mathbb{Z}_p$, the PKG generates random $r_{\mathrm{ID},i} \in \mathbb{Z}_p$ for $i \in \{1,2,3\}$, and outputs the private key

$$d_{\mathrm{ID}} = \{(r_{\mathrm{ID},i}, h_{\mathrm{ID},i}) : i \in \{1,2,3\}\}, \text{ where } h_{\mathrm{ID},i} = \left(h_i q_2^{-r_{\mathrm{ID},i}}\right)^{\frac{1}{\alpha - \mathrm{ID}}} \in G_2$$

If ID $= \alpha$, the PKG aborts. As before, we require that the PKG always use the same random values $\{r_{\mathrm{ID},i}\}$ for ID.

Encrypt: To encrypt $m \in \{1,0\}^n$ using identity ID $\in \mathbb{Z}_p$, the sender generates random $s \in \mathbb{Z}_p$, and sends the ciphertext

$$\begin{aligned} C &= \left(g_1^s p_1^{-s \cdot \mathrm{ID}},\ e(p_1, q_2)^s,\ m \oplus H_2\{e(p_1, h_1)^s\},\ e(p_1, h_2)^s\, e(p_1, h_3)^{s\beta}\right) \\ &= (u, v, w, y) \end{aligned}$$

Note that $u \in G_1, v \in G_T, w \in \{1,0\}^n$ and $y \in G_T$. We set $\beta = H_1\{u, v, w\}$. Encryption does not require any pairing computations once $e(p_1, q_2)$, and $\{e(p_1, h_i)\}$ have been pre-computed or alternatively included in *params*.

Decrypt: To decrypt ciphertext $C = (u, v, w, y)$ with ID, the recipient sets $\beta = H_1\{u, v, w\}$ and tests whether

$$y = e\left(u, h_{\mathrm{ID},2} h_{\mathrm{ID},3}^\beta\right) v^{r_{\mathrm{ID},2} + r_{\mathrm{ID},3}\beta}$$

If the check fails, the recipient outputs $\perp$. Otherwise, it outputs

$$m = w \oplus H_2\{e(u, h_{\mathrm{ID},1})\, v^{r_{\mathrm{ID},1}}\}$$

Appendix

B Installing and Executing the Code

Appendices hold useful data which is not essential to understand the work done in the master thesis. An example is a (program) source. An appendix can also have sections as well as figures and references[**?**].

B.1 Setting up the DKG

B.2 Setting up Scramble

Appendix

C

Dutch Summary

As this thesis is written in English a Dutch summary ranging from 1 to 5 pages is included here.

Appendix

D English Paper

The English PETS paper is included here and should have the IEEE layout as proposed at `http://www.ieee.org/publications_standards/publications/authors/authors_journals.html`

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Master thesis filing card

Student: Stijn Meul

Title: Practical Identity-Based Encryption for Online Social Networks

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Abstract:

Nowadays Online Social Networks (OSNs) constitute an important and useful communication channel. At the same time, coarse-grained privacy preferences protect the shared information insufficiently. Cryptographic techniques can provide interesting mechanism to protect privacy of users in OSNs. However, this approach faces several issues, such as, OSN provider acceptance, user adoption, key management and usability. We suggest a practical solution that uses Identity Based Encryption (IBE) to simplify key management and enforce confidentiality of data in OSNs. Moreover, we devise an outsider anonymous broadcast IBE scheme to disseminate information among multiple users, even if they are not using the system. Finally, we demonstrate the viability and tolerable overhead of our solution via an open-source prototype.

Thesis submitted for the degree of Master of Science in Electrical Engineering, option Embedded Systems and Multimedia

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