Pilvi: Lattice Threshold PKE with Small Decryption Shares and Improved Security

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Abstract. Threshold public-key encryption (tPKE) enables any subset of t out of K parties to decrypt non-interactively, while any ciphertext remains secure if less than t decryption shares are known. Despite recent progress, existing lattice-based tPKEs face at least one of the following drawbacks: (1) having large decryption share size – polynomial in K and some even exponential in t, (2) proven secure only against relaxed security models where the adversary is not allowed to see decryption shares of challenge ciphertexts, and (3) lack of concrete efficiency, in particular due to the requirement of super-polynomial modulus for noise flooding.

We present Pilvi, a new thresholdised variant of Regev's public-key encryption scheme, which achieves both small decryption shares and a strong form of simulation-based security under the Learning with Errors (LWE) assumption. Our construction has decryption share size $t \cdot \log K \cdot \mathsf{poly}(\lambda)$ and allows the use of a polynomial-size modulus assuming an a priori bound on the number of queries Q. It remains secure even when an adaptive adversary requests partial decryptions of both challenge and non-challenge ciphertexts, as long as for each ciphertext the number of corrupt parties plus the number of shares obtained is less than t. We provide concrete parameter suggestions for 128-bit security for a wide range of (t, K, Q), including cases where $t \approx K/2$ for up to $K \leq 32$ users and $Q \leq 2^{60}$ partial decryption queries. The ciphertext size ranges from 14 to 58 KB and the partial decryption share size ranges from 1 to 4 KB.

Along the way, we abstract out a general purpose tool called the threshold-LWE assumption, which we prove to follow from LWE. The threshold-LWE assumption captures the core steps in security proofs of schemes involving Shamir's secret-sharing the LWE secret with carefully chosen evaluation points, the algebraic structures from the latter being what enabling the efficiency of our tPKE scheme. As an additional application, we also show how to construct distributed pseudorandom functions (dPRFs) from the threshold-LWE assumption.

1 Introduction

Threshold cryptography studies how to distribute a cryptographic task (e.g. decryption) to K parties, such that the task can be performed jointly by at least $t \leq K$ parties, and that security properties are retained against any coalition of less than t parties. Of interest is, among others, threshold public-key encryption (tPKE), a classic threshold primitive which has received attention since the earlier 90s [DF90] and gained renewed interests due to NIST's recent call for multi-party threshold schemes [BP23]. In this work, we set out to construct a tPKE scheme, under the learning with errors (LWE) assumption, with (1) an asymptotically small decryption share size of $t \cdot \log K \cdot \mathsf{poly}(\lambda)$, (2) security even against adversaries who are allowed to obtain partial decryptions of challenge ciphertexts, and (3) generally practical parameters for a wide range of (t, K). Our scheme allows non-interactive decryption: no collaboration between decrypting parties is required and the plaintext can be recovered by anyone collecting sufficiently many partial decryption shares.

1.1 Lattice-based Threshold PKE

A tPKE requires decryption to succeed when threshold t many users cooperate, but no information about the encrypted message should be learnt even when $t - 1$ decryption shares are leaked. To achieve this, a common construction template is to make use of secret sharing, where a (master) secret key sk of a plain PKE is

secret-shared into key shares $(\mathsf{sk}_k)_{k\in[K]}$ and distributed to the K system users. Relative to PKE, a tPKE is commonly defined with an additional partial decryption ParDec algorithm, which inputs a ciphertext ctxt and a partial secret key sk_k from a user k, and outputs a partial decryption pd_k. Upon given a set T of partial decryptions $(\mathsf{pd}_k)_{k\in T}$ from threshold t many users, the (full) decryption algorithm then recovers the plaintext. Due to its simplicity and versatility, tPKE is useful in a variety of applications, such as distributed storage, emulation of secret sharing, building block for more advanced encryption-type cryptographic primitives, multi-party computations (MPC), to name just a few.

Threshold PKE over lattices has been a subject of study for over a decade, with the first scheme based on the LWE assumption dating back to [BD10]. Lattice-based tPKE commonly adopts the following LWE-style template: The LWE secret $\mathbf{r}$ is secret-shared into $\{\mathbf{s}_k\}_{k\in[K]}$, the public key consists of a matrix $\mathbf{A}$ and an LWE sample $\mathbf{b}^\intercal = \mathbf{r}^\intercal\mathbf{A} + \mathbf{e}^\intercal \bmod q$, a ciphertext of msg is of the form $(\mathbf{Ax}, \mathbf{b}^\intercal\mathbf{x} + \mathsf{msg}) \bmod q$ for some short vector $\mathbf{x}$, and partial decryption is $\mathsf{pd}_k = \mathbf{s}_k^\intercal \cdot \mathbf{Ax} + e_k \bmod q$ for some fresh masking error e_k. To decrypt given a set of $(\mathsf{pd}_k)_{k\in T}$, run secret-sharing recovery to obtain a noisy version of $\mathbf{r}^\intercal \cdot \mathbf{Ax} \bmod q$ and subtract from $\mathbf{b}^\intercal\mathbf{x} + \mathsf{msg} \bmod q$. Despite the simplicity of the template, the state-of-the-art of this primitive has remained unsatisfactory.

Efficiency bottlenecks. A major obstacle to achieving practical lattice-based tPKE is the difficulty of norm-control on secret sharing. On the one hand, secret sharing schemes with low-norm sharing- and recovery-coefficients are necessary for both correctness and security, since recovery-coefficients are to be multiplied to LWE errors during decryption, whereas the sharing-coefficients (whose information are contained in $\mathsf{sk}_k = \mathbf{s}_k$) must be masked in the partial decryption pd_k by the fresh error e_k. On the other hand, secret sharing schemes with bounded sharing- and recovery-coefficients are scarce, and typically comes at the cost of substantial share sizes. For example, the $\{0,1\}$-LSSS [BGG+18] has sharing- and recovery-coefficients in the low-norm set $\{0,1\}$, but has share size asymptotically $O(K^{4.3})$ per party (c.f. [BS23, Table 1]), which quickly becomes impractical for large number of users K. Another choice is the naive secret sharing (c.f. [BS23, Table 1]), whose share size per party is $\binom{K}{t}$, which scales exponentially in t and cannot practically support large threshold t. Especially in high-traffic applications where partial decryptions are transmitted frequently, the heavy communication costs due to large share sizes make these schemes far from desirable.

Another complication in achieving practical parameters is the need to argue security in presence of partial decryptions pd_k, for which a common technique is to use noise-flooding in security proofs [BD10, BGG+18, DLN+21]. In this type of proof, the fresh masking error e_k in pd_k is required to be super-polynomially large, so as to argue that pd_k does not leak information about the secret key share $\mathbf{s}_k$, but which also lead to a blow up in all other lattice parameters and sizes. Towards improving efficiency, some recent works [BS23, MS25] investigated lattice-based tPKE (and its extension threshold fully homomorphic encryption (tFHE)) with polynomial modulus, but were so far limited to either small threshold t and number of partial decryption queries [BS23], or restricted to support only K-out-of-K sharing [MS25].

(In)security? Other than unsatisfactory efficiency, the security of tPKE schemes also has more to be desired. A tPKE security notion commonly considered [BD10, BGG+18, BS23, MS25] is as follows: Against an adversary $\mathcal{A}$ who

1. can corrupt any subset $\mathcal{C}$ of parties for any $|\mathcal{C}| \le t-1$ to obtain their secret key shares $\{\mathsf{sk}_k\}_{k\in\mathcal{C}}$, and
2. is given access to a partial decryption oracle which, for any ciphertext ctxt not encrypting the challenge message msg_b, returns the decryption shares pd_k of all K parties,

it holds that a challenge ciphertext ctxt^* encrypting the challenge message msg_b remains pseudorandom in the eye of $\mathcal{A}$. While this may seem reasonable at first glance, a second thought reveals a security gap for a common scenario: Think of applications of tPKE where the total number of users K and threshold t are large, and in reality it is difficult for an adversary $\mathcal{A}$ to corrupt (close to) $t-1$ users. Instead, $\mathcal{A}$ may corrupt only a few $|\mathcal{C}| \ll t-1$ users and attempt to observe partial decryptions pd_k's, e.g. from different sets of honest users on different challenge ciphertexts, similar to a chosen ciphertext attack (CCA) scenario, and hope to learn non-trivial information from the collection over time. That is, we are facing an adversary $\mathcal{A}$ who, in addition to Items 1 and 2 above, also

Work	Security				Efficiency	
	Model	$\lvert\mathcal{C}\rvert$	$\mathsf{ParDec}(\mathsf{ctxt}^*)$	|Queries|	Modulus	|Shares|
[MS25]	SIM	$K-1$	-	unbounded	$\mathsf{poly}(\lambda)$	1
[BD10]	SIM	$t-1$	-	unbounded	$\lambda^{\omega(1)}$	$\binom{K}{t}$
[BGG+18]	SIM	$t-1$	-	unbounded	$\lambda^{\omega(1)}$	$K^{4.3}$
[DLN+21]	IND	$\leq t-1$	yes	unbounded	$\lambda^{\omega(1)}$	$K^{2.4}$ *
This work	SIM$^-$	$\leq t-1$	yes	unbounded	$\lambda^{\omega(1)}$	$t \log K$
[BS23]	IND	$\leq t-1$	no	bounded	$\mathsf{poly}(\lambda)$	$\binom{K}{t}$
This work	SIM$^-$	$\leq t-1$	yes	bounded	$\mathsf{poly}(\lambda)$	$t \log K$

Table 1: Overview of existing lattice-based tPKEs. SIM$^-$: restricted simulation-based security. $|\mathcal{C}|$: number of corrupt parties. $\mathsf{ParDec}(\mathsf{ctxt}^*)$: allowing partial decryptions on challenge ciphertexts (Item 3, "-" means not allowed due to assumption of maximum corruption). |Queries|: number of partial decryption queries allowed. |Shares|: size of partial decryption shares from each party (omitting fixed $\mathsf{poly}(\lambda)$ factors). [MS25] considered only K-out-of-K threshold. [BGG+18, BS23] constructed tFHE, the above concerns their schemes when collapsed to a tPKE. *: [DLN+21] claimed a share size $O(K^{2.4})$ using [HMP06], but this approach is disputed in [BS23, P.16].

3. has access to a partial decryption oracle, which returns decryption shares pd_k of challenge ciphertexts ctxt^* so long as ctxt^* cannot be trivially decrypted.

Curiously, while Item 3 seems a natural property to be expected from a tPKE, it has been neglected in most prior works on tPKE [BD10, BGG+18, BS23, MS25]. It is not difficult to see that a security proof without concerning Item 3 is indeed much easier, since in this restricted setting it becomes w.l.o.g. to assume that $\mathcal{A}$ corrupts exactly $|\mathcal{C}| = t-1$ users (precisely the opposite of what likely happens in a large scale application), and any further pd_k (Item 2) implies recovery of the plaintext, which can be trivially simulated[3]. In a concurrent work [BKW25], it has been shown that tPKE without considering Item 3 is provably a strictly weaker security notion, in that there are tPKE schemes which can be proven secure without which but insecure otherwise, precisely by manipulating the partial decryption oracle queries. To our knowledge, the only existing scheme which has taken Item 3 into account is that of [DLN+21], but which unfortunately only provided asymptotic results, without an estimation of its practicality.

1.2 Our Contributions

We provide a lattice-based tPKE which improves upon the state-of-the-art in terms of trade-offs between efficiency and security. At the core is a general-purpose tool targeting the broader context of lattice-based threshold cryptography. Our main results are summarised as follows.

Threshold PKE. We propose Pilvi, a new lattice-based tPKE scheme which offers competitive efficiency and security, based on the standard LWE assumption. Pilvi is a natural thresholdisation of Regev's PKE scheme [Reg05], but with extra designs which utilise the algebraic properties of Shamir's secret sharing over rings. Concretely, Pilvi is the first lattice-based (t, K)-tPKE scheme with the following combination of guarantees:

- (Size) A partial decryption has size $t \cdot \log K \cdot \mathsf{poly}(\lambda)$. This is achieved by carefully analysing and utilising the algebraic structures offered by Shamir's secret sharing over specially chosen rings and evaluation points [AL21], departing from the more common approaches with low-norm secret sharing schemes over integers.
- (Security) Against an adversary $\mathcal{A}$ who can:
  1. corrupt any subset of $\leq t-1$ parties,

[3] This is the approach taken by [BD10, BGG+18, MS25], see Table 1.

2. adaptively request for non-challenge ciphertexts along with their encryption randomness and partial decryptions from all users, and
3. adaptively request for challenge ciphertexts, along with their partial decryptions from any users so long as $\mathcal{A}$ cannot trivially decrypt them,

Pilvi achieves a version of simulation security, where the simulator is able to simulate partial decryption queries upon given only public information (i.e. those available to $\mathcal{A}$). This improves upon the results of all prior works based on the same LWE-style construction paradigm [BD10, BGG+18, BS23, MS25].

– (Poly-modulus) The above security is proven with a modulus $q \leq \sqrt{Q} \cdot K^t \cdot \mathsf{poly}(\lambda)$, where Q is the number of (challenge and non-challenge) ciphertexts on which $\mathcal{A}$ queries partial decryptions.

We provide concrete parameter suggestions in Section 7 for 128-bit security for a wide range of values for the recovery threshold t, the number of parties K and the number of partial decryption queries Q: Any combination of $2 \leq t < K$, $K \in \{8, 16, 32\}$ and $Q \in \{0, 1, 2^{32}, 2^{60}\}$. Regardless of the setting, the ciphertext size ranges from 14 to 58 KB and the partial decryption share size (per party) is around 1 to 4 KB. As highlighted above, on top of achieving stronger security, one of the key strengths of Pilvi is its small partial decryption share size. For example, for $(t, K, Q) = (6, 10, 1)$ or $(11, 20, 10)$, the scheme of [BS23] produces shares of size over 100 MB.

