Multi-Client Functional Encryption with Repetition for Inner Product

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Abstract. Recently, Chotard *et al.* proposed a variant of functional encryption for Inner Product, where several parties can independently encrypt inputs, for a specific time-period or label, such that functional decryption keys exactly reveal the aggregations for the specific functions they are associated with. This was introduced as *Multi-Client Functional Encryption* (MCFE). In addition, they formalized a *Decentralized* version (DMCFE), where all the clients must agree and contribute to generate the functional decryption keys: there is no need of central authority anymore, and the key generation process is non-interactive between the clients. Eventually, they designed concrete constructions, for both the centralized and decentralized settings, for the inner-product function family.

Unfortunately, there were a few limitations for practical use, in the security model: (1) the clients were assumed not to encrypt two messages under the same label. Then, nothing was known about the security when this restriction was not satisfied; (2) more dramatically, the adversary was assumed to ask for the ciphertexts coming from all the clients or none, for a given label. In case of partial ciphertexts, nothing was known about the security either.

In this paper, our contributions are three-fold: we describe two conversions that enhance any MCFE or DMCFE for Inner Product secure in their security model to (1) handle repetitions under the same label and (2) deal with partial ciphertexts. In addition, these conversions can be applied sequentially in any order. The latter conversion exploits a new tool, which we call *Secret Sharing Layer* (SSL). Eventually, we propose a new efficient technique to generate the functional decryption keys in a decentralized way, in the case of Inner Product, solely relying on plain DDH, as opposed to prior work of Chotard *et al.* which relies on pairings.

As a consequence, from the *weak* MCFE for Inner Product proposed by Chotard *et al.*, one can obtain an efficient Decentralized MCFE for Inner Product that handles repetitions and partial ciphertexts.

Keywords. Functional Encryption, Inner Product, Multi-Client, Decentralized.

1 Introduction

Functional Encryption (FE) [SW05, O'N10, BSW11, GKP+13b, GGH+13] is an alternative to Fully Homomorphic Encryption (FHE) in the context of computation on encrypted data. While FHE outputs the result in an encrypted way, FE outputs the result in clear. Besides, FE generates restricted decryption keys for specific functions, that only decrypt their specific function applied to the message. This is in stark contrast with FHE which has no restrictions on the functions that can be computed on the encrypted data. In particular, FE achieves verifiability for free.

More concretely, for any function f, a functional decryption key dk_f allows, given any ciphertext c with underlying plaintext x, to compute $f(x)$, but does not leak any additional information about the plaintext x. While general definitions with some generic constructions have been proposed [SS10, GVW12, GKP+13b, GKP+13a, Wat15, ABSV15, GGG+14, BGJS16, BKS16], only linear and quadratic functions have been efficiently addressed. Abdalla, Bourse, De Caro, and Pointcheval [ABDP15] proposed the first FE for inner-product function family (IP-FE), based on the Decisional Diffie-Hellman (DDH) assumption, but for the selective security model only: encryption queries are known in advance. Agrawal, Libert and Stehlé [ALS16] achieved adaptive security for IP-FE. Extensions to quadratic functions have also been proposed [Gay16, BCFG17, DGP18].

While the basic definition of FE is quite general, as f could in theory be any function, it requires that the whole input x comes from one party, even if x is a vector $\boldsymbol{x} = (x_1, \cdots, x_n)$ with several coordinates. To allow for independent contributions from multiple sources in the case of vector-inputs, two lines of research have been developed: Multi-Input Functional Encryption (MIFE) [GGJS13, GKL+13, GGG+14] and Multi-Client Functional Encryption (MCFE) [GGG+14, GKL+13, CDG+17]. The latter essentially differs from the former with a label which specifies which inputs from the different clients can be combined together. As of today, in these settings, only linear functions have been efficiently addressed. Abdalla *et al.* [AGRW17] proposed an efficient Multi-Input Inner-Product Functional Encryption (IP-MIFE) scheme that relies on the k-Lin assumption in prime-order bilinear groups. Later, Abdalla *et al.* [ACF+18] removed the use of a pairing, building an IP-MIFE from plain DDH, LWE, or the DCR assumption, and adding other features. Recently, Chotard *et al.* [CDG+17] proposed an MCFE and a decentralized MCFE for Inner-Product (IP-MCFE and IP-DMCFE) from the SXDH assumption in prime-order bilinear groups.

1.1 Multi-Client Functional Encryption

For MCFE, as defined in [GGG+14, GKL+13], and more concretely in [CDG+17], both an index i for the client and a label ℓ (possibly a time-stamp) are used for the encryption: $(c_1 = \mathsf{Encrypt}(1, x_1, \ell), \ldots, c_n = \mathsf{Encrypt}(n, x_n, \ell))$. Only ciphertexts with the same label can be used together, in order to get $f(x_1, \ldots, x_n)$ during decryption. This is in contrast to MIFE, where no label, and possibly no index, are provided with the ciphertext, hence many combinations and re-ordering are possible. In such a case, in order to avoid trivial attacks, the adversary is strongly limited with the encryption queries and functional decryption key queries it is allowed to ask. Stated otherwise, the information leaked from the ciphertexts by any decryption key is much more important in the setting of MIFE than in MCFE.

Indeed, with FE and variants, the adversary can get some information from the plaintexts using functional decryption keys. But this should not jeopardize indistinguishability. Hence, one excludes illegitimate attacks that ask for messages that can easily be told apart just from functional decryption keys.

In addition to allowing multiple-source ciphertexts, [CDG+17] goes further in the distributed process: since senders are distinct and might want to keep control on their data, the validation of the functional decryption keys is thus critical, and cannot be given to a unique authority. They thus proposed a decentralized version of MCFE, where no authority is involved, but the generation of functional decryption keys remains an efficient process, without interactions between the clients.

1.2 Limitations on the Security Model

When dealing with multiple independent clients, it is clear that some input might be missing, leading to an incomplete ciphertext. While it could seem natural that no evaluation can be performed on an incomplete ciphertext, there is no guarantee that the functional decryption key cannot reveal some information about the received inputs.

This is indeed an issue with the protocol proposed by Chotard *et al.* [CDG+17]: in the inner-product case, where one computes $\langle \boldsymbol{x}, \boldsymbol{y} \rangle$ on a ciphertext of the vector $\boldsymbol{x}$ given the functional decryption key for $\boldsymbol{y}$, if $y_j = 0$, x_j has no impact on the result. Then, it could seem fine to allow the use of the functional decryption without the j-th ciphertext. But because of the linear properties of the inner-product, and namely for the keys, from many functional keys, one can derive keys for vectors with some zeros, and then decrypt some meaningful information. One could of course keep track of all the possible linear combinations of the keys when deciding on legitimate attacks, but this is very specific to inner-product. Chotard *et al.* [CDG+17] simply decided to declare illegitimate all the attacks with some incomplete ciphertexts.

In an IP-MCFE, each client is allowed to send a unique scalar (one component of the vector). Of course, if he would like to send several, it is possible to register as multiple clients. But then, components would be independent, and would still require the limitation of one value per component and label, whereas in the MIFE, when vectors are input, it makes sense to allow mix-and-match between the inputs. In addition, requiring a unique component per label for each client, while under his responsibility, is a strong limitation. What happens when the client makes a mistake? This is not covered by the security analysis in [CDG+17].

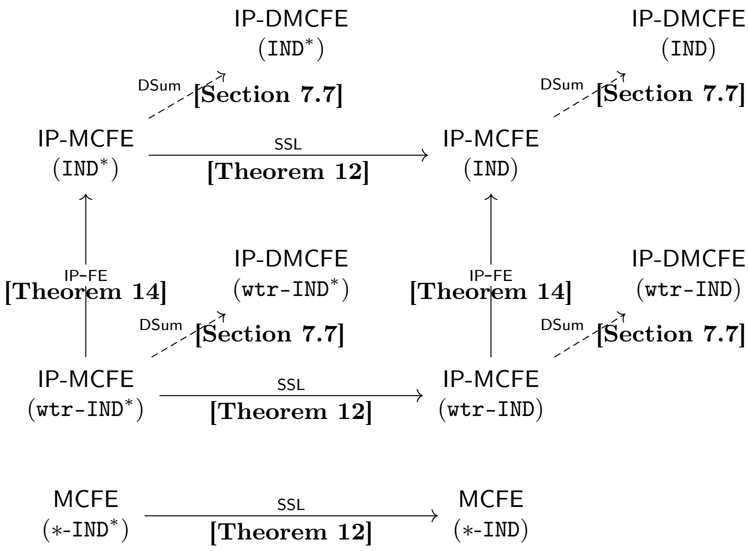

Fig. 1. Contributions and Theorems. Here, `wtr` stands for: "without repetitions".

1.3 Contributions

Our contributions are three-fold, as shown on figure 1, and essentially address the above limitations:

- We first deal with the limitation in the security model from [CDG+17], that requires complete ciphertexts: any attack with partial ciphertexts is declared illegitimate. We denote this (weak) security model IND^*, while our target security model IND still considers such attacks legitimate. Our solution is quite generic, as this is an additional layer, that is applied to the ciphertexts so that, unless the ciphertext is complete (with all the encrypted components), no information leaks about the individual ciphertexts, and thus on each components. This technique relies on a linear secret sharing scheme, hence the name *Secret Sharing Layer* (SSL). It can also be seen as a decentralized version of *All-Or-Nothing Transforms* [Riv97, Boy99, CDH+00]. We propose a concrete instantiation in pairing-friendly groups, under the Decisional Bilinear Diffie-Hellman problem, in the random oracle model. We stress that this conversion transforms any $*$-IND^*-secure MCFE into $*$-IND-secure MCFE.
- Secondly, when starting from an IP-MCFE, we show how another independent layer of IP-FE allows repetitions, where clients can encrypt vectors (and the global input is the concatenation of all the clients' vectors): more precisely, we will be able to remove the restriction of a unique input per client and per label ($\mathsf{wtr\text{-}IND}^*$ or $\mathsf{wtr\text{-}IND}$). We will thus enhance IND^* and IND with repetitions.
- Eventually, we propose an efficient decentralized algorithm to generate a sum of private inputs, hence DSum, which can convert an IP-MCFE into IP-DMCFE: this technique is inspired from [KDK11], and only applies to the functional decryption key generation algorithm, and so this is compatible with the two above conversions. Namely, this improves on the decentralization from [CDG+17] since it does not require pairings.

Efficiency. All the above conversions are efficient, or at least of the same order of magnitude as the initial MCFE. While the SSL techniques introduce pairings, the two others do not: they only rely on the DDH or even CDH assumptions, in the random oracle model.

Technical Tools. In order to deal with partial ciphertexts, we introduce a new tool, called *Secret Sharing Layer* (SSL). In fact, the goal is to allow a user to recover the ciphertexts from the n senders only when he gets the contributions of all of them. At first glance, one may think this could be achieved by using *All-Or-Nothing Transforms* or (n, n)-*Secret Sharing*. However, these settings require an authority who operates on the original messages or generates the shares. Consequently, they are incompatible with our multi-client schemes. Our SSL tool can be seen as a decentralized version of *All-Or-Nothing Transforms* or of (n, n)-*Secret Sharing*: for each label ℓ, each user $i \in [n]$ can generate, on his own, the share $S_{\ell,i}$. And, unless all the shares $S_{i,\ell}$ have been generated, the encapsulated keys are random and perfectly mask all the inputs.

We believe that SSL could be used in other applications. As an example, AONT was used in some traitor tracing schemes [KY02, CPP05]. By using SSL instead of AONT, one can get *decentralized* traitor tracing schemes in which the tracing procedure can only be run if all the authorities agree on the importance of tracing a suspected decoder. This might be meaningful in practice to avoid the abuse of tracing, in particular on-line tracing, which might break the privacy of the users, in case the suspected decoders are eventually legitimate decoders.

2 Definitions and Security Models

In this section, we first review the definitions of MCFE from [CDG$^+$17]. DMCFE will use individual secret keys, instead of the master secret key. This will thus add distributed setup and functional decryption key generation, the public flows being available to the adversary.

2.1 Multi-Client Functional Encryption

As in [GGG$^+$14, GKL$^+$13, CDG$^+$17], we define private-key MCFE, with possible deterministic encryption:

Definition 1 (Multi-Client Functional Encryption). *A multi-client functional encryption on $\mathcal{M}$ over a set of n senders is defined by four algorithms:*

- $\mathsf{SetUp}(\lambda)$*: Takes as input the security parameter λ, and outputs the public parameters* mpk*, the master secret key* msk *and the n encryption keys* ek_i*;*
- $\mathsf{Encrypt}(\mathsf{ek}_i, x_i, \ell)$*: Takes as input a user encryption key* ek_i*, a value x_i to encrypt, and a label ℓ, and outputs the ciphertext $C_{\ell,i}$;*
- $\mathsf{DKeyGen}(\mathsf{msk}, f)$*: Takes as input the master secret key* msk *and a function $f : \mathcal{M}^n \to \mathcal{R}$, and outputs a functional decryption key* dk_f*;*
- $\mathsf{Decrypt}(\mathsf{dk}_f, \ell, \boldsymbol{C})$*: Takes as input a functional decryption key* dk_f*, a label ℓ, and an n-vector ciphertext $\boldsymbol{C}$, and outputs $f(\boldsymbol{x})$, if $\boldsymbol{C}$ is a valid encryption of $\boldsymbol{x} = (x_i)_i \in \mathcal{M}^n$ for the label ℓ, or $\perp$ otherwise.*

As usual, we will assume public keys being included in the associated secret keys, and master keys being included in the individual keys. Correctness states: given $(\mathsf{mpk}, \mathsf{msk}, (\mathsf{ek}_i)_i) \leftarrow \mathsf{SetUp}(\lambda)$, for any label ℓ, any function $f : \mathcal{M}^n \to \mathcal{R}$, and any vector $\boldsymbol{x} = (x_i)_i \in \mathcal{M}^n$, if $C_{\ell,i} \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, x_i, \ell)$, for $i \in \{1, \ldots, n\}$, and $\mathsf{dk}_f \leftarrow \mathsf{DKeyGen}(\mathsf{msk}, f)$, then $\mathsf{Decrypt}(\mathsf{dk}_f, \ell, \boldsymbol{C}_\ell = (C_{\ell,i})_i) = f(\boldsymbol{x} = (x_i)_i)$.

2.2 A New Indistinguishability Security Notion

We introduce a new indistinguishability-based security definition, which naturally addresses the shortcomings of the security achieved in prior work [CDG$^+$17]: first, we authorize several challenge ciphertexts for the same user i and label ℓ, contrary to [CDG$^+$17] where encryption is deterministic and therefore only provides security for a single challenge ciphertext per pair (i, ℓ). This can make sense in applications where this condition is naturally satisfied, for instance when labels correspond to time stamps, used only once. We remove this limitation, thereby broadening the range of applications for MCFE.

Second, we strengthen the security model by allowing the adversary to query the left-or-right encryption oracle for some honest users, but not necessarily all of them, leading to incomplete ciphertexts. In [CDG$^+$17], attacks with incomplete ciphertexts are considered non-legitimate, which means that the possible leakage of information on the plaintext by partial decryption (where ciphertexts are known only for a fraction of the total set of users, for a given label) is not captured by the security model.

As in prior work [CDG+17], we consider the case where clients can be dishonest or corrupted. We thus have to consider collusions, where several clients give their secret keys to an adversary who will play on their behalf.

We define our new security notion below, and highlight the differences with the security definition from [CDG+17]. Namely, the extra requirements (in gray) corresponds to their weaker security definition, which we call IND*, while IND is the new, stronger, security notion.

Definition 2 (IND, IND*-Security Game for MCFE). *Let us consider MCFE, a scheme over a set of n senders. No adversary $\mathcal{A}$ should be able to win the following security game against a challenger $\mathcal{C}$:*

- *Initialize: the challenger $\mathcal{C}$ runs the setup algorithm $(\mathsf{mpk}, \mathsf{msk}, (\mathsf{ek}_i)_i) \leftarrow \mathsf{SetUp}(\lambda)$ and chooses a random bit $b \xleftarrow{\$} \{0,1\}$. It provides mpk to the adversary $\mathcal{A}$;*
- *Encryption queries $\mathsf{QEncrypt}(i, x, \ell)$: $\mathcal{A}$ has unlimited and adaptive access to the encryption oracle, and receives the ciphertext $C_{\ell,i} \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, x, \ell)$;*
- *Challenge queries $\mathsf{QLeftRight}(i, x^0, x^1, \ell)$: $\mathcal{A}$ has unlimited and adaptive access to a Left-or-Right encryption oracle, and receives the ciphertext $C_{\ell,i} \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, x^b, \ell)$;*
- *Functional decryption key queries $\mathsf{QDKeyGen}(f)$: $\mathcal{A}$ has unlimited and adaptive access to the $\mathsf{DKeyGen}(\mathsf{msk}, f)$ algorithm for any input function f of its choice. It is given back the functional decryption key dk_f;*
- *Corruption queries $\mathsf{QCorrupt}(i)$: $\mathcal{A}$ can make an unlimited number of adaptive corruption queries on input index i, to get the encryption key ek_i of any sender i of its choice;*
- *Finalize: $\mathcal{A}$ provides its guess b' on the bit b, and this procedure outputs the result β of the security game, according to the analysis given below.*

The output β of the game depends on some conditions, where $\mathcal{CS}$ is the set of corrupted senders (the set of indexes i input to $\mathsf{QCorrupt}$ during the whole game), and $\mathcal{HS}$ the set of honest (non-corrupted) senders. We set the output to $\beta \leftarrow b'$, unless one of the cases below is true, in which case we set $\beta \xleftarrow{\$} \{0,1\}$:

1. *some $\mathsf{QLeftRight}(i, x_i^0, x_i^1, \ell)$-query has been asked for an index $i \in \mathcal{CS}$ with $x_i^0 \neq x_i^1$;*
2. *for some label ℓ and for some function f asked to $\mathsf{QDKeyGen}$, there exists a pair of vectors $(\boldsymbol{x}^0 = (x_i^0)_i, \boldsymbol{x}^1 = (x_i^1)_i)$ such that $f(\boldsymbol{x}^0) \neq f(\boldsymbol{x}^1)$, when*
   - *$x_i^0 = x_i^1$, for all $i \in \mathcal{CS}$;*
   - *$\mathsf{QLeftRight}(i, x_i^0, x_i^1, \ell)$-queries (or $\mathsf{QEncrypt}(i, x_i, \ell)$-queries if $x_i = x_i^0 = x_i^1$) have been asked for all $i \in \mathcal{HS}$;*
3. *for some label ℓ, a challenge query $\mathsf{QLeftRight}(i, x_i^0, x_i^1, \ell)$ has been asked for some $i \in \mathcal{HS}$, but challenge queries $\mathsf{QLeftRight}(j, x_j^0, x_j^1, \ell)$ or encryption queries $\mathsf{QEncrypt}(j, x_j, \ell)$ have not all been asked for all $j \in \mathcal{HS}$.*

We say MCFE is IND-secure if for any adversary $\mathcal{A}$, $\mathsf{Adv}^{\mathit{IND}}_{\mathit{MCFE}}(\mathcal{A}) = |\Pr[\beta = 1 | b = 1] - \Pr[\beta = 1 | b = 0]|$ is negligible.