Threshold-LWE. On the technical level, Pilvi is enabled by a new general-purpose tool which we call the threshold-LWE assumption.

To recall, the (standard) LWE assumption states that given $(\mathbf{A}, \mathbf{b})$ where $\mathbf{b}^\intercal \approx \mathbf{r}^\intercal \mathbf{A} \bmod q$ are LWE samples with random secret $\mathbf{r}$, the samples $\mathbf{b}$ appear pseudorandom. Roughly, our threshold-LWE assumption states that $\mathbf{b}$ remains pseudorandom even when given additional information of $(\mathbf{x}_j, (\mathbf{b}_{k,j})_{k \in I_j})_j$, where $\mathbf{x}_j$ are short vectors and $\mathbf{b}_{k,j}^\intercal \approx \mathbf{s}_k^\intercal \mathbf{A} \mathbf{x}_j \bmod q$ are LWE samples under secret $\mathbf{s}_k$, the k-th Shamir's secret share of the original LWE secret $\mathbf{r}$ with evaluation points chosen from suitable subtractive sets [AL21]. We show that the threshold-LWE assumption is implied by the standard LWE assumption with modulus $q \leq \sqrt{Q} \cdot K^t \cdot \mathsf{poly}(\lambda)$.

Further application of threshold-LWE. As another application of the threshold-LWE assumption, we present a simple distributed pseudorandom function (dPRF), obtained by thresholdising a PRF, which follows known templates [BPR12, BLMR13] of lattice-based PRFs. We consider the weak pseudorandomness security[4], i.e. the PRF values appear pseudorandom for random inputs, against strong adversaries who corrupt any of $\leq t - 1$ parties and ask for many partial PRF evaluations.

2 Technical Overview

In Section 2.1 we overview our tPKE scheme Pilvi and the design which enables its efficiency, then we give with a more precise description of the security property of tPKE of interest and distil the core challenges in proving it. In Section 2.2, we present a high-level description of the threshold-LWE assumption which abstracts out such core challenges, followed by an overview of our reduction from LWE to threshold-LWE. In Section 2.3 we summarise another example application of threshold-LWE, namely distributed pseudorandom functions (dPRF).

We work over the ring of integers of a cyclotomic field $\mathcal{R} = \mathbb{Z}[\zeta]$, $\zeta = \zeta_\mathfrak{f} \in \mathbb{C}$ is a primitive $\mathfrak{f}$-th root of unity, and its quotient ring $\mathcal{R}_q = \mathcal{R}/q\mathcal{R}$ for some prime q. We will let the number of users $K = \mathfrak{f}$ and $2 \leq t < K$.[5] The ring $\mathcal{R}$ admits a simple ξ-subtractive set [AL21] $\Xi = \{1, \zeta, \ldots, \zeta^{\mathfrak{f}-1}\}$ with $\xi = \xi(t) = \mathfrak{f}$ (or $2^{\lceil \log t \rceil}$ if $\mathfrak{f}$ is a power of 2), i.e. if $\mathbf{V}_T$ is a Vandermonde matrix formed by a t-subset T of the set, then $\xi(t) \cdot \mathbf{V}_T^{-1}$ is defined over $\mathcal{R}$. The notion of subtractive sets will be formally recalled in Section 3.1. In this overview we suppress mod q operations when working over $\mathcal{R}_q$ for the ease of exposition. To denote the noisy version of a term, we use the wavy underline $\underset{\sim}{\cdot}$, e.g. $\underset{\sim}{\mathbf{r}^\intercal \mathbf{A}}$ means $\mathbf{r}^\intercal \mathbf{A} + \mathbf{e}^\intercal$ where $\mathbf{e}$ is short relative to q. We

[4] Weak pseudorandomness can be upgraded to (strong) pseudorandomness with standard techniques in the random oracle model.

[5] We also support $t = K$ but for this setting there are simpler schemes than ours.

abuse χ to denote any Gaussian distributions over $\mathcal{R}$, even if they are with different Gaussian parameters in the formal constructions.

2.1 Threshold PKE

Construction. At a high-level, our tPKE scheme Pilvi follows the existing LWE-style framework [BGG+18, BS23, MS25]:

- The secret key $\mathsf{sk} = \mathbf{r} \in \mathcal{R}_q^n$ is a uniform vector $\mathbf{r} \leftarrow\!\!\$\ \mathcal{R}_q^n$.
- The public key $\mathsf{pk} = (\mathbf{A}, \mathbf{b})$ consists of a $\mathbf{A} \leftarrow\!\!\$\ \mathcal{R}_q^{n\times m}$ and $\mathbf{b}^\mathsf{T} = \underbrace{\mathbf{r}^\mathsf{T}\mathbf{A}}$.
- Shares $(\mathsf{sk}_k)_{k\in[K]}$ of $\mathbf{r}$ are obtained via the Shamir secret sharing scheme using the subtractive set Ξ as evaluation points: Let $\mathbf{R}$ be sampled uniformly at random from $\mathcal{R}_q^{t\times n}$ conditioned on $\mathbf{v}_0^\mathsf{T}\mathbf{R} = \mathbf{r}^\mathsf{T}$,[6] and compute $(\mathbf{s}_k)_{k\in[K]} = \mathbf{V}\cdot\mathbf{R}$ where $\mathbf{V}$ is the $K \times t$ Vandermonde matrix defined by Ξ. Let $\mathsf{sk}_k = \mathbf{s}_k$.
- The ciphertext of a message $\mu \in \mathcal{R}_2$ under pk is $\mathsf{ctxt} = (\mathbf{Ax}, \mathbf{b}^\mathsf{T}\mathbf{x} + \xi^{-1}\cdot\lfloor q/2\rfloor\cdot\mu)$, where $\mathbf{x} \leftarrow\!\!\$\ \mathcal{D}_\mathbf{x}$ is the encryption randomness.
- Party k's partial decryption of ctxt is $\mathsf{pd}_k = \underbrace{\mathbf{s}_k^\mathsf{T}\mathbf{Ax}}$,
- Partial decryption from a set T of t parties $(\underbrace{\mathbf{s}_k^\mathsf{T}\mathbf{Ax}})_{k\in T}$ can be combined to obtain $\xi\cdot\mathbf{v}_0^\mathsf{T}\mathbf{V}_T^{-1}\cdot(\underbrace{\mathbf{s}_k^\mathsf{T}\mathbf{Ax}})_{k\in T} \approx \xi\cdot\underbrace{\mathbf{r}^\mathsf{T}\mathbf{Ax}}$, and therefore the plaintext can be recovered from $\underbrace{\lfloor q/2\rfloor\mu} = \xi\cdot(\mathbf{b}^\mathsf{T}\mathbf{x} + \xi^{-1}\cdot\mu\lfloor q/2\rfloor) - \xi\cdot\underbrace{\mathbf{r}^\mathsf{T}\mathbf{Ax}}$.

We highlight that the scheme presented above is designed to allow using a ξ-subtractive set Ξ with $\xi \neq 1$. This allows the use of the simple set $\Xi = \{1, \zeta, \ldots, \zeta^{\dagger-1}\}$ which has (empirically) good parameters:

- The cardinality of Ξ is relatively large (compared to other known choices of Ξ with $\xi = 1$ [AL21, KLNO24]).
- For $\xi = \xi(t)$ and any t-subset T of Ξ the matrix $\xi\cdot\mathbf{V}_T^{-1}$ is relatively low-norm (compared to other choices of Ξ).

More importantly, we observe empirically that the norm of $\xi\cdot\mathbf{V}_T^{-1}$ grows rather slowly (although still exponentially) in t and peaks at around $t \approx K/2$. This ultimately allows us to give concrete parameter suggestions for the full range $2 \le t \le K$.

The somewhat unnatural encoding $\xi^{-1}\cdot\lfloor q/2\rfloor\cdot\mu$ of the message μ allows the slack ξ to be cancelled out during decryption. If the more natural encoding of $\lfloor q/(2\xi)\rfloor\cdot\mu$ is used, we would need to increase the modulus q by a factor of ξ, which negatively impacts concrete performance.

To support a larger message length $L > 1$, in the actual scheme we let there be L copies of secret keys $(\mathbf{r}_\ell)_{\ell\in L}$, its shares $(\mathsf{sk}_{\ell,k})_{\ell\in L}$ for each party k, and ciphertext components $(\mathbf{b}_\ell\mathbf{x} + \xi^{-1}\lfloor q/2\rfloor\cdot\mu_\ell)_{\ell\in L}$, which only minimally increases the overall ciphertext size, since the encryption randomness $\mathbf{x}$, hence also the dominating component $\mathbf{Ax}$, are reused.

Security. We consider a simulation-based security notion which requires the existence of a PPT simulator, so that:

- After seeing the scheme's public parameters, the PPT adversary specifies a set of corrupted users $\mathcal{C} \subset [K]$, and it is provided with a public key and key-shares corresponding to corrupted parties. Then, the adversary has access to three oracles: EncO, ChalO, and ParDecO.
- EncO: on input a message μ, return the encryption ctxt of μ using randomness rnd, together with the randomness rnd.[7]
- ChalO: on input a message μ, return an encryption ctxt of μ (real exp.), or a random ciphertext sampled from the ciphertext space (ideal exp.).

[6] In other words, the first row of $\mathbf{R}$ is set to $\mathbf{r}^\mathsf{T}$.

[7] Although not necessary for baseline indistinguishability, this extra property further allows to upgrade the tPKE to CCA security via recent NIZK techniques, for more details see discussion in Section 5.

– ParDecO: on input a ciphertext previously returned by either EncO or ChalO and a user index k, return the partial decryption pd_k by user k of the given ciphertext (real exp.), or run the simulator on public inputs, i.e. the public key, corrupt key shares, and the query ciphertext, to simulate pd_k (ideal exp.). To rule out trivial attacks, ParDecO ensures that, for any ciphertext, the number of partial decryption queries plus the number of corrupt users is always less than the threshold t.[8]

Notably, in the last item, an adversary is able to query ParDecO on ciphertexts generated by ChalO, corresponding to the additional adversarial capability sketched as Item 3 in Section 1, a security gap left open in prior works [BGG+18, BS23, MS25] (except [DLN+21]). Note also that, the above simulator does not need to know any information about the LWE secret $\mathbf{r}$, the honest shares $\mathbf{s}_k$ nor messages μ queried to EncO or ChalO.

Abstraction of security argument. To prove that the threshold Regev's PKE satisfies the above security property, one would need to reason about the pseudorandomness of some correlated LWE samples given the shares $(\mathbf{s}_k)_{k\in\mathcal{C}}$ of corrupt parties. These correlated LWE samples roughly take the form:

$$\mathbf{A}, \qquad \underbrace{\mathbf{r}^\intercal\mathbf{A}}, \qquad \Big(\ \mathbf{A}\mathbf{x}, \qquad \underbrace{\mathbf{r}^\intercal\mathbf{A}\mathbf{x}}, \qquad (\underbrace{\mathbf{s}_k^\intercal\mathbf{A}\mathbf{x}})_k \ \Big)_{\mathbf{x}} \tag{1}$$

where $\mathbf{x}$'s are short vectors which rerandomise the public key $\underbrace{\mathbf{r}^\intercal\mathbf{A}}$ into a challenge ciphertext, $\underbrace{\mathbf{s}_k^\intercal\mathbf{A}\mathbf{x}}$ is a partial decryption of said ciphertext by user k, and for each $\mathbf{x}$ the index k ranges over a subset $L_{\mathbf{x}} \subseteq [K]$ such that $|L_{\mathbf{x}} \cup \mathcal{C}| < t$.

Recall that the adversary could request for partial decryptions from different subsets of users for different ciphertexts, and these subsets could jointly cover the set $[K]$ of all users.[9] Therefore, without the rerandomisation factors $\mathbf{x}$, distributions such as the above are clearly not pseudorandom due to the correlations between the LWE samples with correlated secrets. However, due to the correlation between the components, we could not directly appeal to LWE to argue about the pseudorandomness of the distribution either. The core challenge of the security proof is therefore to decouple the correlated LWE samples gradually to uncorrelated ones, from where we can invoke the LWE assumption.

2.2 Threshold-LWE

To argue about the pseudorandomness of LWE samples with secrets correlated via Shamir's secret sharing, we introduce an intermediate assumption called threshold-LWE (th-LWE) which abstracts out the core challenge of proving the security of the tPKE. We believe that the th-LWE assumption is sufficiently general-purpose and can be convenient for proving the security of other threshold schemes based on LWE, as we will demonstrate in Section 2.3 with dPRFs as an example. A technical highlight of this work is a reduction showing that the th-LWE assumption is implied by the standard LWE assumption.

Threshold-LWE Assumption. The threshold-LWE assumption states that a pair of real and ideal experiments, the latter parametrised by a PPT stateful simulator $\mathcal{S}$, are indistinguishable to a PPT adversary $\mathcal{A}$. In both experiments, $\mathcal{A}$ receives a random matrix $\mathbf{A} \leftarrow\!\!\$\ \mathcal{R}_q^{n\times m}$ and specifies a set $\mathcal{C} \subset [K]$ of at most $t-1$ corrupt parties. Then, $\mathcal{A}$ receives a tuple

$$(\mathbf{b}, \mathbf{S}_{\mathcal{C}}) \in \mathcal{R}_q^m \times \mathcal{R}_q^{\mathcal{C}\times n}$$

where in the real experiment $\mathbf{b}^\intercal = \mathbf{r}^\intercal\mathbf{A} + \mathbf{e}^\intercal \bmod q$ is an LWE sample and $\mathbf{S}_{\mathcal{C}}$ consists of the Shamir secret shares of $\mathbf{r}$ for the corrupt parties; and in the ideal experiment both $\mathbf{b}$ and $\mathbf{S}_{\mathcal{C}}$ are uniformly random.