We also define a weaker versions of the security game:

- where the adversary must announce in advance the corruption ($\mathsf{QCorrupt}$) queries: static security (sta-IND*/sta-IND);
- where the adversary must announce in advance the challenge ($\mathsf{QLeftRight}$) queries: selective security (sel-IND*/sel-IND);
- where the adversary is limited to one encryption/challenge query on each (i, ℓ): later queries with the same i and ℓ will be ignored by $\mathsf{QEncrypt}$ and $\mathsf{QLeftRight}$: without-repetition security (wtr-IND*/wtr-IND).

Note that the two first above excluded cases are situations where the adversary could trivially distinguish the encrypted vectors, they are thus considered illegitimate attacks:

1. since the encryption might be deterministic, if we allow challenge queries even for corrupted encryption keys, these queries should be on identical messages: with the encryption key, the adversary could simply re-encrypt and compare in case of deterministic encryption. More concretely, since we possibly consider adaptive corruptions, a $\mathsf{QLeftRight}$-query can be asked at some point for an honest sender that will get corrupted later: with the secret encryption key, the adversary can re-encrypt and compare. In the case of static corruptions, this simply means that the adversary should not ask $\mathsf{QLeftRight}$-queries for corrupted clients;
2. for any functional decryption key, all the possible evaluations should not trivially allow the adversary to distinguish the ciphertexts generated through $\mathsf{QLeftRight}$-queries (on honest components), only when ciphertexts are complete.

For such illegitimate attacks, the guess of the adversary is not considered (a random bit β is output). Otherwise, this is a legitimate attack, and the guess b' of the adversary is output.

In [CDG+17], there is the additional restriction on incomplete ciphertexts (in gray), that corresponds to the weaker $\mathtt{IND}^*$ security notion: if for some label ℓ, a challenge-query $\mathsf{QLeftRight}(i, x_i^0, x_i^1, \ell)$ has been asked for some $i \in \mathcal{HS}$, but the ciphertext is incomplete (which means that there is not at least a challenge-query $\mathsf{QEncrypt}(j, x_j^0, x_j^1, \ell)$ or an encryption-query $\mathsf{QEncrypt}(j, x_j, \ell)$ for all $j \in \mathcal{HS}$), the attack is also considered illegitimate, and one sets $\beta \xleftarrow{\$} \{0,1\}$.

[CDG+17] gave a construction that only satisfies this weaker $\mathtt{wtr\text{-}IND}^*$ security definition for Inner Product. On the one hand, we show how to get to from any variant of $\mathtt{IND}^*$ to the same variant of $\mathtt{IND}$, using an extra Secret Sharing Layer, in Section 5. On the other hand, we show how to allow repetitions for Inner Product, in Section 6, by adding a layer of single-input Functional Encryption for Inner Product.

3 Notations and Assumptions

3.1 Groups

Prime Order Group. We use a prime-order group generator GGen, a probabilistic polynomial time (PPT) algorithm that on input the security parameter 1^λ returns a description $\mathcal{G} = (\mathbb{G}, p, P)$ of an additive cyclic group $\mathbb{G}$ of order p for a 2λ-bit prime p, whose generator is P.

We use implicit representation of group elements as introduced in [EHK+13]. For $a \in \mathbb{Z}_p$, define $[a] = aP \in \mathbb{G}$ as the *implicit representation* of a in $\mathbb{G}$. More generally, for a matrix $\mathbf{A} = (a_{ij}) \in \mathbb{Z}_p^{n\times m}$ we define $[\mathbf{A}]$ as the implicit representation of $\mathbf{A}$ in $\mathbb{G}$:

$$[\mathbf{A}] := \begin{pmatrix} a_{11}P & ... & a_{1m}P \\ & & \\ a_{n1}P & ... & a_{nm}P \end{pmatrix} \in \mathbb{G}^{n\times m}$$

We will always use this implicit notation of elements in $\mathbb{G}$, i.e., we let $[a] \in \mathbb{G}$ be an element in $\mathbb{G}$. Note that from a random $[a] \in \mathbb{G}$, it is generally hard to compute the value a (discrete logarithm problem in $\mathbb{G}$). Obviously, given $[a], [b] \in \mathbb{G}$ and a scalar $x \in \mathbb{Z}_p$, one can efficiently compute $[ax] \in \mathbb{G}$ and $[a + b] = [a] + [b] \in \mathbb{G}$.

Pairing Group. We also use a pairing-friendly group generator PGGen, a PPT algorithm that on input 1^λ returns a description $\mathcal{PG} = (\mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_T, p, P_1, P_2, e)$ of asymmetric pairing groups where $\mathbb{G}_1$, $\mathbb{G}_2$, $\mathbb{G}_T$ are additive cyclic groups of order p for a 2λ-bit prime p, P_1 and P_2 are generators of $\mathbb{G}_1$ and $\mathbb{G}_2$, respectively, and $e : \mathbb{G}_1 \times \mathbb{G}_2 \to \mathbb{G}_T$ is an efficiently computable (non-degenerate) bilinear map. Define $P_T := e(P_1, P_2)$, which is a generator of $\mathbb{G}_T$. We again use implicit representation of group elements. For $s \in \{1, 2, T\}$ and $a \in \mathbb{Z}_p$, define $[a]_s = aP_s \in \mathbb{G}_s$ as the implicit representation of a in G_s . Given $[a]_1$, $[a]_2$, one can efficiently compute $[ab]_T$ using the pairing e. For two matrices $\mathbf{A}$, $\mathbf{B}$ with matching dimensions define $e([\mathbf{A}]_1, [\mathbf{B}]_2) := [\mathbf{AB}]_T \in \mathbb{G}_T$.

3.2 Computational Assumptions

Definition 3 (Computational Diffie-Hellman Assumption). *The Computational Diffie-Hellman (CDH) Assumption states that, in a prime-order group $\mathcal{G} \xleftarrow{\$} \mathsf{GGen}(1^\lambda)$, no PPT adversary can compute $[xy]$, from $[x]$ and $[y]$ for $x, y \xleftarrow{\$} \mathbb{Z}_p$, with non-negligible success probability.*

Equivalently, this assumption states it is hard to compute $[a^2]$ from $[a]$ for $a \xleftarrow{\$} \mathbb{Z}_p$. This comes from the fact that $4[xy] = [(x+y)^2] - [(x-y)^2]$.

Definition 4 (Decisional Diffie-Hellman Assumption). *The Decisional Diffie-Hellman (DDH) Assumption states that, in a group $\mathcal{G} \xleftarrow{\$} \mathsf{GGen}(1^\lambda)$, no PPT adversary can distinguish between the two following distributions with non-negligible advantage: $\{([a],[r],[ar]) \mid a, r \xleftarrow{\$} \mathbb{Z}_p\}$ and $\{([a],[r],[s]) \mid a, r, s \xleftarrow{\$} \mathbb{Z}_p\}$.*

Equivalently, this assumption states it is hard to distinguish, knowing $[a]$, a random element from the span of $[\boldsymbol{a}]$ for $\boldsymbol{a} = \binom{1}{a}$, from a random element in $\mathbb{G}^2$: $[\boldsymbol{a}] \cdot r = [\boldsymbol{a}r] = \binom{[r]}{[ar]} \approx \binom{[r]}{[s]}$.

Definition 5 (Decisional Bilinear Diffie Hellman Assumption). *The Decisional Bilinear Diffie Hellman (DBDH) Assumption states that, in a pairing group $\mathcal{PG} \xleftarrow{\$} \mathsf{PGGen}(1^\lambda)$, for any PPT adversary, the following advantage is negligible, where the probability distribution is over $a, b, c, s \xleftarrow{\$} \mathbb{Z}_p$:*

$$\begin{aligned}\mathsf{Adv}^{\mathsf{DBDH}}_{\mathcal{PG}}(\mathcal{A}) = \mid &\Pr[1 \leftarrow \mathcal{A}(\mathcal{PG}, [a]_1, [b]_1, [b]_2, [c]_2, [abc]_T)] \\ &- \Pr[1 \leftarrow \mathcal{A}(\mathcal{PG}, [a]_1, [b]_1, [b]_2, [c]_2, [s]_T)] \mid.\end{aligned}$$

Definition 6 (Q-fold DBDH). *For any integer Q, the Q-fold DBDH assumption states for any PPT adversary, the following advantage is negligible, where the probability distribution is over $a, b, c_i, s_i \xleftarrow{\$} \mathbb{Z}_p$:*

$$\begin{aligned}\mathsf{Adv}^{Q\text{-}\mathsf{DBDH}}_{\mathcal{PG}}(\mathcal{A}) = \mid &\Pr[1 \leftarrow \mathcal{A}(\mathcal{PG}, [a]_1, [b]_1, [b]_2, \{[c_i]_2, [abc_i]_T\}_{i \in [Q]})] \\ &- \Pr[1 \leftarrow \mathcal{A}(\mathcal{PG}, [a]_1, [b]_1, [b]_2, \{[c_i]_2, [s_i]_T\}_{i \in [Q]})] \mid.\end{aligned}$$

This Q-fold DBDH assumption is equivalent to classical DBDH assumption:

Lemma 7 (Random Self Reducibility of DBDH). *For any adversary $\mathcal{A}$ against the Q-fold DBDH, running within time t, there exists an adversary $\mathcal{B}$ running within time $t + 2Q(t_{\mathbb{G}_T} + t_{\mathbb{G}_2})$, where $t_{\mathbb{G}_T}$ and $t_{\mathbb{G}_2}$ denote respectively the time for an exponentiation in $\mathbb{G}_T$ and $\mathbb{G}_2$ (we only take into account the time for exponentiations here), such that*

$$\mathsf{Adv}^{Q\text{-}\mathsf{DBDH}}_{\mathcal{PG}}(\mathcal{A}) \leq \mathsf{Adv}^{\mathsf{DBDH}}_{\mathcal{PG}}(\mathcal{B}).$$

Proof. Upon receiving a DBDH challenge $(\mathcal{PG}, [a]_1, [b]_1, [b]_2, [c]_2, [s]_T)$, $\mathcal{B}$ samples $\alpha_i, c'_i \xleftarrow{\$} \mathbb{Z}_p$ computes $[c_i]_2 := [\alpha_i \cdot c]_2 + [c'_i]_2$, $[s_i]_T := [\alpha_i \cdot s]_T + [c_i \cdot ab]_T$ for all $i \in [Q]$, and gives the challenge $(\mathcal{PG}, [a]_1, [b]_1, [b]_2, \{[c_i]_2, [s_i]_T\}_{i \in [Q]})$ to $\mathcal{A}$.

3.3 Symmetric Key Encryption

A symmetric key encryption $(\mathsf{SEnc}, \mathsf{SDec})$ with key space $\mathcal{K}$ is defined as:

- $\mathsf{SEnc}(K, m)$: given a key K and a message m, outputs a ciphertext ct;
- $\mathsf{SDec}(K, \mathsf{ct})$: given a key K and a ciphertext ct, output a plaintext.

The following must hold:

Correctness. For all m in the message space, $\Pr[\mathsf{SDec}(K, \mathsf{SEnc}(K, m)) = m] = 1$, where the probability is taken over $K \xleftarrow{\$} \mathcal{K}$.

One Time Security. For any PPT adversary $\mathcal{A}$, the following advantage is negligible:

$$\mathsf{Adv}^{\mathsf{OT}}_{\mathsf{SKE}}(\mathcal{A}) := \left| 2 \times \Pr\left[b' = b : \begin{array}{c} (m_0, m_1) \leftarrow \mathcal{A}(1^\lambda) \\ K \stackrel{\$}{\leftarrow} \mathcal{K}, b \stackrel{\$}{\leftarrow} \{0,1\}, \mathsf{ct} = \mathsf{SEnc}(K, m_b) \\ b' \leftarrow \mathcal{A}(\mathsf{ct}) \end{array} \right] - 1 \right|.$$

If the key space is larger than the message space, on can simply use the one-time pad to build a one-time secure symmetric encryption. Otherwise, a pseudo-random generator can stretch the key to the right length.

3.4 Single Input Functional Encryption

A private-key, single input Functional Encryption for a family $\mathcal{F}$ consists of the following PPT algorithms:

- $\mathsf{SetUp}(\lambda)$: on input a security parameter, it outputs a master secret key msk and a public key mpk. The latter is implicitly input of all other algorithms.
- $\mathsf{Encrypt}(\mathsf{msk}, m)$: on input the master secret key and a message, it outputs a ciphertext ct.
- $\mathsf{DKeyGen}(\mathsf{msk}, f)$: on input the master secret key and a function $f \in \mathcal{F}$, it outputs a decryption key dk_f.
- $\mathsf{Dec}(\mathsf{ct}, \mathsf{dk}_f)$: deterministic algorithm that returns a message or a rejection symbol $\perp$ if it fails.

Correctness and security, as defined below, must hold:

Correctness. For any message m, and any function f in the family $\mathcal{F}$, we have: $\Pr[\mathsf{Dec}(\mathsf{ct}, \mathsf{dk}_f) = f(m)] = 1$, where the probability is taken over $(\mathsf{msk}, \mathsf{mpk}) \leftarrow \mathsf{SetUp}(\lambda)$, $\mathsf{ct} \leftarrow \mathsf{Encrypt}(\mathsf{msk}, m)$, and $\mathsf{dk}_f \leftarrow \mathsf{DKeyGen}(\mathsf{msk}, f)$.

Indistinguishability. The security notion is defined by an indistinguishability game similar to the previous one for MCFE:

Definition 8 (IND-Security Game for FE). *Let* FE *be a functional encryption scheme. No adversary* $\mathcal{A}$ *should be able to win the following security game:*

- *Initialize: runs* $(\mathsf{msk}, \mathsf{mpk}) \leftarrow \mathsf{SetUp}(\lambda)$*, choose a random bit* $b \stackrel{\$}{\leftarrow} \{0,1\}$ *and returns* mpk *to* $\mathcal{A}$.
- $\mathsf{QLeftRight}(m_0, m_1)$*: on input two messages* (m_0, m_1)*, returns* $\mathsf{Enc}(\mathsf{msk}, m_b)$.
- $\mathsf{QDKeyGen}(f)$*: on input a function* $f \in \mathcal{F}$*, returns* $\mathsf{DKeyGen}(\mathsf{msk}, f)$.
- *Finalize: it outputs the guess* b' *of* $\mathcal{A}$ *on the bit* b*, unless some* f *was queried to* $\mathsf{QDKeyGen}$ *and* (m_0, m_1) *was queried to* $\mathsf{QLeftRight}$ *such that* $f(m_0) \neq f(m_1)$*, in which case it outputs a uniformly random bit, independent of* $\mathcal{A}$*'s guess.*

The adversary $\mathcal{A}$ *has unlimited and adaptive access to the left-right encryption oracle* $\mathsf{QLeftRight}$*, and to the key generation oracle* $\mathsf{QDKeyGen}$*. We say* FE *is IND-secure if for any adversary* $\mathcal{A}$*,* $\mathsf{Adv}^{\mathit{IND}}_{\mathsf{FE}}(\mathcal{A}) = |\Pr[b' = 1 | b = 1] - \Pr[b' = 1 | b = 0]|$ *is negligible.*

We can also define a weaker selective variant, where pairs (m_0, m_1) to $\mathsf{QLeftRight}$-queries are known from the beginning.

4 Secret Sharing Layer

As explained in Section 2, the difference between our indistinguishability notion and the previous one [CDG+17], is that incomplete ciphertexts were considered illegitimate. This was with the intuition that no adversary should use it since this leaks no information. But actually, an adversary could exploit that in the real-life. Our new security notion requires the scheme to actually leak nothing in such a case.

Here, we present a generic layer, called the Secret Sharing Layer (SSL), that we will use to encapsulate ciphertexts. It allows a user to recover the ciphertexts from the n senders only when he gets the contributions of all the servers. That is, if one sender did not send anything, the user cannot get any information from any of the ciphertexts of the other senders. More concretely, a share of a key $S_{\ell,i}$ is generated for each user $i \in [n]$ and each label ℓ. Unless all the shares $S_{i,\ell}$ have been generated, the encapsulation keys are random and mask all the ciphertexts.

After giving the definition of SSL, we provide a construction whose security is based on the DBDH assumption.

4.1 Definitions

Definition 9 (Secret Sharing Layer (SSL)). *A secret sharing layer on $\mathcal{K}$ over a set of n senders is defined by four algorithms:*

- $\mathsf{SSL.SetUp}(\lambda)$*: Takes as input a security parameter λ and generates the public parameters $\mathsf{pk_{ssl}}$ and the personal encryption keys are $\mathsf{ek}_{\mathsf{ssl},i}$ for all $i \in [n]$;*
- $\mathsf{SSL.Encaps}(\mathsf{pk_{ssl}}, \ell)$*: Takes as input the public parameters $\mathsf{pk_{ssl}}$ and the label ℓ and outputs a ciphertext C_ℓ and an encapsulation key $K_\ell \in \mathcal{K}$;*
- $\mathsf{SSL.Share}(\mathsf{ek}_{\mathsf{ssl},i}, \ell)$*: Takes as input a personal encryption $\mathsf{ek}_{\mathsf{ssl},i}$ and the label ℓ, outputs the share $S_{\ell,i}$;*
- $\mathsf{SSL.Decaps}(\mathsf{pk_{ssl}}, (S_{\ell,i})_{i\in[n]}, \ell, C_\ell)$*: Takes as input all the shares $S_{\ell,i}$ for all $i \in [n]$, a label ℓ, and a ciphertext C_ℓ, and outputs the encapsulation key K_ℓ.*

Correctness. For any label ℓ, we have: $\Pr[\mathsf{SSL.Decaps}(\mathsf{pk_{ssl}}, (S_{\ell,i})_{i\in[n]}, \ell, C_\ell) = K_\ell] = 1$, where the probability is taken over $\big(\mathsf{pk_{ssl}}, (\mathsf{ek}_{\mathsf{ssl},i})_{i\in[n]}\big) \leftarrow \mathsf{SSL.SetUp}(\lambda)$, $(C_\ell, K_\ell) \leftarrow \mathsf{SSL.Encaps}(\mathsf{pk_{ssl}}, \ell)$, and $S_{\ell,i} \leftarrow \mathsf{SSL.Share}(\mathsf{ek}_{\mathsf{ssl},i}, \ell)$ for all $i \in [n]$.

Indistinguishability. We want to show that the encapsulated keys are indistinguishable from random if not all the shares are known to the adversary. We could define a Real-or-Random security game [BDJR97] for all the masks. Instead, we limit the Real-or-Random queries to one label only (whose index is chosen in advance), and for all the other labels, the adversary can do the encapsulation by itself, since it just uses a public key. This is well-known that a hybrid proof among the label indices (the order they appear in the game) shows that the One-Label security is equivalent to the Many-Label security. The One-Label definition will be enough for our applications.

Definition 10 (`1-Label-IND`-Security Game for SSL). *Let us consider an SSL scheme over a set of n senders. No adversary $\mathcal{A}$ should be able to win the following security game against a challenger $\mathcal{C}$, where $\mathcal{HS}$ is the set of honest senders and $\mathcal{CS}$ the set of corrupted senders, and the labels ℓ_j are ordered by their first use in the game:*

- *Initialize(ρ): the adversary announces the index of the unique label $\ell^* = \ell_\rho$ that will be involved in challenge queries. The challenger $\mathcal{C}$ runs the setup algorithm $(\mathsf{pk_{ssl}}, (\mathsf{ek}_{\mathsf{ssl},i})_{i\in[n]}) \leftarrow \mathsf{SetUp}(\lambda)$ and chooses a random bit $b \xleftarrow{\$} \{0,1\}$. It provides $\mathsf{pk_{ssl}}$ to the adversary $\mathcal{A}$, together with the keys $\{\mathsf{ek}_{\mathsf{ssl},i}\}_{i\in\mathcal{CS}}$;*
- *Challenge queries $\mathsf{QRealRandom}(\ell_\rho)$: $\mathcal{A}$ has an unlimited access to a Real-or-Random encapsulation oracle (for the label ℓ_ρ only), and receives a ciphertext C_{ℓ_ρ}, together with an encapsulation key $K^b_{\ell_\rho}$, where $(C_{\ell_\rho}, K^0_{\ell_\rho}) \leftarrow \mathsf{SSL.Encaps}(\mathsf{pk_{ssl}}, \ell_\rho)$, and $K^1_{\ell_\rho} \xleftarrow{\$} \mathcal{K}$, where $\mathcal{K}$ is the encapsulation key space;*
- *Sharing queries $\mathsf{QShare}(i, \ell_j)$: $\mathcal{A}$ has unlimited and adaptive access to the sharing oracle, and gets $S_{\ell_j,i} \leftarrow \mathsf{SSL.Share}(\mathsf{ek}_{\mathsf{ssl},i}, \ell_j)$;*
- *Corruption queries $\mathsf{QCorrupt}(i)$: $\mathcal{A}$ can make an unlimited number of adaptive corruption queries on input index i, to get the encapsulation key $\mathsf{ek}_{\mathsf{ssl},i}$;*
- *Finalize: $\mathcal{A}$ provides its guess b' on the bit b, and this procedure outputs this $\beta \leftarrow b'$ if, for the label $\ell^* = \ell_\rho$, there is an honest index $i^* \in \mathcal{HS}$ for which (ℓ^*, i^*) has not been asked to the sharing oracle, otherwise a random bit β is output.*

We say this SSL *is* $\texttt{1-Label-IND}$*-secure if for any adversary* $\mathcal{A}$*, its advantage* $\mathsf{Adv}_{\mathsf{SSL}}^{\texttt{1-Label-IND}}(\mathcal{A}) = |\Pr[\beta = 1|b = 1] - \Pr[\beta = 1|b = 0]|$ *is negligible.*

We can also define the weaker static variant, where corruptions are known from the beginning.

4.2 Construction of the Secret Sharing Layer

Let us exhibit a concrete construct for our main tool SSL, in the random oracle model, under the DBDH assumption.

- $\mathsf{SSL.SetUp}(\lambda)$: Takes as input a security parameter λ and generates $\mathcal{PG} = (\mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_T, p_{\mathsf{ssl}}, P_1, P_2, e) \stackrel{\$}{\leftarrow} \mathsf{PGGen}_{\mathsf{ssl}}(1^\lambda)$. Generates a full domain hash function $\mathcal{H}_{\mathsf{ssl}}$ from $\{0,1\}^\lambda$ into $\mathbb{G}_1$. It also generates $\boldsymbol{t} \stackrel{\$}{\leftarrow} \mathbb{Z}_p^n$. The public parameters $\mathsf{pk}_{\mathsf{ssl}}$ consist of $(\mathcal{PG}, \mathcal{H}_{\mathsf{ssl}}, T_2)$, with $T_2 = [\sum_j t_j]_2$ and the personal encapsulation keys are $\mathsf{ek}_{\mathsf{ssl},i} = t_i$.
- $\mathsf{SSL.Share}(\mathsf{ek}_{\mathsf{ssl},i}, \ell)$: Takes as input the key $\mathsf{ek}_{\mathsf{ssl},i} = t_i$ and the label ℓ and outputs the share $S_{\ell,i} = t_i \cdot \mathcal{H}_{\mathsf{ssl}}(\ell) \in \mathbb{G}_1$.
- $\mathsf{SSL.Encaps}(\mathsf{pk}_{\mathsf{ssl}}, \ell)$: Takes as input the public key $\mathsf{pk}_{\mathsf{ssl}} = (\mathcal{PG}, \mathcal{H}_{\mathsf{ssl}}, T_2)$ and the label ℓ, samples $r \stackrel{\$}{\leftarrow} \mathbb{Z}_p$, and outputs the ciphertext C_ℓ and the encapsulation key K_ℓ defined as: $C_\ell = [r]_2, K_\ell = e(\mathcal{H}_{\mathsf{ssl}}(\ell), r \cdot T_2))$.
- $\mathsf{SSL.Decaps}(\mathsf{pk}_{\mathsf{ssl}}, (S_{\ell,i})_{i\in[n]}, \ell, C_\ell)$: Takes as input all the shares $S_{\ell,i}$ for all $i \in [n]$, a label ℓ and a ciphertext C_ℓ, and outputs an encapsulation key

$$K_\ell = e\left(\sum_j S_{\ell,j}, C_\ell\right).$$

We stress here that K_ℓ is not unique for each label ℓ: whereas $S_{\ell,i}$ deterministically depends on ℓ and the client i, K_ℓ is randomized by the random coins r. Hence, with all the shares, using a specific C_ℓ one can recover the associated K_ℓ. Correctness follows from the fact that the above decapsulated key K_ℓ is equal to

$$e\left(\sum_j t_j \mathcal{H}_{\mathsf{ssl}}(\ell), [r]_2\right) = e\left(\mathcal{H}_{\mathsf{ssl}}(\ell), [r \cdot \sum_j t_j]_2\right) = e\left(\mathcal{H}_{\mathsf{ssl}}(\ell), r \cdot T_2\right),$$

where the pair (C_ℓ, K_ℓ) has been generated by the same $\mathsf{SSL.Encaps}$ call, with the same random r. The intuition for the security is that given all the $S_{\ell,i} = t_i \cdot \mathcal{H}_{\mathsf{ssl}}(\ell)$ for a label ℓ, one can recover the masks $K_\ell = e(\mathcal{H}_{\mathsf{ssl}}(\ell), r \cdot T_2)$ using $C_\ell = [r]_2$. However if $S_{\ell,i}$ is missing for one slot i, then all the encapsulation keys K_ℓ are pseudo-random, from the DBDH assumption.

4.3 Security Proof

Let $\mathcal{A}$ be a PPT adversary against the security of the above SSL. We build a PPT adversary $\mathcal{B}$ against the q_r-fold DBDH such that:

$$\mathsf{Adv}_{\mathsf{SSL}}^{\texttt{1-Label-IND}}(\mathcal{A}) \leq n \times \mathsf{Adv}_{\mathcal{PG}}^{q_r\text{-}\mathsf{DBDH}}(\mathcal{B}),$$

where q_h denotes the number of $\mathcal{H}_{\mathsf{ssl}}$ queries (explicit or implicit) and q_r the number of challenge-queries to the $\mathsf{QRealRandom}$ oracle. Applying Lemma 7, one can reduce the security to the DBDH assumption.

Let us thus consider a simulator $\mathcal{B}$ that receives a q_r-fold DBDH challenge $(\mathcal{PG}, [a]_1, [b]_1, [b]_2, \{[c_i]_2, [s_i]_T\}_i)$, and simulates the view of the $\texttt{1-Label-IND}$ for SSL adversary $\mathcal{A}$ as follows:

- Initialize(ρ): $\mathcal{B}$ guesses an index $i^* \stackrel{\$}{\leftarrow} [n]$, samples $t_i \stackrel{\$}{\leftarrow} \mathbb{Z}_p$ for all $i \neq i^*$, sets $[t_{i^*}]_2 \leftarrow [b]_2$, and returns $\mathsf{pk}_{\mathsf{ssl}} = (\mathcal{PG}, T_2 = [\sum_j t_j]_2)$ to $\mathcal{A}$;

– $\mathcal{H}_{\mathsf{ssl}}(\ell)$: if this is the ρ-th new query, one sets $\ell^* \leftarrow \ell$ and $\mathcal{H}_{\mathsf{ssl}}(\ell^*) \leftarrow [a]_1$. For others queries, $\mathcal{B}$ outputs $[h]_1$ for a random $h \xleftarrow{\$} \mathbb{Z}_p$. $\mathcal{B}$ keeps track of the queries and outputs to the random oracle $\mathcal{H}$, so that it answers two identical queries with the same output;
– $\mathsf{QRealRandom}(\ell)$: if not done yet, one asks for $\mathcal{H}_{\mathsf{ssl}}(\ell)$. If ℓ isn't the ρ-th new query ℓ^* to $\mathcal{H}_{\mathsf{ssl}}$, then nothing is returned to $\mathcal{A}$. Otherwise $\mathcal{B}$ sets $C_{\ell^*} \leftarrow [c_j]_2$, for the next index j in the q_r-fold DBDH instance, and computes $K_{\ell^*} \leftarrow [s_j]_T + e([a]_1, (\sum_{i \neq i^*} t_i) \cdot [c_j]_2)$. It returns (C_{ℓ^*}, K_{ℓ^*}) to $\mathcal{A}$;
– $\mathsf{QShare}(i, \ell)$: if not done yet, one asks for $\mathcal{H}_{\mathsf{ssl}}(\ell)$. If $(i, \ell) = (i^*, \ell^*)$, one aborts the simulation. Otherwise, $\mathcal{B}$ computes and gives back the share $S_{\ell,i} = t_i \cdot \mathcal{H}_{\mathsf{ssl}}(\ell)$, where $\mathcal{H}_{\mathsf{ssl}}$ is computed as described above, for $i \neq i^*$, or $S_{\ell,i} = h \cdot [b]_1$, if $i = i^*$, where $\mathcal{H}_{\mathsf{ssl}}(\ell) = [h]_1$, and h is known, since $\ell \neq \ell^*$;
– $\mathsf{QCorrupt}(i)$: if $i = i^*$, one aborts the simulation, otherwise one returns t_i to $\mathcal{A}$.

One can remark that in this simulation we need to query $\mathcal{H}_{\mathsf{ssl}}(\ell)$, if not done yet, during $\mathsf{QRealRandom}$ and QShare queries, in order to determine which ℓ is the ρ-th one in the game. These are the so-called implicit queries. First, one can note that the simulation does not abort if (i^*, ℓ^*) has not been asked to QShare and i^* is not corrupted, which happens with probability greater than $1/n$ if we know that one share is not known for ℓ^*. Then, one also notes that when $\mathcal{B}$ receives a real q_r-fold DBDH challenge, that is $s_j = abc_j$ for all indices j, then $\mathcal{B}$ simulates the `1-Label-IND`-security game with $b = 0$. Indeed, since $b = t_{i^*}$, for the j-th $\mathsf{QRealRandom}$-query, we have:

$$\begin{aligned} K_{\ell^*} &= [s_j]_T + e([a]_1, (\sum_{i \neq i^*} t_i) \cdot [c_j]_2) = [abc_j]_T + e([a]_1, (\sum_{i \neq i^*} t_i) \cdot [c_j]_2) \\ &= e([a]_1, [bc_j]_2) + e([a]_1, (\sum_{i \neq i^*} t_i) \cdot [c_j]_2) = e([a]_1, [bc_j]_2 + (\sum_{i \neq i^*} t_i) \cdot [c_j]_2) \\ &= e([a]_1, (b + \sum_{i \neq i^*} t_i) \cdot [c_j]_2) = e([a]_1, (\sum_{i} t_i) \cdot [c_j]_2) = e(\mathcal{H}_{\mathsf{ssl}}(\ell^*), c_j \cdot T_2) \end{aligned}$$

where $C_{\ell^*} = [c_j]_2$. With a random q_r-fold DBDH challenge, the simulation corresponds to the case $b = 1$, which concludes the proof.

5 Strengthening the Security of MCFE using SSL

We now show how we can enhance the security of any MCFE using a Secret Sharing Layer as defined in Section 4. Namely, we show that the construction of Section 5.2 is `IND` secure if the underlying the MCFE is `1-Label-IND`*-secure, thereby removing the complete-ciphertext restriction. The `1-Label-IND`* security is exactly the same security notion as `IND`* where the challenge $\mathsf{QLeftRight}$ oracle can only be queried with the same label. Hence, as above, the index ρ of the target label ℓ^* is provided by the adversary, at the beginning, and so we can assume that all the encryption queries for $\ell^* = \ell_\rho$ are asked to the $\mathsf{QLeftRight}$ oracle, while the other encryption queries are asked to the $\mathsf{QEncrypt}$ oracle (contrarily to the encapsulation in the SSL scheme, encryption uses a secret key). It is well-known that `1-Label-IND`* and `IND`* are equivalent [BDJR97], but the former is more convenient in our security proof.

5.1 `1-Label-IND`* Security for MCFE

As just explained, the `1-Label-IND`*-security game for MCFE is exactly the `IND`*-security game for MCFE from Definition 2 where only one label ℓ^* is allowed in the challenge $\mathsf{QLeftRight}$ oracle, defined by its index ρ, at the initialization step. We assume that all the other encryption queries are asked to the $\mathsf{QEncrypt}$ oracle.