[8] A stronger flavour of simulation requires the simulator to function properly even after the threshold is exceeded, if it is given as leakage which message the query ciphertext is supposed to be encrypting.

[9] For example, if $(t, K) = (3, 4)$, the adversary could corrupt user 1, then ask for partial decryptions of 3 different ciphertexts from users 2, 3 and 4, respectively.

So far, the views of $\mathcal{A}$ in the real and ideal experiments are trivially indistinguishable by the standard LWE assumption. What makes the experiments interesting is that $\mathcal{A}$ is further given access to a set of oracles which generate correlated leakages. In more detail, in the real experiment $\mathcal{A}$ is given access to the oracles $\mathsf{GenISIS}$, GenLWE, $\mathsf{ShareISIS}$ and $\mathsf{ShareLWE}$, while in the ideal experiment $\mathcal{A}$ is given access to the oracles $\mathsf{SimISIS}$, SimLWE, $\mathsf{ShareISIS}$ and $\mathsf{ShareLWE}$. Let the simulator $\mathcal{S}$ be given $(\mathbf{A}, \mathbf{b}, \mathbf{S}_{\mathcal{C}})$, i.e. what $\mathcal{A}$ sees. The behaviour of these oracles are summarised as follows:

- $\mathsf{GenISIS}$: Sample a short vector $\mathbf{x}$, compute $\mathbf{y} = \mathbf{A}\mathbf{x} \bmod q$ and return $(\mathbf{x}, \mathbf{y})$. Internally, for each $k \in [K]$, generate the LWE samples $c_k = \mathbf{s}_k^{\mathsf{T}}\mathbf{y} + e_k \bmod q$ where $\mathbf{s}_k$ is the k-th share of the main LWE secret $\mathbf{r}$ and store them in the table entry $L_{\mathtt{ISIS}}[\mathbf{y}]$.
- GenLWE: Sample a uniformly random $\mathbf{y} \leftarrow\!\!\$\ \mathcal{R}_q^n$, generate an LWE sample $z = \mathbf{r}^{\mathsf{T}}\mathbf{y} + e \bmod q$ (using the main LWE secret $\mathbf{r}$) and return $(\mathbf{y}, z)$. Internally, generate the LWE samples $d_k = \mathbf{s}_i^{\mathsf{T}}\mathbf{y} + e_k \bmod q$ and store them in the table entry $L_{\mathtt{LWE}}[\mathbf{y}]$.
- $\mathsf{SimISIS}$: Generate and return $(\mathbf{x}, \mathbf{y})$ as in $\mathsf{GenISIS}$. Internally, run the simulator $\mathcal{S}$ on $\mathbf{x}$ to simulate the table entry $L_{\mathtt{ISIS}}[\mathbf{y}]$.
- SimLWE: Generate and return $(\mathbf{y}, z)$ as in GenLWE. Internally, for each $k \in [K]$, run the simulator $\mathcal{S}$ on $\mathbf{y}$ to simulate the table entry $L_{\mathtt{LWE}}[\mathbf{y}]$.
- $\mathsf{ShareISIS}$: On input $(\mathbf{y}, k)$, return the value c_k stored in $L_{\mathtt{ISIS}}[\mathbf{y}]$.
- $\mathsf{ShareLWE}$: On input $(\mathbf{y}, k)$, return the value d_k stored in $L_{\mathtt{LWE}}[\mathbf{y}]$.

Notably, the simulator $\mathcal{S}$ only has access to information which are available also to $\mathcal{A}$, and still we insist that the real and ideal experiments are indistinguishable.

It is not difficult to see that the th-LWE assumption immediately implies the security of the tPKE scheme: The public key is given by $(\mathbf{A}, \mathbf{b})$, the corrupt key shares are given by the rows of $\mathbf{S}_{\mathcal{C}}$, challenge ciphertext queries can be answered using the $\mathsf{GenISIS}/\mathsf{SimISIS}$ oracle, and partial decryption queries can be answered using the $\mathsf{ShareISIS}$ oracle. Note that the GenLWE, SimLWE, and $\mathsf{ShareLWE}$ oracles are not used for tPKE, but they will be used for our dPRFs.

Reduction from LWE. In Theorem 2, we show that the threshold-LWE assumption stated above is implied by the standard LWE assumption. This result assumes that the modulus q is super-polynomial in the security parameter and allows the threshold-LWE adversary to make an unbounded number of queries. To obtain better parameters in applications (e.g. tPKE), we also consider the setting where the threshold-LWE adversary is only allowed to make an a priori bounded $Q_{\mathtt{ISIS}}, Q_{\mathtt{LWE}} = \mathsf{poly}(\lambda)$ number of queries to the $\mathsf{GenISIS}/\mathsf{SimISIS}$ and $\mathsf{GenLWE}/\mathsf{SimLWE}$ oracles. In this case, in Theorem 1, we obtain a reduction with a polynomial size modulus q. We note that the bounded-query setting is commonly considered in the lattice-based threshold cryptography literature (e.g. [DKM+24, EKT24, BKL+25]).

Below, we overview the high level strategy of obtaining these reductions. Without loss of generality, we assume that $\mathcal{A}$ makes at most $Q_{\mathtt{ISIS}}$ queries to the $\mathsf{GenISIS}/\mathsf{SimISIS}$ oracle and $Q_{\mathtt{LWE}}$ queries to the $\mathsf{GenLWE}/\mathsf{SimLWE}$ oracle.[10] We begin by considering a hybrid experiment $\mathsf{Hyb}[D]$ parameterised by a distribution sampler D. At the beginning of the experiment, a random matrix $\mathbf{A}$ is sampled, given which $\mathcal{A}$ outputs the set $\mathcal{C}$ of corrupt parties. The experiment also samples a short random matrix $\mathbf{X} \leftarrow\!\!\$\ \mathcal{R}^{m \times Q_{\mathtt{ISIS}}}$ (as in $\mathsf{GenISIS}$) and a uniformly random matrix $\mathbf{Y} \leftarrow\!\!\$\ \mathcal{R}^{n \times Q_{\mathtt{LWE}}}$ (as in GenLWE). The distribution sampler D, on input $(\mathcal{C}, \mathbf{A}, \mathbf{X}, \mathbf{Y})$, generates a tuple

$$(\mathbf{b}, \mathbf{C}, \mathbf{D}, \mathbf{z}, \mathbf{S}_{\mathcal{C}}) \in \mathcal{R}_q^m \times \mathcal{R}_q^{K \times Q_{\mathtt{ISIS}}} \times \mathcal{R}_q^{K \times Q_{\mathtt{LWE}}} \times \mathcal{R}_q^{Q_{\mathtt{LWE}}} \times \mathcal{R}_q^{\mathcal{C} \times n},$$

where

- $\mathbf{b}$: plays the role of the main LWE sample,
- $\mathbf{C}$: the i-th column corresponds to the correlated LWE samples generated upon the i-th $\mathsf{GenISIS}/\mathsf{SimISIS}$ query,

[10] If $Q_{\mathtt{ISIS}}$ and $Q_{\mathtt{LWE}}$ are not a priori upper bounded, then the reduction can estimate them in polynomial time.

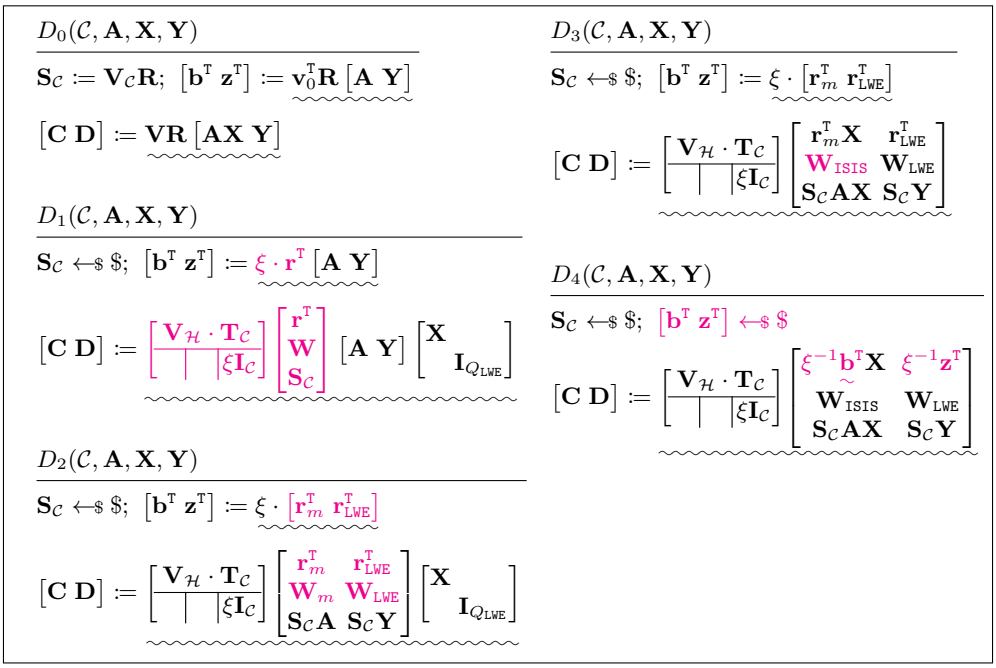

Fig. 1: Simplified description of core distributions D_0 – D_4. The values $\mathbf{X}$, $\mathbf{V}_\mathcal{H} \cdot \mathbf{T}_\mathcal{C}$ and ξ are low-norm. $\mathbf{I}_\mathcal{C}$ is an identity matrix. The values $\mathbf{R}$, $\mathbf{r}$ and $\mathbf{W}$ and their subscripted versions are uniformly random.

- $\mathbf{D}$: the i-th column corresponds to the correlated LWE samples generated upon the i-th $\mathsf{GenLWE}/\mathsf{SimLWE}$ query,
- $\mathbf{z}$: the i-th entry (together with the i-th column of $\mathbf{Y}$) correspond to the response (i.e. LWE sample with main LWE secret $\mathbf{r}$) to the i-th $\mathsf{GenLWE}/\mathsf{SimLWE}$ query, and
- $\mathbf{S}_\mathcal{C}$: consists of the shares of the corrupt parties.

We then define a sequence of samplers $D_0, \ldots, D_4$ such that $\mathsf{Hyb}[D_0]$ is equivalent to the real experiment while $\mathsf{Hyb}[D_4]$ is equivalent to the ideal experiment. A simplified description of the distributions $D_0, \ldots, D_4$ is given in Fig. 1, where e.g. the precise noise distributions are omitted. (See Fig. 9 for the formal description.) It then remains to argue that D_i is indistinguishable to D_{i+1} for all i.[11] While $D_0 \equiv D_1$ and $D_3 \equiv D_4$ are argued by functional equivalence, the remaining two hops $D_1 \approx D_2 \approx D_3$ involve decoupling correlated LWE samples into less correlated ones.

Core Lemma. Abstractly, each of the decoupling hops $D_1 \approx D_2 \approx D_3$ requires to argue that, for some fixed low-norm matrices $\mathbf{N}, \mathbf{M}$ and $\mathbf{X}$, the following distributions are indistinguishable:

$$\left\{\begin{array}{l}(\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{S}_2)\\ \hline \mathbf{B} \coloneqq \mathbf{N}\mathbf{S}_0\mathbf{A}\\ \\ \mathbf{C} \coloneqq \mathbf{M}\begin{bmatrix}\mathbf{S}_0\\ \mathbf{S}_1\\ \mathbf{S}_2\end{bmatrix}\mathbf{A}\mathbf{X}\end{array}\right\} \approx_c \left\{\begin{array}{l}(\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{S}_2)\\ \hline \mathbf{B} \coloneqq \mathbf{N}\bar{\mathbf{S}}_0\\ \\ \mathbf{C} \coloneqq \mathbf{M}\begin{bmatrix}\bar{\mathbf{S}}_0\\ \bar{\mathbf{S}}_1\\ \mathbf{S}_2\mathbf{A}\end{bmatrix}\mathbf{X}\end{array}\right\}.$$

[11] For technical reasons, we actually argue that $\mathsf{Hyb}[D_i]$ is indistinguishable to $\mathsf{Hyb}[D_{i+1}]$ because we have to take the distributions of $(\mathbf{A}, \mathbf{X}, \mathbf{Y})$ into account.

where $\mathbf{A}, \mathbf{S}_0, \mathbf{S}_1, \mathbf{S}_2, \bar{\mathbf{S}}_0, \bar{\mathbf{S}}_1$ are uniformly random and $\mathbf{E}_B, \mathbf{E}_C$ are short Gaussian noise. (Note that the matrices $\mathbf{A}$ and $\mathbf{C}$ here are different from those in Fig. 1.) Establishing the above indistinguishability is the most technical part in this work, and its formal statement is given in Lemma 5. Our proof is based on either the leaky LWE assumption [LSW25], which is implied by standard LWE, or the standard LWE assumption together with noise flooding. The former holds with a polynomial modulus q for a priori bounded $Q_{\texttt{ISIS}}$ and $Q_{\texttt{LWE}}$, while the latter holds with a super-polynomial modulus q for unbounded many queries.