Definition 11 (`1-Label-IND`*-Security Game for MCFE). *Let us consider MCFE, a scheme over a set of n senders. No adversary $\mathcal{A}$ should be able to win the following security game against a challenger $\mathcal{C}$:*

– *Initialize*(ρ)*: the adversary announces the index of the unique label* $\ell^* = \ell_\rho$ *that will be involved in challenge queries. The challenger* $\mathcal{C}$ *runs the setup algorithm* $(\mathsf{mpk}, \mathsf{msk}, (\mathsf{ek}_i)_i) \leftarrow \mathsf{SetUp}(\lambda)$ *and chooses a random bit* $b \stackrel{\$}{\leftarrow} \{0,1\}$*. It provides* mpk *to the adversary* $\mathcal{A}$*;*
– *Encryption queries* $\mathsf{QEncrypt}(i, x, \ell_j)$*:* $\mathcal{A}$ *has unlimited and adaptive access to the encryption oracle (for* $j \neq \rho$*), and receives the ciphertext* $C_{\ell_j,i} \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, x, \ell_j)$*;*
– *Challenge queries* $\mathsf{QLeftRight}(i, x^0, x^1, \ell_\rho)$*:* $\mathcal{A}$ *has unlimited and adaptive access to a Left-or-Right encryption oracle (for the label* ℓ_ρ *only), and receives the ciphertext* $C_{\ell_\rho,i} \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, x^b, \ell_\rho)$*;*
– *Functional decryption key queries* $\mathsf{QDKeyGen}(f)$*:* $\mathcal{A}$ *has unlimited and adaptive access to the* $\mathsf{DKeyGen}(\mathsf{msk}, f)$ *algorithm for any input function* f *of its choice. It is given back the functional decryption key* dk_f*;*
– *Corruption queries* $\mathsf{QCorrupt}(i)$*:* $\mathcal{A}$ *can make an unlimited number of adaptive corruption queries on input index* i*, to get the encryption key* ek_i *of any sender* i *of its choice;*
– *Finalize:* $\mathcal{A}$ *provides its guess* b' *on the bit* b*, and this procedure outputs the result* β *of the security game, according to the analysis given below, where* $\ell^* = \ell_\rho$*.*

The output β *of the game depends on some conditions, where* $\mathcal{CS}$ *is the set of corrupted senders (the set of indexes* i *input to* $\mathsf{QCorrupt}$ *during the whole game), and* $\mathcal{HS}$ *the set of honest (non-corrupted) senders. We set the output to* $\beta \leftarrow b'$*, unless one of the cases below is true, in which case we set* $\beta \stackrel{\$}{\leftarrow} \{0,1\}$*:*

1. *some* $\mathsf{QLeftRight}(i, x_i^0, x_i^1, \ell^*)$*-query has been asked for an index* $i \in \mathcal{CS}$ *with* $x_i^0 \neq x_i^1$*;*
2. *for some function* f *asked to* $\mathsf{QDKeyGen}$*, there exists a pair of vectors* $(\boldsymbol{x}^0 = (x_i^0)_i, \boldsymbol{x}^1 = (x_i^1)_i)$ *such that* $f(\boldsymbol{x}^0) \neq f(\boldsymbol{x}^1)$*, when*
   – $x_i^0 = x_i^1$*, for all* $i \in \mathcal{CS}$*;*
   – $\mathsf{QLeftRight}(i, x_i^0, x_i^1, \ell^*)$*-queries have been asked for all* $i \in \mathcal{HS}$*.*
3. *a challenge query* $\mathsf{QLeftRight}(i, x_i^0, x_i^1, \ell^*)$ *has been asked for some* $i \in \mathcal{HS}$*, but challenge queries* $\mathsf{QLeftRight}(j, x_j^0, x_j^1, \ell^*)$ *have not all been asked for all* $j \in \mathcal{HS}$*.*

We say MCFE is `1-Label-IND`**-secure if for any adversary* $\mathcal{A}$*, its advantage* $\mathsf{Adv}_{\mathit{MCFE}}^{\mathtt{1\text{-}Label\text{-}IND}^*}(\mathcal{A}) = |\Pr[\beta = 1 | b = 1] - \Pr[\beta = 1 | b = 0]|$ *is negligible.*

We can also define the weaker static, selective, and/or without-repetition variants.

5.2 Generic Construction of IND-Secure MCFE

Let $\mathsf{MCFE} := (\mathsf{SetUp}, \mathsf{Encrypt}, \mathsf{DKeyGen}, \mathsf{Decrypt})$ be a Multi-Client Functional Encryption (see Definition 1), $\mathsf{SSL} := (\mathsf{SSL.SetUp}, \mathsf{SSL.Encaps}, \mathsf{SSL.Decaps})$ be a Secret Sharing Layer (see Definition 9), and $\mathsf{SKE} := (\mathsf{SEnc}, \mathsf{SDec})$ be Symmetric Encryption scheme (as defined in Section 3.3) with same key space as SSL, and whose message space is the ciphertext space of MCFE. We define $\mathsf{MCFE}' = (\mathsf{SetUp}', \mathsf{Encrypt}', \mathsf{DKeyGen}', \mathsf{Decrypt}')$ as follows:

– $\mathsf{SetUp}'(\lambda)$: It executes $(\mathsf{mpk}, \mathsf{msk}, (\mathsf{ek}_i)_i) \leftarrow \mathsf{SetUp}(\lambda)$ and $(\mathsf{pk}_{\mathsf{ssl}}, (\mathsf{ek}_{\mathsf{ssl},i})_i) \leftarrow \mathsf{SSL.SetUp}(\lambda)$. The public parameters mpk' consist of $\mathsf{mpk} \cup \mathsf{pk}_{\mathsf{ssl}}$, while the encryption keys are $\mathsf{ek}'_i = \mathsf{ek}_i \cup \mathsf{ek}_{\mathsf{ssl},i}$ for $i = 1, \ldots, n$, and the master secret key is $\mathsf{msk}' = \mathsf{msk}$;
– $\mathsf{Encrypt}'(\mathsf{ek}'_i, x_i, \ell)$: It parses the encryption key ek'_i as $\mathsf{ek}_i \cup \mathsf{ek}_{\mathsf{ssl},i}$, runs $C_{\ell,i} \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, x_i, \ell)$, $(C_\ell, K_\ell) \leftarrow \mathsf{SSL.Encaps}(\mathsf{pk}_{\mathsf{ssl}}, \ell)$, and $S_{\ell,i} \leftarrow \mathsf{SSL.Share}(\mathsf{ek}_{\mathsf{ssl},i}, \ell)$. The ciphertext $C'_{\ell,i}$ is set to $(D_{\ell,i} = \mathsf{SEnc}(K_\ell, C_{\ell,i}), C_\ell, S_{\ell,i})$;
– $\mathsf{DKeyGen}'(\mathsf{msk}', f)$: With $\mathsf{msk} = \mathsf{msk}'$, it runs $\mathsf{dk}_f = \mathsf{DKeyGen}(\mathsf{msk}, f)$;
– $\mathsf{Decrypt}'(\mathsf{dk}_f, \ell, (C'_{\ell,i})_{i \in [n]})$: Takes as input a functional decryption key dk_f, a label ℓ, and ciphertexts $(C'_{\ell,i} = (D_{\ell,i}, C_\ell, S_{\ell,i}))_{i \in [n]}$. It operates in two steps; first it applies $\mathsf{SSL.Decaps}_{\mathsf{ssl}}(\mathsf{pk}_{\mathsf{ssl}}, (S_{\ell,i})_{i \in [n]}, \ell, C_\ell)$ on all the ciphertexts C_ℓ to get all the encapsulation keys K_ℓ's and thus all the plaintexts $C_{\ell,i}$'s using SDec on $D_{\ell,i}$. Then it runs $\mathsf{Decrypt}(\mathsf{dk}_f, \ell, (C_{\ell,i})_{i \in [n]})$.

5.3 Security Analysis

We now show that this generic construction MCFE' achieves $\texttt{IND}$-security, assuming the underlying MCFE is $\texttt{1-Label-IND}^*$-secure (see Definition 11)), SSL is $\texttt{1-Label-IND}$-secure (see Definition 10), and the symmetric encryption is one-time secure (see definition in Section 3.3). More precisely, we can state the following security result:

Theorem 12. *For any adversary $\mathcal{A}$ running within time t, against the $\texttt{IND}$-security of the above MCFE',*

$$\mathsf{Adv}^{\texttt{IND}}_{\mathsf{MCFE}'}(\mathcal{A}) \leq (n+1) \cdot L \times \left(\begin{array}{l} \mathsf{Adv}^{\texttt{1-Label-IND}^*}_{\mathsf{MCFE}}(t) + 2 \cdot \mathsf{Adv}^{\texttt{1-Label-IND}}_{\mathsf{SSL}}(t') \\ +q_e \cdot \mathsf{Adv}^{\mathsf{OT}}_{\mathsf{SKE}}(t'') \end{array} \right),$$

with t' and t'' quite close to t, where L is the total number of labels involved in the security game and q_e is the maximum number of ciphertexts generated under a label. In addition $\mathsf{Adv}(t)$, for any security notion, is the maximum advantage an algorithm can get within time t.

We stress that this security result keeps all the properties of the basic MCFE and the SSL schemes:

- if MCFE and SSL are both secure against adaptive corruptions, MCFE' is also $\texttt{IND}$ against adaptive corruptions;
- if MCFE is secure with repetitions, MCFE' is also $\texttt{IND}$ with repetitions.

The proof uses a hybrid argument that goes over all the labels $\ell_1, \ldots, \ell_L$ used as input to the queries $\mathcal{A}$ makes to $\mathsf{QEncrypt}'$ or $\mathsf{QLeftRight}'$ oracles. We define the following hybrid games, for all $\rho = 0, \ldots, L$:

Game $\mathbf{G}_\rho$: This hybrid game outputs right answers for the $\mathsf{QLeftRight}'$-queries involving the first ρ labels, and left answers for the other labels, to the $\texttt{IND}$-adversary $\mathcal{A}$, as follows:

- Initialize: it gets the global parameters $(\mathsf{mpk}, \mathsf{msk}, (\mathsf{ek}_i)_{i\in[n]}) \leftarrow \mathsf{SetUp}(\lambda)$, $(\mathsf{pk}_{\mathsf{ssl}}, (\mathsf{ek}_{\mathsf{ssl},i})_{i\in[n]}) \leftarrow \mathsf{SSL.SetUp}(\lambda)$ and it returns the public ones $\mathsf{mpk}' = \mathsf{mpk} \cup \mathsf{pk}_{\mathsf{ssl}}$ to the adversary $\mathcal{A}$;
- $\mathsf{QEncrypt}'(i, x, \ell_j)$: it returns $\mathsf{Encrypt}'(\mathsf{ek}_i, x, \ell_j)$;
- $\mathsf{QLeftRight}'(i, x^0, x^1, \ell_j)$: if $j \leq \rho$, it returns $\mathsf{Encrypt}'(\mathsf{ek}_i, x^1, \ell_j)$, if $j > \rho$, it returns $\mathsf{Encrypt}'(\mathsf{ek}_i, x^0, \ell_j)$;
- $\mathsf{QDKeyGen}'(f)$: it returns $\mathsf{DKeyGen}'(\mathsf{msk}, f)$;
- $\mathsf{QCorrupt}'(i)$: it returns $\mathsf{ek}'_i = \mathsf{ek}_i \cup \mathsf{ek}_{\mathsf{ssl},i}$;
- Finalize: as in Definition 2, for $\texttt{IND}$-security.

For any hybrid game $\mathbf{G}_\rho$, we denote by $\mathsf{Adv}_{\mathbf{G}_\rho}(\mathcal{A}) := \Pr[\beta = 1]$, where β is the output of Finalize. Note that $\mathsf{Adv}^{\mathsf{IND}}_{\mathsf{MCFE}'}(\mathcal{A}) = |\mathsf{Adv}_{\mathbf{G}_0}(\mathcal{A}) - \mathsf{Adv}_{\mathbf{G}_L}(\mathcal{A})|$. Lemma 13 states that for all $i \in [L]$, $|\mathsf{Adv}_{\mathbf{G}_{i-1}}(\mathcal{A}) - \mathsf{Adv}_{\mathbf{G}_i}(\mathcal{A})|$ is negligible, which concludes the proof.

Lemma 13. *For any adversary $\mathcal{A}$ against the $\texttt{IND}$-security of the above MCFE', for all $\rho \in [L]$, there exist PPT adversaries $\mathcal{B}_\rho$, $\mathcal{B}'_\rho$, and $\mathcal{B}''_\rho$ such that*

$$|\mathsf{Adv}_{\mathbf{G}_{\rho-1}}(\mathcal{A}) - \mathsf{Adv}_{\mathbf{G}_\rho}(\mathcal{A})| \leq (n+1) \cdot \left(\begin{array}{l} \mathsf{Adv}^{\texttt{1-Label-IND}^*}_{\mathsf{MCFE}}(\mathcal{B}_\rho) + \\ 2 \cdot \mathsf{Adv}^{\texttt{1-Label-IND}}_{\mathsf{SSL}}(\mathcal{B}'_\rho) + q_e \cdot \mathsf{Adv}^{\mathsf{OT}}_{\mathsf{SKE}}(\mathcal{B}''_\rho) \end{array} \right)$$

Proof (of Lemma 13). Actually, two cases can happen between games $\mathbf{G}_{\rho-1}$ and $\mathbf{G}_\rho$, for each $\rho \in [L]$: either all the ciphertexts are generated under ℓ_ρ or not all of them. We first make the guess, and then deal with the two cases: if they are all generated (for honest clients), this is the simple $\texttt{1-Label-IND}^*$ security game for the underlying MCFE, otherwise there is an honest index i^* for which the ciphertext has not been generated, and the SSL scheme will help, together with the symmetric encryption scheme:

Guess of the Case for the ℓ_ρ: We define a new sequence of hybrid games $\mathbf{G}^*_\rho$ for all $\rho = 0, \ldots, n$, which is exactly as above, except that a guess for the missing honest-client ciphertext i^* under ℓ_ρ is performed ($i^* = 0$ means that all the honest-client ciphertexts are expected to be generated under ℓ_ρ):

- Initialize: it first makes a guess for $i^* \xleftarrow{\$} \{0, \ldots, n\}$, and then does as in $\mathbf{G}_\rho$;

– $\mathsf{QEncrypt}'(i, x, \ell_j)$, $\mathsf{QLeftRight}'(i, x^0, x^1, \ell_j)$, $\mathsf{QDKeyGen}'(f)$, $\mathsf{QCorrupt}'(i)$, as in $\mathbf{G}_\rho$;
– Finalize: as in $\mathbf{G}_\rho$, except if
  - $i^* = 0$, but not all the honest ciphertexts under ℓ_ρ have been asked;
  - $i^* \neq 0$, but client i^* is corrupted;
  - $i^* \neq 0$, but the i^*-th client ciphertext has been asked under ℓ_ρ;

  in which cases a random bit is output.

Since $\mathbf{G}^*_\rho$ and $\mathbf{G}_\rho$ are the same unless the guess is incorrect, which happens with probability exactly $1/(n+1)$, for any adversary $\mathcal{A}$: $\mathsf{Adv}_{\mathbf{G}_\rho}(\mathcal{A}) = (n+1) \cdot \mathsf{Adv}_{\mathbf{G}^*_\rho}(\mathcal{A})$.

All the Ciphertexts are Generated under ℓ_ρ: Under the condition that $\mathcal{A}$ asks for all the honest ciphertexts under ℓ_ρ, which means the correct guess is $i^* = 0$, we build a PPT adversary $\mathcal{B}_\rho$ against the $\texttt{1-Label-IND}^*$ security of MCFE such that

$$|\mathsf{Adv}_{\mathbf{G}^*_{\rho-1}}(\mathcal{A} \wedge i^* = 0) - \mathsf{Adv}_{\mathbf{G}^*_\rho}(\mathcal{A} \wedge i^* = 0)| \leq \mathsf{Adv}^{\texttt{1-Label-IND}^*}_{\mathsf{MCFE}}(\mathcal{B}_\rho).$$

$\mathcal{B}_\rho$ simulates the $\texttt{IND}$-adversary $\mathcal{A}$'s view as follows:

– Initialize: it sends ρ and obtains mpk from its own $\texttt{1-Label-IND}^*$-security game for MCFE, samples $(\mathsf{pk}_{\mathsf{ssl}}, (\mathsf{ek}_{\mathsf{ssl},i})_{i\in[n]}) \leftarrow \mathsf{SSL.SetUp}(\lambda)$ and returns $\mathsf{mpk}' = \mathsf{mpk} \cup \mathsf{pk}_{\mathsf{ssl}}$ to the adversary $\mathcal{A}$;
– $\mathsf{QEncrypt}'(i, x, \ell_j)$: it uses its own encryption oracle $\mathsf{QEncrypt}$ to get $C \leftarrow \mathsf{QEncrypt}(i, x, \ell_j)$. Then, it computes $(C_{\ell_j}, K_{\ell_j}) \leftarrow \mathsf{SSL.Encaps}(\mathsf{pk}_{\mathsf{ssl}}, \ell_j)$, and $S_{\ell_j,i} \leftarrow \mathsf{SSL.Share}(\mathsf{ek}_{\mathsf{ssl},i}, \ell_j)$. Eventually, it computes and returns the ciphertext $(\mathsf{SEnc}(K_{\ell_j}, C), C_{\ell_j}, S_{\ell_j,i})$;
– $\mathsf{QLeftRight}'(i, x^0, x^1, \ell_j)$: if $j < \rho$, it uses its own encryption oracle $\mathsf{QEncrypt}$ to get the ciphertext $C \leftarrow \mathsf{QEncrypt}(i, x^1, \ell_j)$; if $j > \rho$, it uses its own encryption oracle $\mathsf{QEncrypt}$ to get $C \leftarrow \mathsf{QEncrypt}(i, x^0, \ell_j)$; if $j = \rho$, then it uses its own left-or-right encryption oracle to get $C \leftarrow \mathsf{QLeftRight}(i, x^0, x^1, \ell_\rho)$. Then, it computes $(C_{\ell_j}, K_{\ell_j}) \leftarrow \mathsf{SSL.Encaps}(\mathsf{pk}_{\mathsf{ssl}}, \ell_j)$, and $S_{\ell_j,i} \leftarrow \mathsf{SSL.Share}(\mathsf{ek}_{\mathsf{ssl},i}, \ell_j)$. Eventually, it computes and returns the ciphertext $(\mathsf{SEnc}(K_{\ell_j}, C), C_{\ell_j}, S_{\ell_j,i})$;
– $\mathsf{QCorrupt}'(i)$: it uses its own corruption oracle to get $\mathsf{ek}_i \leftarrow \mathsf{QCorrupt}(i)$, and returns $\mathsf{ek}'_i = \mathsf{ek}_i \cup \mathsf{ek}_{\mathsf{ssl},i}$;
– Finalize: $\mathcal{B}_\rho$ checks whether all the honest ciphertexts under ℓ_ρ have been asked. If not, it ignores $\mathcal{A}$'s guess and sends a uniformly random bit $\beta \xleftarrow{\$} \{0, 1\}$; Otherwise, it forwards $\mathcal{A}$'s guess.