The first step of the proof involves moving all low-norm matrices $\mathbf{M}$, $\mathbf{N}$ and $\mathbf{X}$ to one side of the products, using (row-style) matrix vectorisation. This reduces the task to showing the indistinguishability of the following:

$$\begin{pmatrix} \mathbf{A},\ \mathbf{b}^\intercal = \underbrace{\mathbf{s}_0^\intercal(\mathbf{I}_{t_0} \otimes \mathbf{A})(\mathbf{N}^\intercal \otimes \mathbf{I}_m)}} \\ \mathbf{c}^\intercal = \underbrace{(\mathbf{s}_0^\intercal, \mathbf{s}_1^\intercal) \cdot (\mathbf{I}_{t_0} \otimes \mathbf{A})(\mathbf{M}_{0,1}^\intercal \otimes \mathbf{X})}} \end{pmatrix} \approx_c \begin{pmatrix} \mathbf{A},\ \mathbf{b}^\intercal = \underbrace{\bar{\mathbf{s}}_0^\intercal(\mathbf{N}^\intercal \otimes \mathbf{I}_m)}} \\ \mathbf{c}^\intercal = \underbrace{(\bar{\mathbf{s}}_0^\intercal, \bar{\mathbf{s}}_1^\intercal) \cdot (\mathbf{M}_{0,1}^\intercal \otimes \mathbf{X})}} \end{pmatrix}$$

where $\mathbf{M}_{0,1}$ is a submatrix of $\mathbf{M}$, and $\mathbf{s}_0$, $\mathbf{s}_1$, $\bar{\mathbf{s}}_0$ and $\bar{\mathbf{s}}_1$ are uniformly random. Now, since $(\mathbf{N}^\intercal \otimes \mathbf{I}_m)$ and $(\mathbf{M}_{0,1}^\intercal \otimes \mathbf{X})$ are low-norm matrices, we can resort to either leaky LWE or noise flooding to establish the indistinguishability.

2.3 Other Application: Distributed PRF

We present an additional application of our threshold-LWE assumption – distributed pseudorandom functions (dPRF) – to demonstrate its utility. A family of deterministic functions is said to be pseudorandom if no efficient adversary can distinguish it from a uniformly random function by only observing its output. The idea of distributed pseudorandom function was introduced by Naor, Pinkas, and Reingold [NPR99]: Each of the K parties receives a key-share of the PRF key from a (t, K)-threshold secret sharing scheme. Using such a key-share, each party can compute a partial evaluation of the PRF on an arbitrary input point. Collecting at least t such partial evaluations allows to recover the PRF value.

Construction. Similar to our tPKE scheme Pilvi, we will make use of a ξ-subtractive set Ξ. Our dPRF, based on [BPR12, BLMR13], works as follows:

- the PRF key is a uniform random vector $\mathbf{r} \leftarrow\!\!\$\ \mathcal{R}_q^n$, and key-shares $(\mathsf{sk}_k)_{k\in[K]} = (\mathbf{s}_k)_{k\in[K]}$ of $\mathbf{r}$ are obtained via the Shamir secret sharing scheme using the subtractive set Ξ as evaluation points, i.e. $(\mathbf{s}_k)_{k\in[K]} = \mathbf{V} \cdot \mathbf{R}$, where $\mathbf{V}$ is the $K \times t$ Vandermonde matrix defined by Ξ and $\mathbf{R}$ is sample uniformly at random from $\mathcal{R}_Q^{t\times n}$ subject on having the first row equal to $\mathbf{r}$,
- the PRF value of $\mathbf{y} \in \mathcal{R}_q^n$ is $\left\lfloor \lfloor \xi \cdot \mathbf{r}^\intercal \mathbf{y} \rceil_p \right\rceil_u$, and its partial PRF evaluation with key-share $\mathbf{s}_k$ is $\lfloor \mathbf{s}_k^\intercal \mathbf{y} \rceil_p$,[12]
- partial PRF evaluations $(\lfloor \mathbf{s}_k^\intercal \mathbf{y} \rceil_p)_{k\in T}$ can be combined to obtain $\xi \cdot \mathbf{v}_0^\intercal \mathbf{V}_T^{-1} \cdot \lfloor \mathbf{s}_k^\intercal \mathbf{y} \rceil_p)_{k\in T} \approx \lfloor \xi \cdot \mathbf{r}^\intercal \mathbf{y} \rceil_p$, and therefore the PRF value can be recovered by rounding the result down modulo u using $\lfloor \cdot \rceil_u$.

Similarly to the tPKE construction from Section 2.1, the use of the ξ factor in the reconstruction ensures that the error term arising includes a factor of the form $\xi \cdot \mathbf{V}_T^{-1}$, which has relatively low norm. Accordingly, the PRF evaluation $\left\lfloor \lfloor \xi \cdot \mathbf{r}^\intercal \mathbf{y} \rceil_p \right\rceil_u$ is defined to include the ξ factor in order to ensure correctness.

Security. We consider the weak pseudorandomness property against adversaries who can statically corrupt an arbitrary number of less than t parties, and requests for full and partial PRF evaluations on uniformly random inputs. That is, against such adversaries, PRF evaluations, both full and partial, on uniformly random inputs, are pseudorandom except for trivially correlated ones.[13] In other words, the view of the adversary is very

[12] $\lfloor \cdot \rceil_p, \lfloor \cdot \rceil_u$ denote the modulus switching operation from q to p and from p to u respectively. We formally define it in Section 6.

[13] Despite our construction being similar to that of [BLMR13], our security notion is incomparable to theirs. In particular, [BLMR13] restricts that an adversary must corrupt $t-1$ many parties, and no queries on partial evaluations of the challenges are allows. We give further discussion in Section 6.

similar to (and simpler than) that in Eq. (1). Similarly to the case of tPKE, the pseudorandomness of the above view follows almost directly from the threshold-LWE assumption.

3 Preliminaries

Let $\lambda \in \mathbb{N}$ denote the security parameter, and $\mathsf{poly}(\lambda)$ and $\mathsf{negl}(\lambda)$ the set of all polynomials and negligible functions in λ, respectively. For $k, n \in \mathbb{N}$, $k \leq n$, we write $[n]$ for $\{1, \ldots, n\}$ and $[k, n]$ for $\{k, \ldots, n\}$. If S is a set, we write $x \leftarrow\!\!\$\ S$ for sampling a uniformly random element from S. If $\mathcal{D}$ is a distribution over S, denoted as $\mathcal{D} \sim S$, we write $x \leftarrow\!\!\$\ \mathcal{D}$ for sampling a random element from S according to the distribution $\mathcal{D}$.

We use bold capital and lower-case letters, e.g. $\mathbf{A}$ and $\mathbf{b}$, to denote matrices and vectors, respectively. We write $\cdot$ for the usual matrix product, which is sometimes omitted, and $\otimes$ for the tensor (i.e. Kronecker) product of matrices. The matrix tensor product satisfies the mixed product property: For all matrices $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$ and $\mathbf{D}$ of suitable dimensions, we have $(\mathbf{A} \otimes \mathbf{B})(\mathbf{C} \otimes \mathbf{D}) = \mathbf{AC} \otimes \mathbf{BD}$.

3.1 Algebraic Number Theory

Let $\mathcal{K} = \mathbb{Q}(\zeta)$ be a cyclotomic field of conductor $\mathfrak{f}$ and $\mathcal{R} = \mathbb{Z}[\zeta]$ be its ring of integers. Write $\varphi = \varphi(\mathfrak{f})$ for the degree of $\mathcal{K}$. For $q \in \mathbb{N}$, define the quotient ring $\mathcal{R}_q \coloneqq \mathcal{R}/q\mathcal{R}$. We denote by $\mathcal{R}^\times$ and $\mathcal{R}_q^\times$ the sets of units in $\mathcal{R}$ and $\mathcal{R}_q$ respectively. We will always assume that q is a rational prime unramified in $\mathcal{K}$, and $\mathcal{R}_q \cong \mathbb{F}_{q^g}^{\varphi/g}$ where $q^{-g} \leq \mathsf{negl}(\lambda)$ for some $g | \varphi$. The latter ensures that matrices $\mathbf{A}$ sampled at random over $\mathcal{R}_q$ are primitive with overwhelming probability in λ.

Canonical embedding and norms. Write $\sigma = (\sigma_i)_{i \in \mathbb{Z}_\mathfrak{f}^\times} : \mathcal{K} \to \mathbb{C}^\varphi$ for the canonical embedding of $\mathcal{K}$. For a vector $\mathbf{x} \in \mathcal{K}^m$, the canonical embedding is extended component-wise, i.e. $\sigma(\mathbf{x}) = (\sigma(x_i))_{i \in [m]}$, and its ℓ_p-norm is taken to be the ℓ_p-norm of its canonical embedding, i.e. $\|\mathbf{x}\|_p \coloneqq \|\sigma(\mathbf{x})\|_p$, where $p = 2$ when omitted. For any $a, b \in \mathcal{R}$, it holds that $\|a \cdot b\|_p \leq \|a\|_\infty \cdot \|b\|_p$ for any $p \geq 1$. For a matrix $\mathbf{M} \in \mathcal{K}^{n \times m}$, its norm is taken to be $\|\mathbf{M}\|_p \coloneqq \sup_{\mathbf{x} \in \mathcal{K}^m} \|\mathbf{M} \cdot \mathbf{x}\|_p / \|\mathbf{x}\|_p$. Consequently, $\|\mathbf{Mx}\|_p \leq \|\mathbf{M}\|_p \cdot \|\mathbf{x}\|_p$ and $\|\mathbf{MN}\|_p \leq \|\mathbf{M}\|_p \cdot \|\mathbf{N}\|_p$. It can be easily checked that $\|\mathbf{M}\|^2 \leq \sum_{j \in [m]} \|\mathbf{m}_j\|^2$, where $\mathbf{m}_j$ is the j-th column of $\mathbf{M}$.

Subtractive sets. We rely on the notion of subtractive sets, proposed by [AL21] and further studied by e.g. [KLNO24]. We adopt a slightly different definition which better suits the purpose of this work.

Definition 1 (Subtractive sets). *For a set $\Xi = \{\mu_1, \ldots, \mu_k\} \subseteq \mathcal{R}$, any $t \leq K$, and any subset $T \subseteq \{0\} \cup \Xi$, let $\mathbf{V}_T$ (with implicit dependency on t) denote the (row-style) $T \times t$ Vandermonde matrix, i.e. its rows are indexed by T and row $\mu \in T$ is given by $(1, \mu, \ldots, \mu^{t-1})^\intercal$.*

Let $\xi = \xi(t) : [k] \to \mathcal{R}$. The set Ξ is said to be ξ-subtractive [AL21] if for any $t \in [k]$ and any size-t subset $T \subseteq \Xi$, it holds that $\xi \cdot \mathbf{V}_T^{-1} \in \mathcal{R}^{t \times t}$.

Consider Ξ with $0 \notin \Xi$. Denote by $\mathbf{v}_0^\intercal \coloneqq \mathbf{V}_{\{0\}} = (1, 0, \ldots, 0)$ the first unit vector. We measure the quality of Ξ by the following quantities:

- *"recovery-expansion factor" $\rho(t) \coloneqq \max_{T \subseteq_t \Xi} \left\| \xi \cdot \mathbf{v}_0^\intercal \cdot \mathbf{V}_T^{-1} \right\|$.*
- *"inverse-expansion factor" $\gamma(t) \coloneqq \max_{T^* \subseteq_{t-1} \Xi} \left\| \xi \cdot \mathbf{V}_\Xi \cdot \mathbf{V}_{\{0\} \cup T^*}^{-1} \right\|$.*

The Vandermonde matrix $\mathbf{V}_\Xi$ defined above is equivalent to the share-generating matrix of the t-out-of-K Shamir's secret sharing with evaluation points in Ξ.

Lemma 1 (Adapted from [AL21, Theorem 1]). *Let $\mathcal{R} = \mathbb{Z}[\zeta]$ be the cyclotomic ring with a power-of-2 conductor $\mathfrak{f} = 2^k$. The set $\left\{1, \zeta, \ldots, \zeta^{\mathfrak{f}-1}\right\}$ is ξ-subtractive for $\xi(t) = 2^{\lceil \log t \rceil}$.*

The next lemmas are convenient for analysing the quality of a subtractive set, implying also the norm quality of the above $\mathbf{V}$. Their proofs are found in Appendix A.2.

Lemma 2. *Let $\mathbf{V} \in \mathcal{K}^{t\times t}$ be the Vandermonde matrix of the set $\{\mu_1, \ldots, \mu_t\} \subset \mathcal{K}$. It holds that $\left\|\mathbf{V}^{-1}\right\| \leq \sqrt{t}\max_\ell \max_{i\in[t]} \prod_{j\in[t],j\neq i} \frac{1+|\sigma_\ell(\mu_j)|}{|\sigma_\ell(\mu_j-\mu_i)|}$ where ℓ ranges over all φ embeddings σ_ℓ from $\mathcal{K}$ to $\mathbb{C}$.*

Lemma 3. *Let $\mathcal{R} = \mathbb{Z}[\zeta]$ be the cyclotomic ring with conductor $\mathfrak{f}$. The set $\Xi = \left\{1, \zeta, \ldots, \zeta^{\mathfrak{f}-1}\right\}$ is ξ-subtractive for $\xi = \xi(t) = \mathfrak{f}$, or $\xi(t) = 2^{\lceil \log t\rceil}$ if $\mathfrak{f}$ is a power of 2. It has the quality $\rho(t) \leq \xi \cdot t\left(\frac{\mathfrak{f}}{2\sqrt{2}}\right)^{t-1}$ and $\gamma(t) \leq \xi \cdot t\sqrt{K}\left(\frac{\mathfrak{f}}{2\sqrt{2}}\right)^{t-1}$. Furthermore, if $\mathfrak{f}$ is a power of 2, then $\xi = 2^{\lceil \log t\rceil}$.*

Note that Lemmas 1 and 3 hold also for any subset of $\left\{1, \zeta, \ldots, \zeta^{\mathfrak{f}-1}\right\}$.