Since we only consider $\mathcal{A}$'s output when all the ciphertexts have been generated, we are in the $\texttt{1-Label-IND}^*$ setting, with the "$*$". $\mathsf{QLeftRight}$-queries are only asked under the label ℓ_ρ. When $b = 0$, these queries are answered by $\mathsf{Encrypt}(\mathsf{ek}_i, x^0, \ell_\rho)$, as in $\mathbf{G}^*_{\rho-1}$, whereas for $b = 1$, they are answered by $\mathsf{Encrypt}(\mathsf{ek}_i, x^1, \ell_\rho)$, as in $\mathbf{G}^*_\rho$.

Some Ciphertexts are Missing under ℓ_ρ: For $\beta \in \{0, 1\}$, we define the game $\mathbf{H}_{\rho,\beta}$ as $\mathbf{G}^*_\rho$, except that when $i^* \neq 0$, $\mathsf{QEncrypt}'(i, x, \ell_\rho)$ encrypts x and $\mathsf{QLeftRight}'(i, x^0, x^1, \ell_\rho)$ encrypts x^β in C, then they both generate $(C_{\ell_\rho}, K_{\ell_\rho}) \leftarrow \mathsf{SSL.Encaps}(\mathsf{pk}_{\mathsf{ssl}}, \ell_\rho)$, $S_{\ell_\rho,i} \leftarrow \mathsf{SSL.Share}(\mathsf{ek}_{\mathsf{ssl},i}, \ell_\rho)$, sample a fresh key $K'_{\ell_\rho} \xleftarrow{\$} \mathcal{K}$ at random in the key space, and return the ciphertext $(\mathsf{SEnc}(K'_{\ell_\rho}, C), C_{\ell_\rho}, S_{\ell_\rho,i})$.

Now, we build PPT adversaries $\mathcal{B}_{\rho,0}$ and $\mathcal{B}_{\rho,1}$ against the $\texttt{1-Label-IND}$-security of the SSL such that

$$|\mathsf{Adv}_{\mathbf{G}^*_{\rho-1}}(\mathcal{A} \wedge i^* \neq 0) - \mathsf{Adv}_{\mathbf{H}_{\rho,0}}(\mathcal{A} \wedge i^* \neq 0)| \leq \mathsf{Adv}^{\texttt{1-Label-IND}}_{\mathsf{SSL}}(\mathcal{B}_{\rho,0});$$
$$|\mathsf{Adv}_{\mathbf{G}^*_{\rho}}(\mathcal{A} \wedge i^* \neq 0) - \mathsf{Adv}_{\mathbf{H}_{\rho,1}}(\mathcal{A} \wedge i^* \neq 0)| \leq \mathsf{Adv}^{\texttt{1-Label-IND}}_{\mathsf{SSL}}(\mathcal{B}_{\rho,1}).$$

Let $\beta \in \{0, 1\}$. We proceed to describe $\mathcal{B}_{\rho,\beta}$. First, $\mathcal{B}_{\rho,\beta}$ samples the guess $i^* \xleftarrow{\$} \{0, \ldots, n\}$. If $i^* = 0$, then $\mathcal{B}_{\rho,\beta}$ behaves exactly as the challenger in the game $\mathbf{G}^*_{\rho-1+\beta}$. Otherwise, it does the following, using the $\texttt{1-Label-IND}$-security game against SSL:

– Initialize: it generates $(\mathsf{mpk}, \mathsf{msk}, (\mathsf{ek}_i)_{i\in[n]}) \leftarrow \mathsf{SetUp}(\lambda)$, and sends ρ to receive $\mathsf{pk}_{\mathsf{ssl}}$ from its own $\texttt{1-Label-IND}$ challenger for SSL. It returns $\mathsf{mpk}' = \mathsf{mpk} \cup \mathsf{pk}_{\mathsf{ssl}}$ to the adversary $\mathcal{A}$;
– $\mathsf{QEncrypt}'(i, x, \ell_j)$: it can compute $C \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, x, \ell_j)$. Then, it call its own oracle to get $S_{\ell_j,i} \leftarrow \mathsf{QShare}(i, \ell_j)$. If $j \neq \rho$, it computes $(C_{\ell_j}, K_{\ell_j}) \leftarrow \mathsf{SSL.Encaps}(\mathsf{pk}_{\mathsf{ssl}}, \ell_j)$, if $j = \rho$ it calls $(C_{\ell_\rho}, K_{\ell_\rho}) \leftarrow \mathsf{QRealRandom}(\ell_\rho)$. Eventually, it returns the ciphertext $(\mathsf{SEnc}(K_{\ell_j}, C), C_{\ell_j}, S_{\ell_j,i})$;

– $\mathsf{QLeftRight}'(i, x^0, x^1, \ell_j)$: if $j < \rho$, it computes $C = \mathsf{Encrypt}(\mathsf{ek}_i, x^1, \ell_j)$; if $j > \rho$, it computes $C = \mathsf{Encrypt}(\mathsf{ek}_i, x^0, \ell_j)$; and if $j = \rho$, it computes $C = \mathsf{Encrypt}(\mathsf{ek}_i, x^\beta, \ell_j)$. Then it call its own oracle to get $S_{\ell_j,i} = \mathsf{QShare}(i, \ell_j)$. If $j \neq \rho$, it computes $(C_{\ell_j}, K_{\ell_j}) \leftarrow \mathsf{SSL.Encaps}(\mathsf{pk}_{\mathsf{ssl}}, \ell_j)$, if $j = \rho$ it calls $(C_{\ell_\rho}, K_{\ell_\rho}) \leftarrow \mathsf{QRealRandom}(\ell_\rho)$. Eventually, it returns the ciphertext $(\mathsf{SEnc}(K_{\ell_j}, C), C_{\ell_j}, S_{\ell_j,i})$;
– $\mathsf{QDKeyGen}'(f)$: it runs and returns $\mathsf{DKeyGen}(\mathsf{msk}, f)$.
– $\mathsf{QCorrupt}'(i)$: it uses its own corruption oracle to get $\mathsf{ek}_{\mathsf{ssl},i} \leftarrow \mathsf{QCorrupt}(i)$, and returns $\mathsf{ek}'_i = \mathsf{ek}_i \cup \mathsf{ek}_{\mathsf{ssl},i}$;
– Finalize: $\mathcal{B}_{\rho,\beta}$ checks whether the ciphertext for the i^*-th client has been asked under ℓ_ρ. If so, it ignores $\mathcal{A}$'s guess and sends a uniformly random bit $\beta \xleftarrow{\$} \{0,1\}$; Otherwise, it forwards $\mathcal{A}$'s guess.

Game $\mathbf{G}_\rho$, which encrypts x^1 under ℓ_ρ just differs from $\mathbf{H}_{\rho,1}$ with real vs. random keys K_{ℓ_ρ}, as emulated by $\mathcal{B}_{\rho,1}$, according to the real-or-random behavior of the `1-Label-IND` game for SSL. Game $\mathbf{G}_{\rho-1}$, which encrypts x^0 under ℓ_ρ just differs from $\mathbf{H}_{\rho,0}$ with real vs. random keys K_{ℓ_ρ}, as emulated by $\mathcal{B}_{\rho,0}$, according to the real-or-random behavior of the `1-Label-IND` game for SSL.

Since the encapsulation keys K_{ℓ_ρ} are uniformly random in games $\mathbf{H}_{\rho,0}$ and $\mathbf{H}_{\rho,1}$, we can use the one-time security of SKE, for each ciphertext for the label ℓ_ρ, to obtain a PPT adversary $\mathcal{B}''_\rho$ such that:

$$|\mathsf{Adv}_{\mathbf{H}_{\rho,0}}(\mathcal{A} \wedge i^* \neq 0) - \mathsf{Adv}_{\mathbf{H}_{\rho,1}}(\mathcal{A} \wedge i^* \neq 0)| \leq q_e \cdot \mathsf{Adv}^{\mathsf{OT}}_{\mathsf{SKE}}(\mathcal{B}''_\rho),$$

where q_e denotes maximum number of ciphertexts generated under a label.

Putting everything together, for the case $i^* \neq 0$, we obtain PPT adversaries $\mathcal{B}'_\rho$ and $\mathcal{B}''_\rho$ such that:

$$|\mathsf{Adv}_{\mathbf{G}^*_{\rho-1}}(\mathcal{A} \wedge i^* \neq 0) - \mathsf{Adv}_{\mathbf{G}^*_\rho}(\mathcal{A} \wedge i^* \neq 0)| \leq 2\mathsf{Adv}^{\texttt{1-Label-IND}}_{\mathsf{SSL}}(\mathcal{B}'_\rho) + q_e \cdot \mathsf{Adv}^{\mathsf{OT}}_{\mathsf{SKE}}(\mathcal{B}''_\rho))$$

Since for any game $\mathbf{G}$ and any adversary $\mathcal{A}$, $\mathsf{Adv}_{\mathbf{G}}(\mathcal{A}) = \mathsf{Adv}_{\mathbf{G}}(\mathcal{A} \wedge i^* = 0) + \mathsf{Adv}_{\mathbf{G}}(\mathcal{A} \wedge i^* \neq 0)$, this concludes the proof of Lemma 13.

6 IP-MCFE with Repetitions

In this section, we add an extra layer of IP-FE on top of the IP-MCFE from [CDG+17], to remove the restriction of having a unique challenge ciphertext per client and per label. Our construction works for any IP-FE that is compatible with the IP-MCFE from [CDG+17], namely, an IP-FE whose message space is the ciphertext space of the IP-MCFE. For correctness, we exploit the fact that decryption of the IP-MCFE computes the inner product of the ciphertext together with the decryption keys. For security, we exploit the fact that the IP-MCFE is linearly homomorphic, in the sense that given an input $\boldsymbol{x}$, one can publicly maul an encryption of $\boldsymbol{x}'$ into an encryption of $\boldsymbol{x} + \boldsymbol{x}'$. This is used to bootstrap the security from one to many challenge ciphertexts per (user,label) pair, similarly to [AGRW17, ACF+18] in the context of multi-input IP-FE. In fact, [ACF+18] uses a one-time secure multi-input FE as inner layer, and a single-input IP-FE as outer layer, while we use an IP-MCFE as inner layer, and an IP-FE as outer layer. The main technical challenge is to handle the case of (adaptive) corruptions, which are not considered in [AGRW17, ACF+18] (even in the static case where corruptions are known beforehand).

We first recall the IP-MCFE from [CDG+17] extended to handle vectors as inputs of the encryption algorithm. Also, we make use of the fact that the encryption algorithm can act on vectors of group elements, in $\mathbb{G}^m$, where $\mathbb{G}$ is a prime-order group, as opposed to vectors over $\mathbb{Z}$. Decryption recovers the inner product in the group $\mathbb{G}$, without any restriction on the size of the input of the encryption and decryption key generation algorithms. Namely, the message space of IP-FE is $\mathbb{G}^m$,for some dimension m, its decryption key space is $\mathbb{Z}_p^m$, where p is the order of $\mathbb{G}$, and for any $[\boldsymbol{x}] \in \mathbb{G}^m$, $\boldsymbol{y} \in \mathbb{Z}_p^m$, $\mathsf{IP.Dec}(\mathsf{ct}, \mathsf{dk}_{\boldsymbol{y}}) = [\boldsymbol{x}^\top \boldsymbol{y}]$ with probability one, where $\mathsf{ct} \leftarrow \mathsf{IP.Encrypt}(\mathsf{IP.msk}, [\boldsymbol{x}])$, $\mathsf{dk}_{\boldsymbol{y}} \leftarrow \mathsf{IP.DKeyGen}(\mathsf{IP.msk}, \boldsymbol{y})$, and $(\mathsf{IP.mpk}, \mathsf{IP.msk}) \leftarrow \mathsf{IP.SetUp}(\lambda)$. for Then we give our generic construction to obtain security with repetitions.

6.1 Reproduction of the IP-MCFE from [CDG+17]

In [CDG+17], Chotard *et al.* proposed an IND*-secure IP-MCFE. Roughly speaking, it relies on a private-key variant of Abdalla *et al.* [ABDP15] IP-FE, where a random oracle is used to generate common randomness among the different users, that is used to produce the ciphertexts. We extend it to handle vector-inputs for each client, instead of just scalars.

- $\mathsf{SetUp}(\lambda)$: samples $\mathcal{G} := (\mathbb{G}, p, P) \xleftarrow{\$} \mathsf{GGen}(1^\lambda)$, a full-domain hash function $\mathcal{H}$ onto $\mathbb{G}^2$, $\mathbf{S}_i \xleftarrow{\$} \mathbb{Z}_p^{m\times 2}$, for $i = 1, \ldots, n$. Returns the public key $\mathsf{mpk} := (\mathcal{G}, \mathcal{H})$, encryption keys $\mathsf{ek}_i = \mathbf{S}_i$ for $i = 1, \ldots, n$, and the master secret key $\mathsf{msk} = ((\mathbf{S}_i)_i)$, (in addition to mpk, which is omitted);
- $\mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i, \ell)$: Takes as input the value $\boldsymbol{x}_i \in \mathbb{Z}_p^m$ to encrypt, under the key $\mathsf{ek}_i = \mathbf{S}_i$ and the label ℓ. It computes $[\boldsymbol{u}_\ell] := \mathcal{H}(\ell) \in \mathbb{G}^2$, and outputs the ciphertext $[\boldsymbol{c}_i] = [\mathbf{S}_i\boldsymbol{u}_\ell + \boldsymbol{x}_i] \in \mathbb{G}^m$;
- $\mathsf{DKeyGen}(\mathsf{msk}, \boldsymbol{y})$: Takes as input $\mathsf{msk} = (\mathbf{S}_i)_i$ and an inner-product function defined by $\boldsymbol{y} \in \mathbb{Z}_p^{m\cdot n}$ as $f_{\boldsymbol{y}}(\boldsymbol{x}) = \langle \boldsymbol{x}, \boldsymbol{y}\rangle$,where $\boldsymbol{x} = (\boldsymbol{x}_1\|\cdots\|\boldsymbol{x}_n) \in \mathbb{Z}_p^{nm}$, and outputs the functional decryption key $\mathsf{dk}_{\boldsymbol{y}} = \left(\boldsymbol{y}, \sum_i \mathbf{S}_i^\top \boldsymbol{y}_i\right) \in \mathbb{Z}_p^{mn} \times \mathbb{Z}_p^2$;
- $\mathsf{Decrypt}(\mathsf{dk}_{\boldsymbol{y}}, \ell, ([\boldsymbol{c}_i])_{i\in[n]})$: Takes as input a functional decryption key $\mathsf{dk}_{\boldsymbol{y}} = (\boldsymbol{y}, \boldsymbol{d})$, a label ℓ, and ciphertexts. It computes $[\boldsymbol{u}_\ell] := \mathcal{H}(\ell)$ and returns $[\alpha] = \sum_i [\boldsymbol{c}_i]^\top \boldsymbol{y}_i - [\boldsymbol{u}_\ell]^\top \boldsymbol{d}$.

For correctness, one can check that:

$$\begin{aligned}
[\alpha] &= \sum_i [\boldsymbol{c}_i]^\top \boldsymbol{y}_i - [\boldsymbol{u}_\ell]^\top \boldsymbol{d} = \sum_i [\mathbf{S}_i\boldsymbol{u}_\ell + \boldsymbol{x}_i]^\top \boldsymbol{y}_i - [\boldsymbol{u}_\ell]^\top \sum_i \mathbf{S}_i^\top \boldsymbol{y}_i \\
&= \sum_i [\mathbf{S}_i\boldsymbol{u}_\ell]^\top \boldsymbol{y}_i + [\boldsymbol{x}_i]^\top \boldsymbol{y}_i - \sum_i [\mathbf{S}_i\boldsymbol{u}_\ell]^\top \boldsymbol{y}_i = \sum_i [\boldsymbol{x}_i]^\top \boldsymbol{y}_i = [\boldsymbol{x}^\top \boldsymbol{y}] = [\langle \boldsymbol{x}, \boldsymbol{y}\rangle].
\end{aligned}$$

For security, we will use the two following properties of the IP-MCFE from [CDG+17]:

- *Linear Homomorphism of ciphertexts*: for any $i \in [n]$, $\boldsymbol{x}_i, \boldsymbol{x}'_i \in \mathbb{Z}_p$, and any label ℓ, we have $[\boldsymbol{c}_i] + [\boldsymbol{x}'_i] = \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i + \boldsymbol{x}'_i, \ell)$, where $[\boldsymbol{c}_i] = \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i, \ell)$.
- *Deterministic Encryption.* In particular, together with the linear homomorphism of ciphertexts, this implies that for any $\boldsymbol{x}_i, \boldsymbol{x}'_i \in \mathbb{Z}_p^m$ and any label ℓ, we have: $\mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i, \ell) - \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}'_i, \ell) = [\boldsymbol{x}_i - \boldsymbol{x}'_i]$.