3.2 Discrete Gaussians

We denote by $D^m_{\mathcal{R},\chi}$ the (centred) discrete Gaussian distribution over $\mathcal{R}^m$ with parameter χ, i.e. the distribution over $\mathcal{R}^m$ where for all $\mathbf{x} \in \mathcal{R}^m$, the probability mass function $D^m_{\mathcal{R},\chi}(\mathbf{x}) \propto e^{-\pi\|\mathbf{x}\|^2/\chi^2}$.

3.3 Lattice Assumptions

We recall a (standard) generalisation of the LWE assumption where the LWE matrix $\mathbf{A}$ and secret $\mathbf{s}$ are sampled from distribution $\mathcal{D}_\mathtt{A}$ and $\mathcal{D}_\mathtt{s}$ that are not necessarily uniform.

Definition 2 (LWE assumption). *Let*

$$\mathsf{params} = (\mathcal{R}, n, m, q, \chi, \mathcal{D}_\mathtt{A}, \mathcal{D}_\mathtt{s})$$

be parametrised by λ. The (decision) $\mathsf{LWE}_{\mathsf{params}}$ assumption states that for any PPT adversary $\mathcal{A}$, for the experiment $\mathsf{Exp\text{-}LWE}^b$ given in Fig. 2, it holds that

$$\left|\Pr\left[\mathsf{Exp\text{-}LWE}^0_{\mathsf{params},\mathcal{A}}(1^\lambda) = 1\right] - \Pr\left[\mathsf{Exp\text{-}LWE}^1_{\mathsf{params},\mathcal{A}}(1^\lambda) = 1\right]\right| \leq \mathsf{negl}(\lambda).$$

The parameters $\mathcal{D}_\mathtt{A}, \mathcal{D}_\mathtt{s}$ are suppressed if they are the uniform distribution over $\mathcal{R}_q^{n\times m}$ and $\mathcal{R}_q$ respectively.

We state a special case of the leaky LWE assumption of [LSW25], which is also a generalisation of the error-leakage LWE assumption of [DKL+23].

Definition 3 (LLWE assumption [LSW25]). *Let*

$$\mathsf{params} = (\mathcal{R}, n, m, k, q, \bar{\chi}, \chi, \mathcal{L}, \mathcal{D})$$

be parametrised by λ, where $\mathcal{D} \sim \mathcal{R}_q^{n\times m}$ is a distribution. The (decision) $\mathsf{LLWE}_{\mathsf{params}}$ assumption states that for any PPT adversary $\mathcal{A}$, for the experiment $\mathsf{Exp\text{-}LLWE}^b$ given in Fig. 2, it holds that

$$\left|\Pr\left[\mathsf{Exp\text{-}LLWE}^0_{\mathsf{params},\mathcal{A}}(1^\lambda) = 1\right] - \Pr\left[\mathsf{Exp\text{-}LLWE}^1_{\mathsf{params},\mathcal{A}}(1^\lambda) = 1\right]\right| \leq \mathsf{negl}(\lambda).$$

The parameter $\mathcal{D}$ is suppressed if it is the uniform distribution over $\mathcal{R}_q^{n\times m}$.

In [LSW25] it is proven that the leaky LWE assumption is implied by the LWE assumption, with polynomial-size modulus q, appropriate (not necessarily spherical) Gaussian noise distributions and ℓ_2-norm bounded leakage. A similar proof (with more restrictive distributions and parameters) can be found in [DKL+23]. Below is the reduction of [LSW25] specialised to cyclotomic rings $\mathcal{R}$ with the canonical embedding and spherical Gaussian noise distributions.

Lemma 4 (Special case of [LSW25, Theorem 3]). *Let $\mathcal{R}, n, m, k, q, \beta, \bar{\chi}, \chi, \chi^*, \mathcal{L}, \mathcal{D}$ be parametrised by λ, where $\mathcal{R} = \mathbb{Z}[\zeta]$, $n, m, k, q \in \mathbb{N}$, $\mathcal{D} \sim \mathcal{R}_q^{n\times m}$, $\chi^* \geq \sqrt{2}\cdot\eta_\epsilon(\mathcal{R}^m)$, $\bar{\chi} > 0$, $\chi > 0$, and $\mathcal{L} = \left\{\mathbf{Z} \in \mathcal{R}^{m\times k} : \|\mathbf{Z}\| \leq \beta\right\}$, where $\beta = \chi \cdot \sqrt{(2\eta_\epsilon(\mathcal{R}^m)^2 + (\chi^*)^2)^{-1} - \bar{\chi}^{-2}}$. Then, the $\mathsf{LLWE}_{\mathcal{R},n,m,k,q,\bar{\chi},\chi,\mathcal{L},\mathcal{D}}$ assumption holds if the $\mathsf{LWE}_{\mathcal{R},n,m,q,\chi^*,\mathcal{D}}$ assumption holds.*

$\mathsf{Exp\text{-}LWE}^b_{\mathsf{params},\mathcal{A}}(1^\lambda)$

$\mathbf{A} \leftarrow \mathcal{D}_{\mathtt{A}}$
$\mathbf{r} \leftarrow\!\$\ \mathcal{D}_{\mathtt{s}}^n;\ \mathbf{e} \leftarrow\!\$\ D^m_{\mathcal{R},\chi}$
if $b = 0$ **then** $\mathbf{b}^{\mathsf{T}} \coloneqq \mathbf{r}^{\mathsf{T}}\mathbf{A} + \mathbf{e}^{\mathsf{T}} \bmod q$
if $b = 1$ **then** $\mathbf{b} \leftarrow\!\$\ \mathcal{R}_q^m$
return $\mathcal{A}(\mathbf{A}, \mathbf{b})$

$\mathsf{Exp\text{-}LLWE}^b_{\mathsf{params},\mathcal{A}}(1^\lambda)$

$\mathbf{A} \leftarrow \mathcal{D}$
$\mathbf{Z} \leftarrow \mathcal{A}(\mathbf{A});$ **assert** $\mathbf{Z} \in \mathcal{L}$
$\mathbf{r} \leftarrow\!\$\ \mathcal{R}_q^n;\ \bar{\mathbf{e}} \leftarrow\!\$\ D^m_{\mathcal{R},\bar{\chi}};\ \mathbf{e} \leftarrow\!\$\ D^k_{\mathcal{R},\chi}$
if $b = 0$ **then** $\mathbf{b}^{\mathsf{T}} \coloneqq \mathbf{r}^{\mathsf{T}}\mathbf{A} + \bar{\mathbf{e}}^{\mathsf{T}} \bmod q$
if $b = 1$ **then** $\mathbf{b} \leftarrow\!\$\ \mathcal{R}_q^m$
$\mathbf{l}^{\mathsf{T}} \coloneqq \bar{\mathbf{e}}^{\mathsf{T}}\mathbf{Z} + \mathbf{e}^{\mathsf{T}};$ **return** $\mathcal{A}(\mathbf{b}, \mathbf{l})$

Fig. 2: Experiments for the LWE and the Leaky LWE assumptions.

4 Threshold LWE

We introduce the threshold-LWE (thLWE) assumption which couples the LWE assumption with a Sharmir's secret sharing scheme with evaluation points chosen from a subtractive set Ξ (Definition 1), i.e. the share-generating matrix is the Vandermonde matrix $\mathbf{V}_\Xi$. We show that the th-LWE assumption is implied by the LWE assumption.

4.1 Threshold-LWE Assumption

We define the threshold-LWE assumption for both the unbounded- and bounded-query settings.

Definition 4 (Threshold-LWE Assumption). *Let the parameters*

$$\mathsf{params} = ((\mathcal{R}, n, m, q, \mathcal{D}_{\mathtt{A}}, \mathcal{D}_{\mathtt{x}}, \chi), (t, K, \Xi)),$$

be parametrised by λ, where $\mathcal{R}, n, m, q$ are lattice parameters, $\mathcal{D}_{\mathtt{A}} \sim \mathcal{R}_q^{n\times m}$, $\mathcal{D}_{\mathtt{x}} \sim \mathcal{R}^m$ and $\chi \sim \mathcal{R}$ are distributions, $t \le K$ are threshold parameters, and Ξ is a size-K subtractive set.

The (decisional) $\mathsf{thLWE}_{\mathsf{params}}$ *assumption is said to hold if there exists a (possibly stateful) PPT simulator $\mathcal{S} = (\mathcal{S}_{\mathsf{Init}}, \mathcal{S}_{\mathsf{ISIS}}, \mathcal{S}_{\mathsf{LWE}})$, such that for any PPT $\mathcal{A}$, for $\{\mathsf{Real}, \mathsf{Ideal}\}$-$\mathsf{thLWE}^b_{\mathsf{params},\mathcal{A},\mathcal{S}}$ defined in Fig. 3 it holds that*

$$\left|\Pr\left[\mathsf{Real\text{-}thLWE}_{\mathsf{params},\mathcal{A},\mathcal{S}}(1^\lambda) = 1\right] - \Pr\left[\mathsf{Ideal\text{-}thLWE}_{\mathsf{params},\mathcal{A},\mathcal{S}}(1^\lambda) = 1\right]\right| \le \mathsf{negl}(\lambda).$$

Furthermore, let

$$\mathcal{V}_{\mathcal{A},\mathsf{Ideal\text{-}thLWE}}(1^\lambda) \coloneqq \left\{\mathbf{A}, \mathbf{b}, \mathbf{S}_{\mathcal{C}}, \begin{pmatrix} \mathbf{x}, & \mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}} = (c_{\mathbf{x},k})_{k\notin\mathcal{C}} \\ & \mathbf{c}_{\mathbf{x},\bar{\mathcal{C}}} = (c_{\mathbf{x},k})_{k\in\mathcal{C}} \end{pmatrix}_{\mathbf{x}}, \begin{pmatrix} \mathbf{y}, & z_{\mathbf{y}}, & \mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}} = (d_{\mathbf{y},k})_{k\notin\mathcal{C}} \\ & & \mathbf{d}_{\mathbf{y},\bar{\mathcal{C}}} = (d_{\mathbf{y},k})_{k\in\mathcal{C}} \end{pmatrix}_{\mathbf{y}}, \mathsf{coins}_{\mathcal{A}}\right\}$$

be the view (all inputs, including randomness) of $\mathcal{A}$ in the $\mathsf{Ideal\text{-}thLWE}$ *experiment. The (decisional)* $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ *assumption is said to hold if the* $\mathsf{thLWE}_{\mathsf{params}}$ *assumption holds and additionally*

$$\mathcal{V}_{\mathcal{A},\mathsf{Ideal\text{-}thLWE}}(1^\lambda) \equiv \left\{ \begin{pmatrix} \mathbf{A}, \mathbf{b}, \mathbf{S}_{\mathcal{C}}, \\ (\mathbf{x}, \mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}}, \mathbf{c}_{\mathbf{x},\bar{\mathcal{C}}})_{\mathbf{x}}, \\ (\mathbf{y}, z_{\mathbf{y}}, \mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}}, \mathbf{d}_{\mathbf{y},\bar{\mathcal{C}}})_{\mathbf{y}}, \\ \mathsf{coins}_{\mathcal{A}} \end{pmatrix} \;\middle|\; \begin{array}{l} \left\{\mathbf{A}, \mathbf{b}, \mathbf{S}_{\mathcal{C}}, \begin{pmatrix} \mathbf{x}, & \mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}} \\ & \mathbf{c}_{\mathbf{x},\bar{\mathcal{C}}} \end{pmatrix}_{\mathbf{x}}, \begin{pmatrix} \mathbf{y}, & z_{\mathbf{y}}, & \mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}} \\ & & \mathbf{d}_{\mathbf{y},\bar{\mathcal{C}}} \end{pmatrix}_{\mathbf{y}}, \mathsf{coins}_{\mathcal{A}}\right\} \\ \quad \leftarrow \mathcal{V}_{\mathcal{A},\mathsf{Ideal\text{-}thLWE}}(1^\lambda) \\ \forall\ \mathbf{x}\ \mathbf{do} \\ \quad \mathbf{if}\ |\mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}}| + |\mathcal{C}| < t\ \mathbf{then}\ \mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}} \leftarrow\!\$\ \mathcal{R}_q^\ell \\ \forall\ \mathbf{y}\ \mathbf{do} \\ \quad \mathbf{if}\ |\mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}}| + |\mathcal{C}| < t\ \mathbf{then}\ z_{\mathbf{y}} \leftarrow\!\$\ \mathcal{R}_q;\ \mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}} \leftarrow\!\$\ \mathcal{R}_q^\ell \end{array} \right\},$$

i.e. the LWE samples and shares for inadmissible queries on honest indices outputted by the simulator $\mathcal{S}$ is uniformly random in the view of $\mathcal{A}$.

Definition 5 ($(Q_{\mathtt{ISIS}}, Q_{\mathtt{LWE}})$-bounded Threshold-LWE Assumption). *Let $Q_{\mathtt{ISIS}}, Q_{\mathtt{LWE}} \in \mathsf{poly}(\lambda)$. The $(Q_{\mathtt{ISIS}}, Q_{\mathtt{LWE}})$-bounded* $\mathsf{thLWE}_{\mathsf{params}}$ *assumption is almost identical to the* $\mathsf{thLWE}_{\mathsf{params}}$ *assumption, except that a winning PPT $\mathcal{A}$ is additionally restricted to make at most $Q_{\mathtt{ISIS}}$ and $Q_{\mathtt{LWE}}$ many queries to* GenISIS *and* GenLWE *respectively. Formally, this condition is highlighted in gray in Fig. 3. The $(Q_{\mathtt{ISIS}}, Q_{\mathtt{LWE}})$-bounded* th-$\$$-$\mathsf{LWE}_{\mathsf{params}}$ *assumption is defined analogously.*

$\mathsf{Real\text{-}thLWE}_{\mathsf{params},\mathcal{A},\mathcal{S}}(1^\lambda)$

$L_{\mathtt{LWE}}[\cdot] \coloneqq \emptyset;\ L_{\mathtt{ISIS}}[\cdot] \coloneqq \emptyset$
$\mathbf{A} \leftarrow\!\$\ \mathcal{D}_{\mathtt{A}}$
$\mathcal{C} \leftarrow \mathcal{A}(\mathbf{A})$; **assert** $|\mathcal{C}| < t$
$\mathbf{R} = (\mathbf{r}_i^{\mathsf{T}})_{i\in[t]} \leftarrow\!\$\ \mathcal{R}_q^{t\times n}$
$\mathbf{S}_{\mathcal{C}} \coloneqq \mathbf{V}_{\mathcal{C}} \cdot \mathbf{R} \bmod q \in \mathcal{R}_q^{\mathcal{C}\times n}$
$\mathbf{r} \coloneqq \mathbf{v}_0^{\mathsf{T}}\mathbf{R} \bmod q;\quad \mathbf{e} \leftarrow\!\$\ D_{\mathcal{R},\chi}^m$
$\mathbf{b}^{\mathsf{T}} \coloneqq \mathbf{r}^{\mathsf{T}}\mathbf{A} + \mathbf{e}^{\mathsf{T}} \bmod q$

$b' \leftarrow \mathcal{A}^{\mathsf{GenISIS},\mathsf{GenLWE},\mathsf{ShareISIS},\mathsf{ShareLWE}}(\mathbf{b}, \mathbf{S}_{\mathcal{C}})$
assert $|L_{\mathtt{ISIS}}| \le Q_{\mathtt{ISIS}}$ // at most $Q_{\mathtt{ISIS}}$ shared $\mathbf{Ax}$
assert $|L_{\mathtt{LWE}}| \le Q_{\mathtt{LWE}}$ // at most $Q_{\mathtt{LWE}}$ shared $\mathbf{y}$
return b'

$\mathsf{GenISIS}()$

$\mathbf{x} \leftarrow\!\$\ \mathcal{D}_{\mathtt{x}};\quad \mathbf{y} \coloneqq \mathbf{Ax} \bmod q$
$\mathbf{e} \leftarrow\!\$\ D_{\mathcal{R},\chi}^K$
$\mathbf{c} \coloneqq \mathbf{VRy} + \mathbf{e} \bmod q$
$L_{\mathtt{ISIS}}[\mathbf{y}] = \mathbf{c}$
return $(\mathbf{x}, \mathbf{y})$

$\mathsf{SimISIS}()$

$\mathbf{x} \leftarrow\!\$\ \mathcal{D}_{\mathtt{x}};\quad \mathbf{y} \coloneqq \mathbf{Ax} \bmod q$
$(\mathbf{c}, \mathsf{st}) \leftarrow \mathcal{S}_{\mathsf{ISIS}}(\mathbf{x}, \mathsf{st})$
$L_{\mathtt{ISIS}}[\mathbf{y}] = \mathbf{c}$
return $(\mathbf{x}, \mathbf{y})$

$\mathsf{ShareISIS}(\mathbf{y}, k \in [K])$

parse $\mathbf{c} \leftarrow L_{\mathtt{ISIS}}[\mathbf{y}] \in \mathcal{R}_q^K$
return c_k

$\mathsf{Ideal\text{-}thLWE}_{\mathsf{params},\mathcal{A},\mathcal{S}}(1^\lambda)$

$L_{\mathtt{LWE}}[\cdot] \coloneqq \emptyset;\ L_{\mathtt{ISIS}}[\cdot] \coloneqq \emptyset$
$\mathbf{A} \leftarrow\!\$\ \mathcal{D}_{\mathtt{A}}$
$\mathcal{C} \leftarrow \mathcal{A}(\mathbf{A})$; **assert** $|\mathcal{C}| < t$

$\mathbf{S}_{\mathcal{C}} \leftarrow\!\$\ \mathcal{R}_q^{\mathcal{C}\times n}$

$\mathbf{b} \leftarrow\!\$\ \mathcal{R}_q^m$
$\mathsf{st} \leftarrow \mathcal{S}_{\mathsf{Init}}(\mathbf{A}, \mathbf{b}, \mathbf{S}_{\mathcal{C}})$ // State of simulator $\mathcal{S}$
$b' \leftarrow \mathcal{A}^{\mathsf{SimISIS},\mathsf{SimLWE},\mathsf{ShareISIS},\mathsf{ShareLWE}}(\mathbf{b}, \mathbf{S}_{\mathcal{C}})$
assert $|L_{\mathtt{ISIS}}| \le Q_{\mathtt{ISIS}}$ // at most $Q_{\mathtt{ISIS}}$ shared $\mathbf{Ax}$
assert $|L_{\mathtt{LWE}}| \le Q_{\mathtt{LWE}}$ // at most $Q_{\mathtt{LWE}}$ shared $\mathbf{y}$
return b'

$\mathsf{GenLWE}()$

$\mathbf{y} \leftarrow\!\$\ \mathcal{R}_q^n$
$e \leftarrow\!\$\ \chi;\ \mathbf{e} \leftarrow\!\$\ D_{\mathcal{R},\chi}^K$
$z \coloneqq \mathbf{v}_0^{\mathsf{T}}\mathbf{Ry} + e \bmod q;\ \mathbf{d} \coloneqq \mathbf{VRy} + \mathbf{e} \bmod q$
$L_{\mathtt{LWE}}[\mathbf{y}] = \mathbf{d}$
return $(\mathbf{y}, z)$

$\mathsf{SimLWE}()$

$\mathbf{y} \leftarrow\!\$\ \mathcal{R}_q^n$
$(z, \mathbf{d}, \mathsf{st}) \leftarrow \mathcal{S}_{\mathsf{LWE}}(\mathbf{y}, \mathsf{st})$
$L_{\mathtt{LWE}}[\mathbf{y}] = \mathbf{d}$
return $(\mathbf{y}, z)$

$\mathsf{ShareLWE}(\mathbf{y}, k \in [K])$

parse $\mathbf{d} \leftarrow L_{\mathtt{LWE}}[\mathbf{y}] \in \mathcal{R}_q^K$
return d_k

Fig. 3: Experiment for $((Q_{\mathtt{ISIS}}, Q_{\mathtt{LWE}})$-bounded$)$ Threshold-LWE assumption.

Remark 1 (Potential Generalisations). It is possible to define generalisations of the threshold-LWE assumption, e.g. by adopting different noise distributions for different types of queries in the Share_b oracle, and by replacing

Shamir's secret sharing by other linear secret sharing (LSS) schemes for more general access structures. We consider the stated version which admits a proof of security reduction and suffices for the applications in this work.

We remark that our security reduction relies on the algebraic properties of Shamir's secret sharing and the proof techniques do not seem to easily generalise to other access structures.

4.2 Reduction from LWE

We rely on the following core lemma, which allows us to decouple correlations in the reduction from LWE to Th-LWE (Theorem 1,Theorem 2).

Lemma 5. *Let $\mathcal{R}, n, m, q, t_0, t_1, t_2, r_N, r_M, Q, \mathcal{D}_{\mathtt{A}}$ be parametrised by λ, where $\mathcal{D}_{\mathtt{A}} \sim \mathcal{R}_q^{n\times m}$ is a distribution. Consider arbitrary fixed matrices $\mathbf{N} \in \mathcal{R}^{r_N\times t_0}, \mathbf{M} \in \mathcal{R}^{r_M\times(t_0+t_1+t_2)}$ and $\mathbf{X} \in \mathcal{R}^{m\times Q}$, and denote $\mathbf{M} = (\mathbf{M}_{0,1}, \mathbf{M}_2)$ where $\mathbf{M}_{0,1} \in \mathcal{R}^{r_M\times(t_0+t_1)}$, $\mathbf{M}_2 \in \mathcal{R}^{r_M\times t_2}$.*

Suppose χ, χ^* are such that one of the following holds:

1. *$\chi^* \geq \sqrt{2}\cdot\eta_\epsilon(\mathcal{R}^m)$, $\chi > 0$, and there exists $\bar{\chi} > 0$ satisfying $\|\mathbf{N}\| + \|\mathbf{M}_{0,1}\|\|\mathbf{X}\| \leq \beta$, where $\beta \coloneqq \chi\cdot\sqrt{(2\eta_\epsilon(\mathcal{R}^m)^2 + (\chi^*)^2)^{-1} - \bar{\chi}^{-2}}$.*
2. *$\lambda^{\omega(1)}\cdot\chi^*\sqrt{m}\cdot\max(\|\mathbf{N}\|^{\mathsf{T}}, \|\mathbf{M}_{0,1}^{\mathsf{T}}\|\|\mathbf{X}\|) < \chi$.*

If the $\mathsf{LWE}_{\mathcal{R},n,m,q,\chi^*,\mathcal{D}_A}$ assumption holds, then the following distributions are computationally indistinguishable:

$$\left\{\begin{array}{l}\big(\mathbf{A}, \mathbf{S}_2, \mathbf{B}, \mathbf{C}\big)\\ \hline \mathbf{A} \leftarrow\!\$\ \mathcal{D}_{\mathtt{A}};\ \mathbf{S}_2 \leftarrow\!\$\ \mathcal{R}_q^{t_2\times n}\\ \mathbf{S}_0 \leftarrow\!\$\ \mathcal{R}_q^{t_0\times n};\ \mathbf{S}_1 \leftarrow\!\$\ \mathcal{R}_q^{t_1\times n}\\ \mathbf{E}_B \leftarrow\!\$\ D_{\mathcal{R},\chi}^{r_N\times m};\ \mathbf{E}_C \leftarrow\!\$\ D_{\mathcal{R},\chi}^{r_M\times Q}\\ \mathbf{B} \coloneqq \mathbf{N}\mathbf{S}_0\mathbf{A} + \mathbf{E}_B \bmod q\\ \mathbf{C} \coloneqq \mathbf{M}\begin{bmatrix}\mathbf{S}_0\\ \mathbf{S}_1\\ \mathbf{S}_2\end{bmatrix}\mathbf{A}\mathbf{X} + \mathbf{E}_C \bmod q\end{array}\right\} \approx_c \left\{\begin{array}{l}\big(\mathbf{A}, \mathbf{S}_2, \mathbf{B}, \mathbf{C}\big)\\ \hline \mathbf{A} \leftarrow\!\$\ \mathcal{D}_{\mathtt{A}};\ \mathbf{S}_2 \leftarrow\!\$\ \mathcal{R}_q^{t_2\times n}\\ \bar{\mathbf{S}}_0 \leftarrow\!\$\ \mathcal{R}_q^{t_0\times m};\ \bar{\mathbf{S}}_1 \leftarrow\!\$\ \mathcal{R}_q^{t_1\times m}\\ \mathbf{E}_B \leftarrow\!\$\ D_{\mathcal{R},\chi}^{r_N\times m};\ \mathbf{E}_C \leftarrow\!\$\ D_{\mathcal{R},\chi}^{r_M\times Q}\\ \mathbf{B} \coloneqq \mathbf{N}\bar{\mathbf{S}}_0 + \mathbf{E}_B \bmod q\\ \mathbf{C} \coloneqq \mathbf{M}\begin{bmatrix}\bar{\mathbf{S}}_0\\ \bar{\mathbf{S}}_1\\ \mathbf{S}_2\mathbf{A}\end{bmatrix}\mathbf{X} + \mathbf{E}_C \bmod q\end{array}\right\}.$$

Roughly, Lemma 5 says that the "LWE samples" of the forms $\mathbf{B} = \mathbf{N}\mathbf{S}\mathbf{A} + \mathbf{E} \bmod q$ and $\mathbf{C} = \mathbf{M}\mathbf{S}\mathbf{A}\mathbf{X} + \mathbf{E} \bmod q$, where the product $\mathbf{S}\mathbf{A}$ of the LWE secret and matrix is left- and right-multiplied by low-norm matrices $\mathbf{N}, \mathbf{M}$ and $\mathbf{X}$ respectively, are indistinguishable from $\mathbf{N}\bar{\mathbf{S}} + \mathbf{E} \bmod q$ and $\mathbf{M}\bar{\mathbf{S}}\mathbf{X} + \mathbf{E} \bmod q$ for some uniform $\bar{\mathbf{S}}$. This is the case even when the LWE secret is correlated in these two blocks of samples. The bottom LWE secret chunk $\mathbf{S}_2$ in $\mathbf{C}$ will correspond to shares of the corrupt indices $\mathbf{S}_{\mathcal{C}}$, which is available in plain in the distribution and therefore indistinguishability does not apply to its "LWE samples". The proof, which essentially involves using the leaky LWE assumption to decouple the correlations induced by the low-norm "leakage matrices" $\mathbf{M}$, $\mathbf{N}$ and $\mathbf{X}$, is given in Appendix A.4.

Theorems 1 and 2 below state that the th-$-LWE assumption is implied by the LWE assumption. Their proofs are in Appendices A.5 and A.6 respectively.