6.2 Construction of IND-Secure IP-MCFE with Repetitions

Let $\mathsf{MCFE} = (\mathsf{SetUp}, \mathsf{Encrypt}, \mathsf{DKeyGen}, \mathsf{Decrypt})$ be the above IP-MCFE scheme, and $\mathsf{IP\text{-}FE} = (\mathsf{IP.SetUp}, \mathsf{IP.Encrypt}, \mathsf{IP.DKeyGen}, \mathsf{IP.Dec})$ be a single-input Inner Product FE (as defined in Section 3.4) whose message space is the ciphertext space of MCFE. We define a new $\mathsf{MCFE}' = (\mathsf{SetUp}', \mathsf{Encrypt}', \mathsf{DKeyGen}', \mathsf{Decrypt}')$ as follows:

- $\mathsf{SetUp}'(\lambda)$: It executes $(\mathsf{mpk}, \mathsf{msk}, (\mathsf{ek}_i)_i) \leftarrow \mathsf{SetUp}(\lambda)$ as well as, for $i = 1, \ldots, n$, $(\mathsf{IP.mpk}_i, \mathsf{IP.msk}_i) \leftarrow \mathsf{IP.SetUp}(\lambda)$. The encryption keys are $\mathsf{ek}'_i = (\mathsf{ek}_i, \mathsf{IP.msk}_i)$ for all $i = 1, \ldots, n$, the public key is $\mathsf{mpk}' := (\mathsf{mpk}, \{\mathsf{IP.mpk}_i\}_i)$, and the master secret key is $\mathsf{msk}' = (\mathsf{msk}, \{\mathsf{IP.msk}_i\}_i)$;
- $\mathsf{Encrypt}'(\mathsf{ek}'_i, \boldsymbol{x}_i, \ell)$: It parses the encryption key ek'_i as $(\mathsf{ek}_i, \mathsf{IP.msk}_i)$, runs $[\boldsymbol{c}_{i,\ell}] \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i, \ell)$, and returns $C'_{\ell,i} := \mathsf{IP.Encrypt}(\mathsf{IP.msk}_i, [\boldsymbol{c}_{i,\ell}])$;
- $\mathsf{DKeyGen}'(\mathsf{msk}', \boldsymbol{y})$: on input $\boldsymbol{y} := (\boldsymbol{y}_1\|\cdots\|\boldsymbol{y}_n) \in \mathbb{Z}_p^{nm}$, it computes $\mathsf{dk}_{\boldsymbol{y}} = \mathsf{DKeyGen}(\mathsf{msk}, \boldsymbol{y})$, and for all $i \in [n]$: $\mathsf{dk}_{\boldsymbol{y}_i} = \mathsf{IP.DKeyGen}(\mathsf{msk}_i, \boldsymbol{y}_i)$. It returns $\mathsf{dk}'_{\boldsymbol{y}} = \left(\mathsf{dk}_{\boldsymbol{y}}, \{\mathsf{dk}_{\boldsymbol{y}_i}\}_{i\in[n]}\right)$.

The three above algorithms are enough to show the security (as proven below), which holds with respect to any IP-MCFE that satisfies the Linearly Homomorphism of ciphertexts, and deterministic encryption, as defined above. However, correctness only holds for the particular IP-MCFE from [CDG+17], where decryption computes the inner product between ciphertexts and decryption keys. That prevents from a generic transformation.

We now prove correctness when using the IP-MCFE from [CDG+17] in MCFE':

– $\mathsf{Decrypt}'(\mathsf{dk}'_{\boldsymbol{y}}, \ell, (C'_{\ell,i})_{i\in[n]})$: Takes as input a functional decryption key $\mathsf{dk}'_{\boldsymbol{y}} = \big(\mathsf{dk}_{\boldsymbol{y}}, \{\mathsf{dk}_{\boldsymbol{y}_i}\}_{i\in[n]}\big)$, where $\mathsf{dk}_{\boldsymbol{y}} = (\boldsymbol{y}, \boldsymbol{d} = \sum_i \mathbf{S}_i^\top \boldsymbol{y}_i)$, a label ℓ, and ciphertexts $(C'_{\ell,i})_{i\in[n]}$. First, it computes $[d_{i,\ell}] = \mathsf{IP.Dec}(\mathsf{dk}_{\boldsymbol{y}_i}, C'_{\ell,i})$ for all $i \in [n]$. Then it computes $[\boldsymbol{u}_\ell] = \mathcal{H}(\ell)$, and computes $[\alpha] = [\sum_i d_{i,\ell}] - \boldsymbol{d}^\top[\boldsymbol{u}_\ell]$. Finally, it returns the discrete logarithm $\alpha \in \mathbb{Z}_p$.

Correctness. By correctness of the $\mathsf{IP\text{-}FE}$, we have for all $i \in [n]$, and any label ℓ: $[d_{i,\ell}] = [\langle \boldsymbol{y}_i, \boldsymbol{x}_i + \mathbf{S}_i \boldsymbol{u}_\ell\rangle] = [\langle \boldsymbol{y}_i, \boldsymbol{x}_i\rangle] + \langle \boldsymbol{y}_i, \mathbf{S}_i\rangle \cdot [\boldsymbol{u}_\ell]$. Thus, $\sum_i [d_{i,\ell}] = [\langle \boldsymbol{y}, \boldsymbol{x}\rangle] + (\sum_i \boldsymbol{y}_i^\top \mathbf{S}_i) \cdot [\boldsymbol{u}_\ell]$. Since $\boldsymbol{d} = \sum_i \mathbf{S}_i^\top \boldsymbol{y}_i$, we have $\sum_i [d_{i,\ell}] = [\langle \boldsymbol{y}, \boldsymbol{x}\rangle] + \boldsymbol{d}^\top[\boldsymbol{u}_\ell]$, hence $\alpha = \langle \boldsymbol{x}, \boldsymbol{y}\rangle$.

6.3 Security Analysis

In this section, we will prove that the above MCFE' achieves `1-Label-IND`*-security if the MCFE from [CDG+17] is `wtr-IND`*-secure (which has been proven in [CDG+17]) and the $\mathsf{IP\text{-}FE}$ is `IND`-secure (which has been proven in [ABDP15]). More precisely, we can state the following security result:

Theorem 14. *For any adversary $\mathcal{A}$, against the `1-Label-IND`*-security of the above MCFE',*

$$\mathsf{Adv}_{\mathsf{MCFE}'}^{\texttt{1-Label-IND}^*}(\mathcal{A}) \leq \mathsf{Adv}_{\mathsf{MCFE}}^{\texttt{wtr-IND}^*}(t') + n \cdot \mathsf{Adv}_{\mathsf{IP\text{-}FE}}^{\texttt{IND}}(t''),$$

where both t' and t'' are close to the running time t of $\mathcal{A}$.

As a consequence, starting from both the $\mathsf{IP\text{-}FE}$ from [ALS16], the $\mathsf{IP\text{-}MCFE}$ from [CDG+17], and adding the above SSL scheme, one gets an $\mathsf{IP\text{-}MCFE}$ that is `IND`-secure, with repetitions and with adaptive corruptions.

The proof uses a series of hybrid games, defined below. For any game $\mathbf{G}$, we denote $\mathsf{Adv}_{\mathbf{G}}(\mathcal{A})$ the advantage of $\mathcal{A}$ in the game $\mathbf{G}$, that is, the probability that the procedure Finalize in the game $\mathbf{G}$ outputs 1. For any user $i \in [n]$, we denote by Q_i the number of queries to the oracle $\mathsf{QLeftRight}'$ containing the user i, that is, of the form: $\mathsf{QLeftRight}'(i, \boldsymbol{x}_i^{k,0}, \boldsymbol{x}_i^{k,1}, \ell)$, for $k \in \{1, \ldots, Q_i\}$. When all the Q_i's are 1, there is no repetition, but here we are dealing with repetitions. The counter k numbers the repetitions.

Game $\mathbf{G}_\beta$: For any $\beta \in \{0,1\}$, we define the following game, where multiple plaintexts can be queried for the same user i and the same label. We use a counter k, which starts at 1 to number the queries $(\boldsymbol{x}_i^{k,0}, \boldsymbol{x}_i^{k,1})$, under the label $\ell^* = \ell_\rho$. We do not keep track of the queries under other labels (as in previous definitions).

– Initialize(ρ): it generates $(\mathsf{mpk}, \mathsf{msk}, (\mathsf{ek}_i)_{i\in[n]}) \leftarrow \mathsf{SetUp}(\lambda)$, and for all $i \in [n]$, $(\mathsf{IP.mpk}_i, \mathsf{IP.msk}_i) \leftarrow \mathsf{IP.SetUp}(\lambda)$. It returns $\mathsf{mpk}' := (\mathsf{mpk}, (\mathsf{IP.mpk}_i)_{i\in[n]})$ to the adversary $\mathcal{A}$;
– $\mathsf{QEncrypt}'(i, \boldsymbol{x}_i, \ell_j)$: it first computes $[\boldsymbol{c}_i] \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i, \ell_j)$, and returns $\mathsf{IP.Enc}(\mathsf{msk}_i, [\boldsymbol{c}_i])$;
– $\mathsf{QLeftRight}'(i, \boldsymbol{x}_i^{k,0}, \boldsymbol{x}_i^{k,1}, \ell_\rho)$: it computes $[\boldsymbol{c}_i^k] \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i^{k,\beta}, \ell_\rho)$, and returns $\mathsf{IP.Enc}(\mathsf{msk}_i, [\boldsymbol{c}_i^k])$;
– $\mathsf{QDKeyGen}'(\boldsymbol{y})$: on input $\boldsymbol{y} := (\boldsymbol{y}_1 \| \cdots \| \boldsymbol{y}_n) \in \mathbb{Z}_p^{nm}$, it first computes $\mathsf{dk}_{\boldsymbol{y}} = \mathsf{DKeyGen}(\mathsf{msk}, \boldsymbol{y})$, and for all $i \in [n]$: $\mathsf{dk}_{\boldsymbol{y}_i} = \mathsf{IP.DKeyGen}(\mathsf{msk}_i, \boldsymbol{y}_i)$. It returns $\mathsf{dk}'_{\boldsymbol{y}} = \big(\mathsf{dk}_{\boldsymbol{y}}, \{\mathsf{dk}_{\boldsymbol{y}_i}\}_{i\in[n]}\big)$.
– $\mathsf{QCorrupt}'(i)$: on input a user $i \in [n]$, it returns $(\mathsf{ek}_i, \mathsf{IP.msk}_i)$.
– Finalize: as in Definition 11.

Note that:

$$\mathsf{Adv}_{\mathsf{MCFE}'}^{\texttt{1-Label-IND}^*}(\mathcal{A}) = |\mathsf{Adv}_{\mathbf{G}_0}(\mathcal{A}) - \mathsf{Adv}_{\mathbf{G}_1}(\mathcal{A})|.$$

Game $\mathbf{H}_0$: Now we consider the game $\mathbf{H}_0$ defined exactly as $\mathbf{G}_0$, except in $\mathsf{QLeftRight}'(i, \boldsymbol{x}_i^{k,0}, \boldsymbol{x}_i^{k,1}, \ell_\rho)$, one computes $[\boldsymbol{c}_i^k] \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i^{k,0} + \boldsymbol{x}_i^{1,1} - \boldsymbol{x}_i^{1,0}, \ell_\rho)$. Then it returns $\mathsf{IP.Enc}(\mathsf{IP.msk}_i, [\boldsymbol{c}_i^k])$. The transition from $\mathbf{G}_0$ and $\mathbf{H}_0$ uses `1-Label-IND`* security and the linear homomorphism of the ciphertexts of MCFE. Namely, we build a PPT adversary $\mathcal{B}$ against the `1-Label-IND`* security of MCFE such that:

$$|\mathsf{Adv}_{\mathbf{G}_0}(\mathcal{A}) - \mathsf{Adv}_{\mathbf{H}_0}(\mathcal{A})| \leq \mathsf{Adv}_{\mathsf{MCFE}}^{\texttt{1-Label-IND}^*}(\mathcal{B}).$$

$\mathcal{B}$ simulates the view of the `1-Label-IND`*-adversary $\mathcal{A}$ against MCFE' as follows:

– Initialize(ρ): after having sent ρ, it gets mpk from its $\texttt{1-Label-IND}^*$ challenger. For all $i \in [n]$, $(\mathsf{IP.mpk}_i, \mathsf{IP.msk}_i) \leftarrow \mathsf{IP.SetUp}(\lambda)$, and it returns $\mathsf{mpk}' := (\mathsf{mpk}, (\mathsf{IP.mpk}_i)_{i\in[n]})$ to the adversary $\mathcal{A}$;
– $\mathsf{QEncrypt}'(i, \boldsymbol{x}_i, \ell_j)$: it first computes $[\boldsymbol{c}_i] \leftarrow \mathsf{QEncrypt}(i, \boldsymbol{x}_i, \ell_j)$, and returns $\mathsf{IP.Enc}(\mathsf{msk}_i, [\boldsymbol{c}_i])$;
– $\mathsf{QLeftRight}'(i, \boldsymbol{x}_i^{k,0}, \boldsymbol{x}_i^{k,1}, \ell_\rho)$: for $k = 1$, i.e. the first query for user i, $\mathcal{B}$ queries its own $\mathsf{QLeftRight}$ oracle to get $[\boldsymbol{c}_i^1] = \mathsf{QLeftRight}(i, \boldsymbol{x}_i^{k,0}, \boldsymbol{x}_i^{k,1}, \ell_\rho)$; otherwise it computes $[\boldsymbol{c}_i^k] := [\boldsymbol{c}_i^1] + [\boldsymbol{x}_i^{k,0} - \boldsymbol{x}_i^{1,0}]$. It then returns $\mathsf{IP.Encrypt}(\mathsf{IP.msk}_i, [\boldsymbol{c}_i^k])$ to $\mathcal{A}$;
– $\mathsf{QDKeyGen}'(\boldsymbol{y})$: on input $\boldsymbol{y} := (\boldsymbol{y}_1 \| \cdots \| \boldsymbol{y}_n) \in \mathbb{Z}_p^{nm}$, it first computes $\mathsf{dk}_{\boldsymbol{y}} = \mathsf{DKeyGen}(\mathsf{msk}, \boldsymbol{y})$, and for all $i \in [n]$: $\mathsf{dk}_{\boldsymbol{y}_i} = \mathsf{IP.DKeyGen}(\mathsf{msk}_i, \boldsymbol{y}_i)$. It returns $\mathsf{dk}'_{\boldsymbol{y}} = \big(\mathsf{dk}_{\boldsymbol{y}}, \{\mathsf{dk}_{\boldsymbol{y}_i}\}_{i\in[n]}\big)$.
– $\mathsf{QCorrupt}'(i)$: $\mathcal{B}$ queries its own oracle to obtain $\mathsf{ek}_i \leftarrow \mathsf{QCorrupt}(i)$, and returns $(\mathsf{ek}_i, \mathsf{IP.msk}_i)$ to $\mathcal{A}$.
– Finalize: $\mathcal{B}$ verifies that the conditions in Definition 11 are satisfied; if they are, it forwards the guess b' of $\mathcal{A}$, otherwise, it sends a random bit to its own Finalize oracle.

Note that the constraints $\mathcal{B}$ has to verify in the finalize procedure, and namely for condition (2), might look exponential for general functionalities. But in the case of inner-product, one just has to look at spanned vector sub-spaces. Namely, all queries $(i, \boldsymbol{x}_i^{k_i,0}, \boldsymbol{x}_i^{k_i,1}, \ell_\rho)_{i\in[n],k_i\in[Q_i]}$ to $\mathsf{QLeftRight}'$ and all queries $\boldsymbol{y} := (\boldsymbol{y}_1 \| \cdots \| \boldsymbol{y}_n)$ to $\mathsf{QDKeyGen}'$ must satisfy: $\sum_i \langle \boldsymbol{x}_i^{k_i,0}, \boldsymbol{y}_i \rangle = \sum_i \langle \boldsymbol{x}_i^{k_i,1}, \boldsymbol{y}_i \rangle$. This is an exponential number of linear equations, but, as noted in [AGRW17], it suffices to verify the linearly independent equations, of which there can be at most $n \cdot m$. This can be done efficiently given the queries.

One can note that, for the label $\ell_\rho = \ell^*$, $[\boldsymbol{c}_i^1]$ received by $\mathcal{B}$ is actually $[\boldsymbol{c}_i^1] = \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i^{1,b}, \ell^*)$, where b is the random bit chosen by the $\texttt{1-Label-IND}^*$ security game for MCFE that $\mathcal{B}$ is interacting with. By linear homomorphism of the ciphertexts of MCFE, for all $k \in [Q_i]$, we have: $[\boldsymbol{c}_i^k] = \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i^{1,b}, \ell^*) + [\boldsymbol{x}_i^{k,0} - \boldsymbol{x}_i^{1,0}] = \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i^{k,0} + \boldsymbol{x}_i^{1,b} - \boldsymbol{x}_i^{1,0}, \ell^*)$. So, when $b = 0$, $\mathcal{B}$ simulates $\mathbf{G}_0$, while it simulates $\mathbf{H}_0$ when $b = 1$, which proves $|\mathsf{Adv}_{\mathbf{G}_0}(\mathcal{A}) - \mathsf{Adv}_{\mathbf{H}_0}(\mathcal{A})| \leq \mathsf{Adv}_{\mathsf{MCFE}}^{\texttt{1-Label-IND}^*}(\mathcal{B})$.