Theorem 1 (Poly-modulus LWE $\implies$ bounded-query th-$-LWE). *Let*

$$\mathsf{params} = ((\mathcal{R}, n, m, q, \mathcal{D}_{\mathtt{A}}, \mathcal{D}_{\mathtt{x}}, \chi), (t, K, \Xi))$$

be thLWE parameters. Let $Q_{\mathtt{ISIS}}, Q_{\mathtt{LWE}} \in \mathsf{poly}(\lambda)$, γ be the inverse-expansion factor of Ξ, $\beta_{\mathtt{x}} \in \mathbb{R}$ be such that $\Pr(\|\mathbf{x}\| \leq \beta_{\mathtt{x}} | \mathbf{x} \leftarrow\!\$\ \mathcal{D}_{\mathtt{x}}) \geq 1 - \mathsf{negl}(\lambda)$, $\mathcal{D}_1 = \mathcal{D}_{\mathtt{A}} \times \mathcal{R}_q^{n\times Q_{\mathtt{LWE}}}$ and $\mathcal{D}_2 = \mathcal{D}_{\mathtt{x}}^{Q_{\mathtt{ISIS}}}$. Suppose q and ξ are coprime, and $\chi_1^* \geq \sqrt{2}\cdot\eta_\epsilon(\mathcal{R}^{m+Q_{\mathtt{LWE}}})$, $\chi_2^* \geq \sqrt{2}\cdot\eta_\epsilon(\mathcal{R}^{Q_{\mathtt{ISIS}}})$, $\chi > 0$ are such that there exists $\bar{\chi}_1, \bar{\chi}_2 > 0$ satisfying

$$\xi + \gamma\cdot(\beta_{\mathtt{x}}\cdot\sqrt{Q_{\mathtt{ISIS}}} + 1) \leq \chi\cdot\sqrt{(2\eta_\epsilon(\mathcal{R}^{m+Q_{\mathtt{LWE}}})^2 + (\chi_1^*)^2)^{-1} - \bar{\chi}_1^{-2}},$$

$$\gamma \leq \chi \cdot \sqrt{(2\eta_\epsilon(\mathcal{R}^{Q_{\mathtt{ISIS}}})^2 + (\chi_2^*)^2)^{-1} - \bar{\chi}_2^{-2}}.$$

The $(Q_{\mathtt{ISIS}}, Q_{\mathtt{LWE}})$*-bounded* $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ *assumption holds if the following assumptions hold:*

$$\mathsf{LWE}_{\mathcal{R},n,m+Q_{\mathtt{LWE}},q,\chi_1^*,\mathcal{D}_1} \qquad \textit{and} \qquad \mathsf{LWE}_{\mathcal{R},m,Q_{\mathtt{ISIS}},q,\chi_2^*,\mathcal{D}_2}.$$

Theorem 2 (LWE $\implies$ th-$-LWE). *Let*

$$\mathsf{params} = ((\mathcal{R}, n, m, q, \mathcal{D}_{\mathtt{A}}, \mathcal{D}_{\mathbf{x}}, \chi), (t, K, \Xi))$$

be thLWE parameters. Let γ *be the inverse-expansion factor of* Ξ*,* $\beta_{\mathbf{x}} \in \mathbb{R}$ *be such that* $\Pr(\|\mathbf{x}\| \leq \beta_{\mathbf{x}} | \mathbf{x} \leftarrow\$ \mathcal{D}_{\mathbf{x}}) \geq 1 - \mathsf{negl}(\lambda)$*,* $\mathcal{D}_1 = \mathcal{D}_{\mathtt{A}} \times \mathcal{R}_q^{n \times Q_{\mathtt{LWE}}}$ *and* $\mathcal{D}_2 = \mathcal{D}_{\mathbf{x}}^{Q_{\mathtt{ISIS}}}$*. Suppose* q *and* ξ *are coprime, and* χ, χ^* *are such that for any* $Q_{\mathtt{ISIS}}, Q_{\mathtt{LWE}} \in \mathsf{poly}(\lambda)$*,*

$$\lambda^{\omega(1)} \cdot \chi^* \cdot \max\left(\xi\sqrt{m},\ \gamma \cdot \sqrt{m} \cdot (\beta_{\mathbf{x}} \cdot \sqrt{Q_{\mathtt{ISIS}}} + 1),\ \gamma \cdot \sqrt{Q_{\mathtt{ISIS}}}\right) < \chi.$$

The $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ *assumption holds if the following assumptions hold for any* $Q_{\mathtt{ISIS}}, Q_{\mathtt{LWE}} \in \mathsf{poly}(\lambda)$*:*

$$\mathsf{LWE}_{\mathcal{R},n,m+Q_{\mathtt{LWE}},q,\chi^*,\mathcal{D}_1} \qquad \textit{and} \qquad \mathsf{LWE}_{\mathcal{R},m,Q_{\mathtt{ISIS}},q,\chi^*,\mathcal{D}_2}.$$

5 Threshold PKE – Pilvi

A t-out-of-K threshold public-key encryption, or (t, K)-tPKE, for a set of K parties, threshold $t \leq K$, a message space $\mathcal{M}$, and a ciphertext space $\mathcal{CT}$, consists of PPT algorithms $(\mathsf{Setup}, \mathsf{KGen}, \mathsf{Enc}, \mathsf{ParDec}, \mathsf{Dec})$ with the following syntax:

- $\mathsf{pp} \leftarrow \mathsf{Setup}(1^\lambda)$: The setup algorithm, on input the security parameter 1^λ, generetas the public parameters pp.
- $\left(\mathsf{pk}, (\mathsf{sk}_k)_{k\in[K]}\right) \leftarrow \mathsf{KGen}(\mathsf{pp})$: The key generation algorithm, on input the public parameters pp, generates the public key pk and a tuple of K secret keys $(\mathsf{sk}_k)_{k\in[K]}$ for each user $k \in [K]$.
- $\mathsf{ctxt} \leftarrow \mathsf{Enc}(\mathsf{pk}, \mu)$: The encryption algorithm encrypts a message $\mu \in \mathcal{M}$ w.r.t. the public key pk.
- $\mathsf{pd}_k \leftarrow \mathsf{ParDec}(\mathsf{sk}_k, \mathsf{ctxt})$: The partial decryption algorithm takes the secret key sk_k of a user k and a ciphertext $\mathsf{ctxt} \in \mathcal{CT}$, where $\mathcal{CT}$ denotes the ciphertext space, and outputs a partial decryption pd_k.
- $\mu' \leftarrow \mathsf{Dec}\left(T, (\mathsf{pd}_k)_{k\in T}, \mathsf{ctxt}\right)$: The reconstruction algorithm, on input a tuple of partial decryptions $(\mathsf{pd}_k)_{k\in T}$ from a set T of t users and a ciphertext ctxt, outputs some μ'.

Definition 6 (Correctness). *A* (t, K)*-tPKE is said to be correct, if for any* $\mathsf{pp} \in \mathsf{Setup}(1^\lambda)$*,* $(\mathsf{pk}, (\mathsf{sk}_k)_{k\in[K]}) \in \mathsf{KGen}(\mathsf{pp})$*, any set* T *of threshold size* t*, and any* $\mu \in \mathcal{M}$*, it holds that*

$$\Pr\left[\mu' = \mu \;\middle|\; \begin{array}{l} \mathsf{ctxt} \leftarrow \mathsf{Enc}(\mathsf{pk}, \mu) \\ \mathsf{pd}_k \leftarrow \mathsf{ParDec}(\mathsf{sk}_k, \mathsf{ctxt}) \quad \forall k \in T \\ \mu' \leftarrow \mathsf{Dec}\left(T, (\mathsf{pd}_k)_{k\in T}, \mathsf{ctxt}\right) \end{array}\right] \geq 1 - \mathsf{negl}(\lambda).$$

Definition 7 (Security). *A* (t, K)*-tPKE scheme* Π *is said to be simulation secure, if there exists a (possibly stateful) PPT simulator* $\mathcal{S}$*, such that for any PPT adversary* $\mathcal{A}$ *it holds that*

$$\left|\Pr\left[\mathsf{Exp}^0_{\Pi,\mathcal{A}}(1^\lambda) = 1\right] - \Pr\left[\mathsf{Exp}^1_{\Pi,\mathcal{A}}(1^\lambda) = 1\right]\right| \leq \mathsf{negl}(\lambda),$$

where $\mathsf{Exp}^b_{\Pi,\mathcal{A}}$ *is defined in Fig. 4.*

In our security definition, the adversary is allowed to query $\mathsf{ParDecO}$ on up to $t-1$ partial decryptions of challenge ciphertexts, and requires that they are indistinguishable from outputs of a simulator who does not know the secret key shares. This improves upon the security notion considered in all prior works under the same threshold-Regev-PKE paradigm [BD10, BGG+18, BS23, MS25].

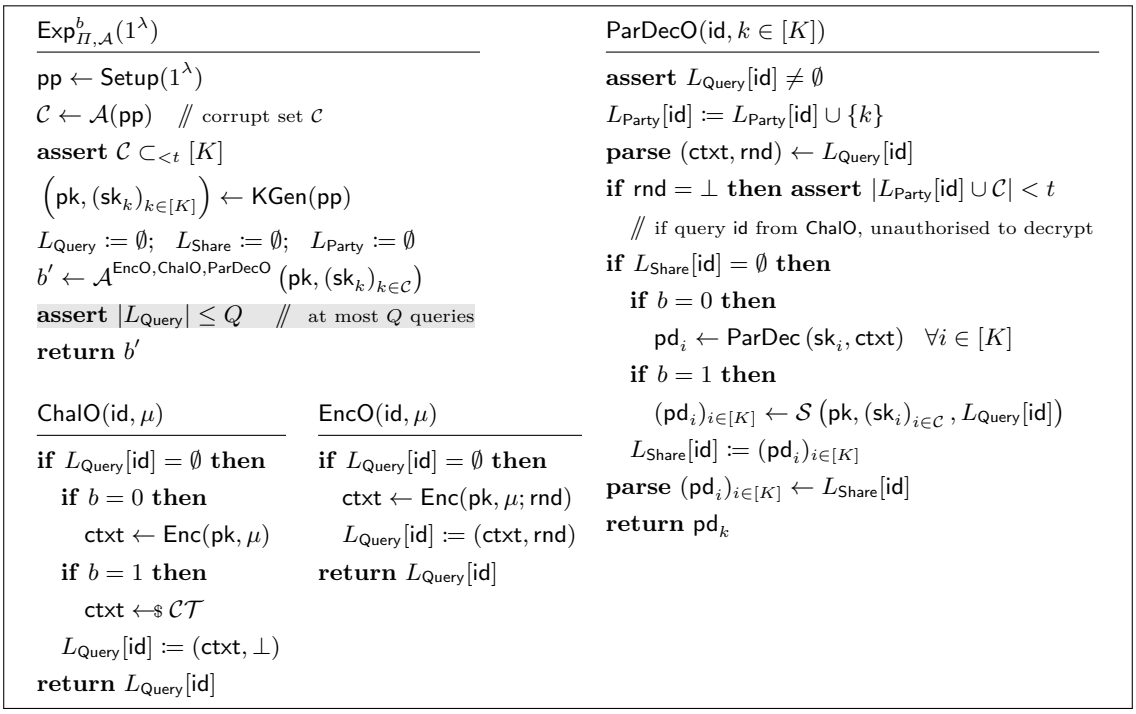

Fig. 4: Security experiment for (t, k)-tPKE Π. Gray code for the Q-bounded security described in Remark 2.

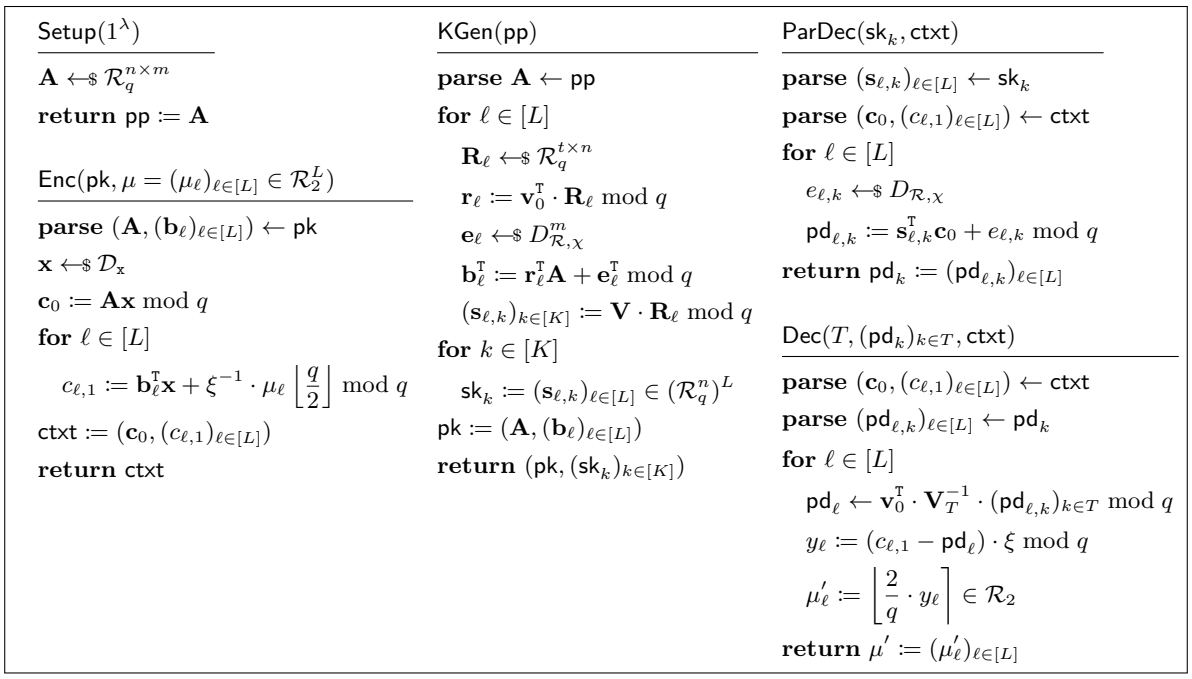

Fig. 5: (t, K)-tPKE scheme Pilvi, with a ξ-subtractive set Ξ of size K. $\mathbf{V} \in \mathcal{R}^{K\times t}$ denotes the Vandermonde matrix with entries in Ξ.