We define the following hybrid games $\mathbf{H}_r$, for all $r \in [n]$, as $\mathbf{H}_0$, except for $\mathsf{QLeftRight}'(i, \boldsymbol{x}_i^{k,0}, \boldsymbol{x}_i^{k,1}, \ell_\rho)$: for all $i \leq r$, it sets $[\boldsymbol{c}_i^k] \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i^{k,1}, \ell_\rho)$, instead of $[\boldsymbol{c}_i^k] \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i^{k,0} + \boldsymbol{x}_i^{1,1} - \boldsymbol{x}_i^{1,0}, \ell_k)$, and returns $\mathsf{IP.Enc}(\mathsf{msk}_i, [\boldsymbol{c}_i^k])$. Note that this definition is compatible with $\mathbf{H}_0$ defined previously, and $\mathbf{H}_n$ is $\mathbf{G}_1$. Thus, it suffices to build a PPT adversary $\mathcal{B}_r$ for all $r \in [n]$, against the $\texttt{IND}$-security of the $\mathsf{IP\text{-}FE}$, such that:

$$|\mathsf{Adv}_{\mathbf{H}_{r-1}}(\mathcal{A}) - \mathsf{Adv}_{\mathbf{H}_r}(\mathcal{A})| \leq \mathsf{Adv}_{\mathsf{IP\text{-}FE}}^{\texttt{IND}}(\mathcal{B}_r).$$

We distinguish two cases. The first case occurs when $\mathcal{A}$ queries the user r to its oracle $\mathsf{QCorrupt}'$. Then, conditioned on the event that Finalize doesn't output a random bit, it must be the case that for all $k \in [Q_r]$, $\boldsymbol{x}_r^{k,0} = \boldsymbol{x}_r^{k,1}$. If we call E this first case, we have: $\mathsf{Adv}_{\mathbf{H}_{r-1}}(\mathcal{A} \wedge E) = \mathsf{Adv}_{\mathbf{H}_r}(\mathcal{A} \wedge E)$. The second case corresponds to the event $\neg E$: $\mathcal{A}$ does not query $\mathsf{QCorrupt}'$ on r. We build a PPT adversary $\mathcal{B}$ such that $|\mathsf{Adv}_{\mathbf{H}_{r-1}}(\mathcal{A}|\neg E) - \mathsf{Adv}_{\mathbf{H}_r}(\mathcal{A}|\neg E) \leq \mathsf{Adv}_{\mathsf{IP\text{-}FE}}^{\texttt{IND}}(\mathcal{B}_r)$, which implies that $|\mathsf{Adv}_{\mathbf{H}_{r-1}}(\mathcal{A} \wedge \neg E) - \mathsf{Adv}_{\mathbf{H}_r}(\mathcal{A} \wedge \neg E) \leq \mathsf{Adv}_{\mathsf{IP\text{-}FE}}^{\texttt{IND}}(\mathcal{B}_r)$. We conclude using the fact that for any game $\mathbf{G}$ and event E: $\mathsf{Adv}_{\mathbf{G}}(\mathcal{A}) = \mathsf{Adv}_{\mathbf{G}}(\mathcal{A} \wedge E) + \mathsf{Adv}_{\mathbf{G}}(\mathcal{A} \wedge \neg E)$. We now proceed to describe $\mathcal{B}_r$, which simulates the view of the $\texttt{1-Label-IND}^*$-adversary $\mathcal{A}$ against MCFE' as follows:

– Initialize(ρ): $\mathcal{B}_r$ obtains $\mathsf{IP.mpk}_r$ from its own Initialize oracle, and generates $(\mathsf{IP.mpk}_i, \mathsf{IP.msk}_i) \leftarrow \mathsf{IP.SetUp}(\lambda)$ for all $i \neq r$, $(\mathsf{mpk}, \mathsf{msk}, (\mathsf{ek}_i)_i) \leftarrow \mathsf{SetUp}(\lambda)$ and returns $\mathsf{mpk}' := (\mathsf{mpk}, (\mathsf{IP.mpk}_i)_i)$ to $\mathcal{A}$.
– $\mathsf{QEncrypt}'(i, \boldsymbol{x}_i, \ell_j)$: it computes $[\boldsymbol{c}_i] \leftarrow \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i, \ell_j)$. If $i \neq r$, it returns $\mathsf{IP.Enc}(\mathsf{msk}_i, [\boldsymbol{c}_i])$; if $i = r$, it returns $\mathsf{QLeftRight}([\boldsymbol{c}_i], [\boldsymbol{c}_i])$.
– $\mathsf{QLeftRight}'(i, \boldsymbol{x}_i^{k,0}, \boldsymbol{x}_i^{k,1}, \ell_\rho)$: $\mathcal{B}$ computes $[\boldsymbol{c}_i^{k,0}] = \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i^{k,1}, \ell_\rho)$ and $[\boldsymbol{c}_i^{k,1}] = \mathsf{Encrypt}(\mathsf{ek}_i, \boldsymbol{x}_i^{k,0} + \boldsymbol{x}_i^{1,1} - \boldsymbol{x}_i^{1,0}, \ell_\rho)$, and uses its own $\mathsf{QLeftRight}$ oracle to output the ciphertext to $\mathcal{A}$
  - if $i < r$, it outputs $\mathsf{IP.Enc}(\mathsf{msk}_i, [\boldsymbol{c}_i^{k,0}])$;
  - if $i > r$, it outputs $\mathsf{IP.Enc}(\mathsf{msk}_i, [\boldsymbol{c}_i^{k,1}])$;
  - if $i = r$, it outputs $\mathsf{QLeftRight}([\boldsymbol{c}_i^{k,0}], [\boldsymbol{c}_i^{k,1}])$.
– $\mathsf{QDKeyGen}'(\boldsymbol{y})$: on input $\boldsymbol{y} := (\boldsymbol{y}_1 \| \cdots \| \boldsymbol{y}_n) \in \mathbb{Z}_p^{nm}$, $\mathcal{B}_r$ computes $\mathsf{dk}_{\boldsymbol{y}} = \mathsf{DKeyGen}(\mathsf{msk}, \boldsymbol{y})$, for all $i \neq r$: it computes $\mathsf{dk}_{\boldsymbol{y}_i} = \mathsf{IP.DKeyGen}(\mathsf{msk}_i, \boldsymbol{y}_i)$, and it queries its $\mathsf{QDKeyGen}$ oracle to obtain $\mathsf{QDKeyGen}(\boldsymbol{y}_r)$. It returns $\mathsf{dk}'_{\boldsymbol{y}} = \big(\mathsf{dk}_{\boldsymbol{y}}, \{\mathsf{dk}_{\boldsymbol{y}_i}\}_{i\in[n]}\big)$ to $\mathcal{A}$.

– $\mathsf{QCorrupt}(i)$: if $i = r$, $\mathcal{B}$ aborts the simulation and sends a random bit to its Finalize oracle. Otherwise, it returns $\mathsf{IP.msk}_i$.
– Finalize: $\mathcal{B}_r$ verifies that the conditions in Definition 11 are satisfied; if they are, it forwards the guess b' of $\mathcal{A}$, otherwise, it sends a random bit to its own Finalize oracle.

Note that when the random bit b used by the $\mathtt{IND}$-security game of $\mathsf{IP\text{-}FE}$ that $\mathcal{B}_r$ is interacting with is equal to 0, then, $\mathcal{B}_r$ simulates the game $\mathbf{H}_r$ to $\mathcal{A}$; otherwise, it simulates the game $\mathbf{H}_{r-1}$. In particular, the condition of the Finalize from Definition 11 implies that for all queries $(i, \boldsymbol{x}_i^{k_i,0}, \boldsymbol{x}_i^{k_i,1}, \ell_\rho)$ to $\mathsf{QLeftRight}'$, we have: $\sum_i \langle \boldsymbol{x}_i^{k_i,0}, \boldsymbol{y}_i \rangle = \sum_i \langle \boldsymbol{x}_i^{k_i,1}, \boldsymbol{y}_i \rangle$ for all $k_i \in [Q_i]$. Thus, we have in particular, for all $k \in [Q_r]$:

$$\begin{aligned}
&\langle \boldsymbol{x}_r^{k,0} - \boldsymbol{x}_\rho^{1,0}, \boldsymbol{y}_r \rangle = \langle \boldsymbol{x}_r^{k,1} - \boldsymbol{x}_\rho^{1,1}, \boldsymbol{y}_r \rangle \Rightarrow \\
&\langle \boldsymbol{x}_r^{k,0} + \boldsymbol{x}_r^{1,1} - \boldsymbol{x}_\rho^{1,0}, \boldsymbol{y}_r \rangle = \langle \boldsymbol{x}_r^{k,1} + \boldsymbol{x}_r^{1,1} - \boldsymbol{x}_\rho^{1,1}, \boldsymbol{y}_r \rangle \Rightarrow \\
&\langle \boldsymbol{c}_r^{k,0}, \boldsymbol{y}_r \rangle = \langle \boldsymbol{c}_r^{k,1}, \boldsymbol{y}_r \rangle,
\end{aligned}$$

where $[\boldsymbol{c}_r^{k,0}] = \mathsf{Encrypt}(\mathsf{ek}_r, (\boldsymbol{x}_r^{k,0} + \boldsymbol{x}_r^{1,1} - \boldsymbol{x}_r^{1,0}), \ell_\rho)$ and $[\boldsymbol{c}_r^{k,1}] = \mathsf{Encrypt}(\mathsf{ek}_r, (\boldsymbol{x}_r^{k,1} + \boldsymbol{x}_r^{1,1} - \boldsymbol{x}_r^{1,1}), \ell_\rho)$. The last implication uses the structural properties of the $\mathsf{IP\text{-}MCFE}$ scheme, namely, the property of linear homomorphism, and deterministic encryption. The last equality corresponds exactly to the condition to prevent the Finalize oracle from the $\mathtt{IND}$ security game of the $\mathsf{IP\text{-}FE}$ from outputting a random bit (see Definition 8).

This proves $|\mathsf{Adv}_{\mathbf{H}_{r-1}}(\mathcal{A}) - \mathsf{Adv}_{\mathbf{H}_r}(\mathcal{A})| \leq \mathsf{Adv}^{\mathtt{IND}}_{\mathsf{IP\text{-}FE}}(\mathcal{B}_r)$, and concludes the security proof.

7 DMCFE from MCFE without Pairings

7.1 Decentralized Multi-Client Functional Encryption

In [CDG+17], Chotard *et al.* defined the notion of DMCFE, where the generation of the functional decryption keys is distributed among the clients, so that they keep control on these keys. For efficiency reasons, they focused on efficient one-round key generation protocols $\mathsf{DKeyGen}$ that can be split in a first step $\mathsf{DKeyGenShare}$ that generates partial keys and the combining algorithm $\mathsf{DKeyComb}$ that combines partial keys into the functional decryption key. The full definition can be found in [CDG+17], and we briefly recall it here for completeness.

Definition 15 (Decentralized Multi-Client Functional Encryption). *A decentralized multi-client functional encryption on $\mathcal{M}$ between a set of n senders $(\mathcal{S}_i)_i$, for $i = 1, \dots, n$, and a functional decrypter $\mathcal{FD}$ is defined by the setup protocol and four algorithms:*

– $\mathsf{SetUp}(\lambda)$*: This is a protocol between the senders $(\mathcal{S}_i)_i$ that generate their own secret keys sk_i and encryption keys ek_i, and eventually output the public parameters mpk;*
– $\mathsf{Encrypt}(\mathsf{ek}_i, x_i, \ell)$*: Takes as input a user encryption key ek_i, a value x_i to encrypt, and a label ℓ, and outputs the ciphertext $C_{\ell,i}$;*
– $\mathsf{DKeyGenShare}(\mathsf{sk}_i, \ell_f)$*: Takes as input a user secret key sk_i and a label ℓ_f, and outputs the partial functional decryption key $\mathsf{dk}_{f,i}$ for a function $f : \mathcal{M}^n \to \mathcal{R}$ that is described in ℓ_f;*
– $\mathsf{DKeyComb}((\mathsf{dk}_{f,i})_i, \ell_f)$*: Takes as input the partial functional decryption keys and eventually outputs the functional decryption key dk_f;*
– $\mathsf{Decrypt}(\mathsf{dk}_f, \ell, \boldsymbol{C})$*: Takes as input a functional decryption key dk_f, a label ℓ, and an n-vector ciphertext $\boldsymbol{C}$, and outputs $f(\boldsymbol{x})$, if $\boldsymbol{C}$ is a valid encryption of $\boldsymbol{x} = (x_i)_i \in \mathcal{M}^n$ for the label ℓ, or $\perp$ otherwise;*

The correctness property essentially states the combined key corresponds to the functional decryption key. The security model is quite similar to the previous one for MCFE (see Definition 2), except that

– for the $\mathsf{DKeyGen}$ protocol: the adversary has access to transcripts of the communications, thus modeled by a query $\mathsf{QDKeyGen}(i, f)$ that executes $\mathsf{DKeyGenShare}(\mathsf{sk}_i, \ell_f)$, where ℓ_f is a description of f;

– corruption queries additionally reveal the secret keys sk_i;
– the Finalize procedure ignores incomplete functional decryption keys: for condition (2), only functions f for which all the honest key-shares have been asked are considered.

The critical point is the last one: the distributed key generation must guarantee that without all the shares, no information is known about the functional decryption key. In addition, the protocol must be efficient.

7.2 Distributed Sum

In order to convert an MCFE scheme into a DMCFE, one needs to allow efficient distributed computation of the functional decryption key. In many cases, this can be seen as a particular MCFE for the unique sum function on the contributions of all the clients. As an example, for the IP-MCFE from [CDG+17], $\mathsf{dk}_{\boldsymbol{y}} = \left(\boldsymbol{y}, \sum_i \mathbf{S}_i^\top \boldsymbol{y}_i\right)$, and namely one has to compute $\sum_i x_i = \sum_i \mathbf{S}_i^\top \boldsymbol{y}_i$, where the x_i's can be computed by each client.

In this section, we thus focus on the functionality of publishing the sum of individual secrets, in an efficient manner.

Definition 16 (Ideal Protocol DSum). *A DSum on a group $\boldsymbol{G}$ among n senders is defined by three algorithms:*

– $\mathsf{DSum.SetUp}(\lambda)$*: Takes as input the security parameter λ. Generates the public parameters* pp *and the personal secret keys* sk_i *for $i = 1 \cdots n$;*
– $\mathsf{DSum.Encode}(x_i, \ell, \mathsf{sk}_i)$*: Takes the x_i value to encode, a label ℓ and the personal secret key* sk_i *of the user i. Returns the share $M_{\ell,i}$*
– $\mathsf{DSum.Combine}(\boldsymbol{M})$*: Takes as input a vector $\boldsymbol{M} = (M_{\ell,i})_i$ of shares. Returns the value $\sum_i M_{\ell,i}$;*

Correctness. For any label ℓ, we want $\Pr[\mathsf{DSum.Combine}(\boldsymbol{M}_\ell) = \sum_i x_i] = 1$, where the probability is taken over $M_{\ell,i} \leftarrow \mathsf{DSum.Encode}(x_i, \ell, \mathsf{sk}_i)$ for all $i \in [n]$, and $(\mathsf{pp}, (\mathsf{sk}_i)_i) \leftarrow \mathsf{DSum.SetUp}(\lambda)$.

Security Notion. This protocol must guarantee the privacy of the x_i's, their sum possibly excepted when all the shares are known. This is the classical security notion for multi-party computation, where the security proof is performed by simulating the view of the adversary from the output of the result: nothing when not all the shares are asked, and just the sum of the inputs when all the shares are queried. We also have to deal with the corruptions, which give the users' secret keys.

7.3 DSum Protocol in the Random Oracle Model

The protocol below is similar to [KDK11], with a hash function. We provide a new security analysis, which relies on the CDH problem in the Random Oracle Model.

– $\mathsf{DSum.SetUp}(\lambda)$: Takes as input the security parameter λ and generates a group $\mathbb{G}$ of prime order p, with a generator g, were the CDH assumption holds. It also generates a hash function $\mathcal{H} : \{0,1\}^* \to \mathbf{G}$, for any group $\mathbf{G}$, denoted additively. Each user i, picks $t_i \xleftarrow{\$} \mathbb{Z}_p$. The public parameters pp are $(\mathbb{G}, p, g, \mathcal{H}, ([t_i])_i)$ and the personal secret keys $\mathsf{sk}_i = t_i$ for $i = 1 \cdots n$ (with the public parameters);
– $\mathsf{DSum.Encode}(x_i, \ell, \mathsf{sk}_i)$: Takes the x_i value to encode, a label ℓ and the personal secret key $\mathsf{sk}_i = t_i$ of the user i, it returns $M_{\ell,i}$ computed as below, where $h_{\ell,i,j} = \mathcal{H}([t_{\min\{i,j\}}], [t_{\max\{i,j\}}], t_i \cdot [t_j], \ell) = h_{\ell,j,i}$:

$$M_{\ell,i} = x_i - \sum_{j<i} h_{\ell,i,j} + \sum_{j>i} h_{\ell,i,j}.$$

– $\mathsf{DSum.Combine}(\boldsymbol{M} = (M_{\ell,i})_i)$: Takes as input a vector $\boldsymbol{M}$ of shares. Computes and return the value $\sum_i M_{\ell,i}$;

Correctness. The correctness should show that the sum of the shares is equal to the sum of the x_i's: the former is equal to

$$\sum_i \left(x_i - \sum_{j<i} h_{\ell,i,j} + \sum_{j>i} h_{\ell,i,j} \right) = \sum_i x_i - \sum_i \sum_{j<i} h_{\ell,i,j} + \sum_i \sum_{j>i} h_{\ell,j,i}$$
$$= \sum_i x_i - \sum_i \sum_{j<i} h_{\ell,i,j} + \sum_j \sum_{i<j} h_{\ell,j,i} = \sum_i x_i$$

7.4 Security Analysis (in the Random Oracle Model)

We will prove that there exists a simulator that generates the view of the adversary from the output only. In this proof, we will assume static corruptions (the set $\mathcal{CS}$ of the corrupted clients is known from the beginning) and the hardness of the CDH problem. However, this construction will only tolerate up to $n-2$ corruptions, so that there are at least 2 honest users. But this is also the case for the MCFE.

W.l.o.g., we can assume that $\mathcal{HS} = \{1, \ldots, n-c\}$ and $\mathcal{CS} = \{n-c+1, \ldots, n\}$, by simply reordering the clients, when $\mathcal{CS}$ is known. We will gradually modify the behavior of the simulator, with less and less powerful queries. At the beginning, the $\mathsf{DSum.Encode}$-query takes all the same inputs as in the real game, including the secret keys. At the end, it should just take the sum (when all the queries have been asked), as well as the corrupted x_j's.

Game $\mathbf{G}_0$: The simulator runs as in the real game, with known $\mathcal{CS}$.

Game $\mathbf{G}_1$: The simulator is given a group $\mathbb{G}$ with a generator g and a random pair $(X = [t]; Y = [t^2])$.

- $\mathsf{DSum.SetUp}$: the simulator randomly chooses $\alpha_i \xleftarrow{\$} \mathbb{Z}_p$, for $i = 1, \ldots, n-c$, and defines $X_i \leftarrow X + [\alpha_i]$. This sets $t_i = t + \alpha_i$. It can also set $Y_{i,j} = \mathsf{CDH}(X_i, X_j) = Y + (\alpha_i + \alpha_j) \cdot X + [\alpha_i \alpha_j]$, for $i, j \leq n-c$. It then randomly choses $t_i \leftarrow \mathbb{Z}_p$ for $i > n-c$ and sets $X_i = [t_i]$. It can also generate all the other $Y_{i,j} = \mathsf{CDH}(X_i, X_j)$'s, using the known t_i's. It sends the X_i's as the pp, and the secret keys t_i of the corrupted users;
- $\mathsf{DSum.Encode}(x_i, \ell)$: the simulator generates all the required $h_{\ell,i,j}$ using the X_j's and $Y_{i,j}$'s, querying the hash function, and returns $M_{\ell,i} = x_i - \sum_{j<i} h_{\ell,i,j} + \sum_{j>i} h_{\ell,i,j}$.

Game $\mathbf{G}_2$: The simulator does as above, but just uses a random $Y' \xleftarrow{\$} \mathbb{G}$ instead of Y, to answer the $\mathsf{DSum.Encode}$-queries.

This can make a difference for the adversary if the latter asks for the hash function on some tuple $(X_{\min\{i,j\}}, X_{\max\{i,j\}}, \mathsf{CDH}(X_i, X_j), \ell)$, for $i, j \leq n-c$, as this will not be the value $h_{\ell,i,j}$, which has been computed using $Y_{i,j} \neq \mathsf{CDH}(X_i, X_j)$. In such a case, one can find $\mathsf{CDH}(X_i, X_j) = Y + [\alpha_i + \alpha_j] \cdot X + [\alpha_i \alpha_j]$ in the list of the hash queries, and thus extract $Y = \mathsf{CDH}(X, X)$. As a consequence, under the hardness of the square Diffie-Hellman problem (which is equivalent to the CDH problem), this simulation is indistinguishable from the previous one.

Game $\mathbf{G}_3$: The simulator does as above except for the $\mathsf{DSum.Encode}$-queries. If this is not the last-honest query under label ℓ, the simulator returns $M_{\ell,i} = -\sum_{j<i} h_{\ell,i,j} + \sum_{j>i} h_{\ell,i,j}$; for the last honest query, it returns $M_{\ell,i} = S_H - \sum_{j<i} h_{\ell,i,j} + \sum_{j>i} h_{\ell,i,j}$, where $S_H = \sum_{j \in \mathcal{HS}} x_j$.

Actually, for a label ℓ, if we denote i_ℓ the index of the honest player involved in the last query, the view of the adversary is exactly the same as if, for every $i \neq i_\ell$, we have replaced h_{ℓ,i,i_ℓ} by $h_{\ell,i,i_\ell} + x_i$ (if $i_\ell > i$) or by $h_{\ell,i,i_\ell} - x_i$ (if $i_\ell < i$). We thus replace uniformly distributed variables by other uniformly distributed variables: this simulation is perfectly indistinguishable from the previous one.

Game $\mathbf{G}_4$: The simulator now ignores the values $h_{\ell,i,j}$ for honest i, j. But for each label, it knows the corrupted x_j's, and can thus compute the values $M_{\ell,j}$ for the corrupted users, using the corrupted x_j's and secret keys. If this is not the last honest query, it returns a random $M_{\ell,i}$. For the last honest query, knowing $S = \sum_j x_j$, it outputs $M_{\ell,i} = S - \sum_{j \neq i} M_{\ell,j}$.

As in the previous analysis, if one first sets all the $h_{\ell,i,j}$, for $j \neq i_\ell$, this corresponds to define h_{ℓ,i,i_ℓ} from $M_{\ell,i}$, for $i \neq i_\ell$.

7.5 DSum Protocol in the Standard Model

A variant of this protocol can also be described with a randomness extractor and a PRF. We then provide the security analysis under the DDH assumption and the PRF indistinguishability. More precisely, for the randomness extractor, we can use the Left-over-Hash-Lemma [ILL89, HILL99], with a random seed k in the CRS to extract random keys K for a PRF $(\mathcal{F}_K)_K$, with a universal hash function $(H_k)_k$:

- $\mathsf{DSum.SetUp}(\lambda)$: Takes as input the security parameter λ and generates a group $\mathbb{G}$ of prime order p, with a generator g. From a family of universal hash functions $(H_k)_k$ and a random key k, this define the randomness extractor $\mathcal{E}(\cdot) = H_k(\cdot)$, later used to generate the keys K of a PRF $(\mathcal{F}_K)_K$. Each user i, picks $t_i \xleftarrow{\$} \mathbb{Z}_p$. The public parameters pp are $(\mathbb{G}, p, g, \mathcal{E}, (\mathcal{F}_K)_K, ([t_i])_i)$ and the personal secret keys $\mathsf{sk}_i = t_i$ for $i = 1 \cdots n$ (with the public parameters);
- $\mathsf{DSum.Encode}(x_i, \ell, \mathsf{sk}_i)$: Takes the x_i value to encode, a label ℓ and the personal secret key $\mathsf{sk}_i = t_i$ of the user i, it returns $M_{\ell,i}$ computed as below, where $h_{\ell,i,j} = \mathcal{F}_{K_{i,j}}(\ell)$ with $K_{i,j} = \mathcal{E}(t_i \cdot [t_j])$:

$$M_{\ell,i} = x_i - \sum_{j<i} h_{\ell,i,j} + \sum_{j>i} h_{\ell,i,j}.$$

- $\mathsf{DSum.Combine}(\boldsymbol{M} = (M_{\ell,i})_i)$: Takes as input a vector $\boldsymbol{M}$ of shares. Computes and return the value $\sum_i M_{\ell,i}$;

The correctness is the same as above, since it just makes use of $h_{\ell,i,j}$. The security however requires the DDH assumption, in order to guarantee the randomness of all the Diffie-Hellman values $[t_i \cdot t_j]$. The Left-over-Hash Lemma thereafter ensures the uniform and independent distributions of the $K_{i,j}$'s which then make the $h_{\ell,i,j}$'s unpredictable for all the honest i, j.

7.6 Security Analysis (in the Standard Model)

In the previous section, we observe that we do not exploit programmability of the random oracle, and can actually use the Decisional Diffie-Hellman assumption to prove it in the standard model. The key used $K_{i,j}$ for $\mathcal{F}$ is $\mathcal{E}([t_i t_j])$, where $\mathcal{E}$ is a randomness extractor, and the input is ℓ. We still assume that $\mathcal{HS} = \{1, \ldots, n-c\}$.

Game $\mathbf{G}_0$: The simulator runs as in the real game, with known $\mathcal{CS}$ (assumed to be $\{n-c+1, \ldots, n\}$, without loss of generality, since we are in the static corruption setting).

Game $\mathbf{G}_1$: The simulator does as above, but just uses a random value $Y_{i,j} \xleftarrow{\$} \mathbb{G}$ instead of the key $[t_i t_j]$, when both $i \neq j \in \mathcal{HS}$, to generate the $K_{i,j}$'s to answer the $\mathsf{DSum.Encode}$-queries. After the hybrid sequence described below, the advantage for the adversary is:

$$|\mathsf{Adv}_{\mathbf{G}_0}(\mathcal{A}) - \mathsf{Adv}_{\mathbf{G}_1}(\mathcal{A})| \leq \frac{(n-c)^2}{2} \cdot \mathsf{Adv}^{\mathsf{ddh}}(\mathcal{B}),$$

for some adversary $\mathcal{B}$ running with a similar time as $\mathcal{A}$.

Game $\mathbf{G}_2$: The simulator now uses random keys $K_{i,j}$'s in the cases $i < j$ are both honest, and $K_{j,i} = K_{i,j}$. Because of the entropy on the $Y_{i,j}$'s, the Left-over-Hash Lemma guarantees a statistical indistinguishability with the previous game.

Game $\mathbf{G}_3$: The simulator now chooses random $h_{\ell,i,j}$ for any ℓ, in the cases $i < j$ are both honest, and $h_{\ell,j,i} = h_{\ell,i,j}$. Under the indistinguishability of the PRF with random keys, this game is indistinguishable from $\mathbf{G}_2$.

Now, the rest of the proof is similar to the previous one, with a final simulation as in above game $\mathbf{G}_4$.

Hybrid Sequence: Here we present the hybrid games $\mathbf{H}_{i,j,k}$ between $\mathbf{G}_0$ and $\mathbf{G}_1$. An iteration of this sequence describes how to replace the value $[t_{i^*}t_{j^*}]$ used in the setup phasis, for honest $i^* < j^*$, by random $Y_{i^*,j^*} \xleftarrow{\$} \mathbb{G}$. The progression follows the lexicographical order on the pairs $(i,j) \in \mathcal{HS}$ where $i < j$, and $\mathsf{Succ}(i,j)$ denotes the next pair. It will be clear that $\mathbf{G}_0 = \mathbf{H}_{1,2,0}$ and $\mathbf{G}_1 = \mathbf{H}_{n-c-1,n-c,3}$. In addition, for all $(1,2) \leq (i^*,j^*) < (n-c-1,n-c)$, $\mathbf{H}_{i^*,j^*,3} = \mathbf{H}_{\mathsf{Succ}(i^*,j^*),0}$. We indeed insist that $K_{i,i}$ is never used, so only Diffie-Hellman values for two different keys are used.

Game $\mathbf{H}_{i^*,j^*,0}$: The simulator runs the real game, except that it additionally initializes $Y_{i,j}$ in the $\mathsf{DSum.SetUp}$, used for the extracted keys $K_{i,j} = \mathcal{E}(Y_{i,j})$ during the $\mathsf{DSum.Encode}$, either correctly as $[t_it_j]$ or at random:

– $\mathsf{DSum.SetUp}$: after having generated the group $\mathbb{G}$ of prime order p, with a generator g, the randomness extractor $\mathcal{E}(\cdot)$, and the PRF $(\mathcal{F}_K)_K$, the simulator generates the secret keys $t_i \xleftarrow{\$} \mathbb{Z}_p$ and sets $X_i \leftarrow [t_i]$, for all i. Then it defines:
  - for $(i,j) < (i^*,j^*)$, where $i < j$ are both honest, pick a random element $Y_{i,j} \xleftarrow{\$} \mathbb{G}$
  - for $(i,j) \geq (i^*,j^*)$, where $i < j$ are both honest, set $Y_{i,j} \leftarrow [t_it_j]$
  - for (i,j) where $i < j$ and some of them is corrupted, set $Y_{i,j} \leftarrow [t_it_j]$
  - for (i,j) where $i > j$, set $Y_{i,j} \leftarrow Y_{j,i}$

It sends the X_i's as the pp, and the secret keys t_i of the corrupted users;

Game $\mathbf{H}_{i^*,j^*,1}$: for $i^* < j^*$, the simulator is given a group $\mathbb{G}$ with a generator g and a random Diffie-Hellman tuple $(X = [x], Y = [y], Z = [xy])$.

– $\mathsf{DSum.SetUp}$: it uses the above group $\mathbb{G}$ and generator g, and generates $\mathcal{E}$ and $(\mathcal{F}_K)_K$. For the indices i^*, j^*, the simulator defines $X_{i^*} \leftarrow X$ and $X_{j^*} \leftarrow Y$. This sets $t_{i^*} \leftarrow x$ and $t_{j^*} \leftarrow y$. It can also set $Y_{i^*,j^*} = \mathsf{CDH}(X_{i^*}, X_{j^*}) = Z$. It then randomly chooses $t_i \xleftarrow{\$} \mathbb{Z}_p$ for $i \neq i^*, j^*$ and sets $X_i \leftarrow [t_i]$. It can also generate $Y_{i,j} = \mathsf{CDH}(X_i, X_j)$, using the known t_i, for $(i,j) > (i^*,j^*)$ and $i < j$. The cases $(i,j) < (i^*,j^*)$ for $i < j$ and the cases $i > j$ remain unchanged. It sends the X_i's as the pp, and the secret keys t_i of the corrupted users;

The view of the adversary remains the same.

Game $\mathbf{H}_{i^*,j^*,2}$: for $i^* < j^*$, the simulator is given a random tuple $(X = [x], Y = [y], Z \xleftarrow{\$} \mathbb{G})$, and does as above. Under the hardness of the Decisional Diffie-Hellman problem, this simulation is indistinguishable from the previous one.

Game $\mathbf{H}_{i^*,j^*,3}$: this is quite similar to game $\mathbf{H}_{i^*,j^*,0}$, but with difference for $(i,j) = (i^*,j^*)$:

– $\mathsf{DSum.SetUp}$: after having generated the group $\mathbb{G}$ of prime order p, with a generator g, the randomness extractor $\mathcal{E}(\cdot)$, and the PRF $(\mathcal{F}_K)_K$, the simulator generates the secret keys $t_i \xleftarrow{\$} \mathbb{Z}_p$ and sets $X_i \leftarrow [t_i]$, for all i. Then it defines:
  - for $(i,j) \leq (i^*,j^*)$, where $i < j$ are both honest, pick a random element $Y_{i,j} \xleftarrow{\$} \mathbb{G}$
  - for $(i,j) > (i^*,j^*)$, where $i < j$ are both honest, set $Y_{i,j} \leftarrow [t_it_j]$
  - for (i,j) where $i < j$ and some of them is corrupted, set $Y_{i,j} \leftarrow [t_it_j]$
  - for (i,j) where $i > j$, set $Y_{i,j} \leftarrow Y_{j,i}$

The view of the adversary does not change.

Starting from $(1,2)$ up to $(n-c-1, n-c)$, there are $(n-c)(n-c-1)/2$ cases with $i^* < j^*$ which involve the DDH assumption, hence the conclusion.

7.7 Application to IP-DMCFE

One can generically convert an $\mathsf{IP\text{-}MCFE}$ into an $\mathsf{IP\text{-}DMCFE}$, when $\mathsf{dk}_{\boldsymbol{y}} = (\boldsymbol{y}, \boldsymbol{d}_{\boldsymbol{y}})$, where $\boldsymbol{d}_{\boldsymbol{y}} = \sum_i x_i$, with the x_i's computed by each client, as $x_i \leftarrow \mathbf{S}_i^\top \boldsymbol{y}_i$ in [CDG+17], by letting the clients generating the DSum secret keys at the setup time, and the label is the vector $\boldsymbol{y}$:

– $\mathsf{DKeyGenShare}(\mathsf{sk}_i, \boldsymbol{y})$: outputs $M_{\boldsymbol{y},i} \leftarrow \mathsf{DSum.Encode}(x_i, \boldsymbol{y}, \mathsf{sk}_i)$;
– $\mathsf{DKeyComb}((M_{\boldsymbol{y},i})_i, \boldsymbol{y})$: outputs the functional decryption key $\mathsf{dk}_{\boldsymbol{y}} = (\boldsymbol{y}, \boldsymbol{d}_{\boldsymbol{y}})$, where $\boldsymbol{d}_{\boldsymbol{y}}$ is publicly computed as $\mathsf{DSum.Combine}((M_{\boldsymbol{y},i})_i)$;

Using the last simulation game, we can now show that all the $\mathsf{DKeyGenShare}(\mathsf{sk}_i, \boldsymbol{y})$ are first simulated at random, and only the last query requires making the DKeyGen-query to the IP-MCFE scheme to get the sum and program the output. Hence, unless all the honest queries are asked, the functional decryption key is unknown.

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