Pilvi. Let $\Xi \subset \mathcal{R}$ with $|\Xi| = K$ be a ξ-subtractive set. Our t-out-of-K threshold-PKE construction Pilvi is given in Figure 5.

Theorem 3 (Correctness). *Let $q > 4\chi\sqrt{\varphi} \cdot (\xi \cdot \beta_{\mathtt{x}}\sqrt{m} + \sqrt{t} \cdot \rho(t))$, where $\rho(t)$ is the recovery-expansion factor of Ξ, and $\beta_{\mathtt{x}} > 0$ is such that $\Pr(\|\mathbf{x}\| \leq \beta_{\mathtt{x}} | \mathbf{x} \leftarrow\!\!\$\ \mathcal{D}_{\mathtt{x}}) \geq 1 - \mathsf{negl}(\lambda)$. Then,* Pilvi *is correct.*

The proof is in Appendix B.[14]

Theorem 4 (Security). *Let $\mathcal{R}_q$ split into super-polynomial-size fields, q be prime, $\mathcal{D}_{\mathtt{A}}$ be the uniform distribution over $\mathcal{R}_q^{n \times m}$, and $\mathcal{D}_{\mathtt{x}} = D^m_{\mathcal{R},\sigma_{\mathtt{x}}}$ for some $\sigma_{\mathtt{x}} > 0$. For*

$$\mathsf{params}_0 = ((\mathcal{R}, n, m, q, \mathcal{D}_{\mathtt{A}}, \mathcal{D}_{\mathtt{x}}, \chi), (t, K, \Xi)),$$
$$\mathsf{params}_1 = (\mathcal{R}, m - n - L, n + L, q, \sigma_{\mathtt{x}}, D_{\mathcal{R},\sigma_{\mathtt{x}}}).$$

Pilvi *is simulation secure under the* $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}_0}$ *and* $\mathsf{LWE}_{\mathsf{params}_1}$ *assumptions.*

The proof follows a hybrid argument over the message length L: the computational indistinguishability of each pair of consecutive hybrids is almost a direct reduction from the $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ assumption, where the security experiments oracles $\mathsf{EncO}, \mathsf{ChalO}$ and $\mathsf{ParDecO}$ are simulated via the assumption oracle $\mathsf{SimISIS}$ and $\mathsf{ShareISIS}$ respectively. This allows to eventually swap the partial decryptions of challenge ciphertexts to random values. The $\mathsf{LWE}_{\mathcal{R},m-n-L,n+L,q,\mathcal{D}_{\mathtt{x}},\mathcal{D}_{\mathtt{x}}}$ assumption is then used to switch the challenge ciphertexts to random. The detailed proof is in Appendix B.

Remark 2 (Q-bounded Security). If the numbers of queries $|L_{\mathsf{Query}}|$ an adversary can make in the security experiment is bounded by Q (formally given in gray in Fig. 4), the same proof from above shows that Pilvi is simulation secure under the $(Q, 0)$-bounded $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ assumption. Note that $|L_{\mathsf{Query}}| \leq Q$ restricts both the numbers of (challenge/non-challenge) ciphertext and their partial decryption queries. This aspect differs from the bounded-query security defined in [BS23] which does not restrict the number of ciphertext queries.

Discussion: CCA security. Obtaining CCA security[15] for tPKE is not as easy as for ordinary PKE. Indeed, common transformations do not seem to work out of the box:

- The Fujisaki-Okamoto transform [FO13] requires the decryption algorithm to recover the encryption randomness and use it to re-compute the input ciphertext. It is unclear how to apply this technique, since the encryption randomness should not be recoverable given only $< t$ partial decryption keys.
- The Naor-Yung transform [NY90] requires the encryption algorithm to prove the integrity of the (CPA secure) ciphertext with a simulation-sound straightline-extractable zero-knowledge proof, which would be verified by the decryption algorithm before performing decryption. While the adapted transform on tPKE achieves correctness, it is unclear how to prove (our notion of) security, i.e. how to simulate partial decryptions given the encrypted message and the encryption randomness of a given ciphertext, without making further structural assumptions about the underlying tPKE scheme.
- The BCHK transform [BCHK07] turns a CPA secure identity-based encryption (IBE) scheme into a PKE scheme. For this transform to work in the threshold setting, we first need to design a threshold IBE scheme.

[14] The lower bound of q is conservative in that it ensures the canonical ℓ_2-norm, rather than the coefficient ℓ_∞-norm, of the error term is at most $q/4$. Moreover, the proof uses a trivial upper bound of the norm of the inner product of two Gaussian vectors.

[15] For tPKE, CCA means the partial decryption oracle answers to any ciphertext queries, including the ones maliciously generated by the adversary. In contrast, for CPA-security [BS23] it only answers to those honestly generated by the experiment.

Fortunately, a concurrent work [BKW25] provides a generic transformation that turns a CPA-secure tPKE into a CCA-secure one, conditioned on that EncO is able to also return the encryption randomness rnd of the non-challenge ciphertexts to an adversary. We highlight that our scheme Pilvi achieved from th-LWE natively supports this security property, which is another security aspect unconsidered in prior threshold PKE works.

The transform of [BKW25] is based on a primitive that they call non-interactive proof of randomness which they show can be generically constructed from commitments and zero-knowledge proofs. In a nutshell, the augmented encryption algorithm proves that the ciphertext is computed correctly using randomness which is secret-shared into two parts – one provided by the encryptor and another output by a random oracle when evaluated on the commitment of the message and the encryptor's randomness. When instantiating Pilvi with a "proof-friendly" noise distribution, e.g. a bounded-uniform distribution, such relations can be proven efficiently using state-of-the-art lattice-based proof systems, e.g. [LNP22]. Consequently, using th-LWE, we can also easily obtain a CCA-secure tPKE with reasonable efficiency.

6 Distributed Weak Pseudorandom Function

We showcase a second application of the th-LWE assumption, and construct a distributed weak pseudorandom function admitting a very simple security proof. The definition of a pseudorandom function (PRF) is given in Appendix C.

Definition 8 (Distributed Weak PRF). *A (t, K)-distributed pseudorandom function Π is a tuple $(\mathsf{Setup}, \mathsf{KGen}, \mathsf{Eval}, \mathsf{Share}, \mathsf{ParEval}, \mathsf{Rec})$ of PPT algorithms defined over a key space $\mathcal{K}$, a message space $\mathcal{X}$, and an image space $\mathcal{Y}$, such that*

- *$(\mathsf{Setup}, \mathsf{KGen}, \mathsf{Eval})$ is a pseudorandom function defined over $\mathcal{K}$, $\mathcal{X}$, and $\mathcal{Y}$, denoted by PRF.*
- *The key sharing algorithm $\mathsf{Share}(\mathsf{k} \in \mathcal{K})$ outputs K shares $(\mathsf{k}_1, \ldots, \mathsf{k}_K) \in \mathcal{K}^K$.*
- *The share evaluation algorithm $\mathsf{ParEval}(\mathsf{k}_k, x \in \mathcal{X})$ returns a partial evaluation c_k.*
- *The image recovery algorithm Rec inputs a subset $T \subseteq_t [K]$ and t partial evaluations $(c_k)_{k \in T}$, and returns an image $c \in \mathcal{Y}$.*

Definition 9 (Correctness for Random Inputs). *A (t, K)-distributed pseudorandom function $\Pi = (\mathsf{Setup}, \mathsf{KGen}, \mathsf{Eval}, \mathsf{Share}, \mathsf{ParEval}, \mathsf{Rec})$ is said to be correct for random inputs if for any $\mathsf{pp} \in \mathsf{Setup}(1^\lambda)$, any $\mathsf{k} \in \mathsf{KGen}(\mathsf{pp})$, any $(\mathsf{k}_1, \ldots, \mathsf{k}_K) \in \mathsf{Share}(\mathsf{k})$, any $c_k \in \mathsf{ParEval}(\mathsf{k}_k, x)$ for $k \in [K]$, and any $T \subseteq_t [K]$, it holds that*

$$\Pr\left[\mathsf{Eval}(\mathsf{k}, x) = \mathsf{Rec}(T, (c_k)_{k \in T}) \;\middle|\; \begin{array}{l} (\mathsf{k}_1, \ldots, \mathsf{k}_K) \leftarrow \mathsf{Share}(\mathsf{k}) \\ x \leftarrow \mathcal{X} \\ c_k \leftarrow \mathsf{ParEval}(\mathsf{k}_k, x) \quad \forall k \in T \end{array}\right] \geq 1 - \mathsf{negl}(\lambda).$$

Definition 10. *A (t, K)-distributed pseudorandom function $\Pi = (\mathsf{Setup}, \mathsf{KGen}, \mathsf{Eval}, \mathsf{Share}, \mathsf{ParEval}, \mathsf{Rec})$ is said to be weakly secure, if for any PPT adversary $\mathcal{A}$,*

$$\left|\Pr\left[\mathsf{WPRF\text{-}Exp}^0_{\Pi,\mathcal{A}}(1^\lambda) = 1\right] - \Pr\left[\mathsf{WPRF\text{-}Exp}^1_{\Pi,\mathcal{A}}(1^\lambda) = 1\right]\right| \leq \mathsf{negl}(\lambda),$$

where the security experiment $\mathsf{WPRF\text{-}Exp}^b_{\Pi,\mathcal{A}}$ is defined in Fig. 6.

Analogous to the threshold PKE setting, our Definition 10 allows the adversary to flexibly query $\mathsf{ParEvalO}$ for partial evaluation values on challenges as long as $\mathcal{A}$ cannot trivially distinguish. This is, for example, an aspect strictly stronger than the security notion considered in Boneh et al. [BLMR13], where the latter did not consider the leakage on partial evaluations – no partial evaluation could be given to the adversary for any of the challenges $(x_j, y_j = \mathsf{Eval}(\mathsf{k}, x_j))_j$. The th-LWE assumption allows us to easily prove the stated security.

$\mathsf{WPRF\text{-}Exp}^{b}_{\Pi,\mathcal{A}}(1^\lambda)$

$\mathsf{pp} \leftarrow \mathsf{Setup}(1^\lambda)$
$\mathcal{C} \leftarrow \mathcal{A}(\mathsf{pp})$ // corrupt set $\mathcal{C}$
assert $\mathcal{C} \subset_{<t} [K]$
$\mathsf{k} \leftarrow \mathsf{KGen}(\mathsf{pp})$
$(\mathsf{k}_k)_{k\in[K]} \leftarrow \mathsf{Share}(\mathsf{k})$
$L_{\mathsf{Query}} \coloneqq \emptyset$; $L_{\mathsf{Share}} \coloneqq \emptyset$; $L_{\mathsf{Party}} \coloneqq \emptyset$
$b' \leftarrow \mathcal{A}^{\mathsf{EvalO},\mathsf{ParEvalO}}\left((\mathsf{k}_k)_{k\in\mathcal{C}}\right)$
assert $|L_{\mathsf{Query}}| \le Q$ // at most Q queries
return b'

$\mathsf{ChalO}(\mathsf{id})$

if $L_{\mathsf{Query}}[\mathsf{id}] = \emptyset$ **then**
  $\mathsf{rnd} \leftarrow\!\$\ \mathcal{X}$ // random input
  if $b = 0$ **then** $c \leftarrow \mathsf{Eval}(\mathsf{k}, \mathsf{rnd})$
  if $b = 1$ **then** $c \leftarrow\!\$\ \mathcal{Y}$
  $\mathtt{is_chal} \coloneqq 1$
  $L_{\mathsf{Query}}[\mathsf{id}] \coloneqq (c, \mathsf{rnd}, \mathtt{is_chal})$
return $L_{\mathsf{Query}}[\mathsf{id}]$

$\mathsf{EvalO}(\mathsf{id})$

if $L_{\mathsf{Query}}[\mathsf{id}] = \emptyset$ **then**
  $\mathsf{rnd} \leftarrow\!\$\ \mathcal{X}$ // random input
  $c \leftarrow \mathsf{Eval}(\mathsf{k}, \mathsf{rnd})$
  $\mathtt{is_chal} \coloneqq 0$
  $L_{\mathsf{Query}}[\mathsf{id}] \coloneqq (c, \mathsf{rnd}, \mathtt{is_chal})$
return $L_{\mathsf{Query}}[\mathsf{id}]$

$\mathsf{ParEvalO}(\mathsf{id}, k \in [K])$

assert $L_{\mathsf{Query}}[\mathsf{id}] \neq \emptyset$
$L_{\mathsf{Party}}[\mathsf{id}] \coloneqq L_{\mathsf{Party}}[\mathsf{id}] \cup \{k\}$
parse $(c, \mathsf{rnd}, \mathtt{is_chal}) \leftarrow L_{\mathsf{Query}}[\mathsf{id}]$
if $\mathtt{is_chal} = 1$ **then assert** $|L_{\mathsf{Party}}[\mathsf{id}] \cup \mathcal{C}| < t$
  // if query id from ChalO, unauthorised to evaluate
if $L_{\mathsf{Share}}[\mathsf{id}] = \emptyset$ **then**
  if $b = 0$ **then**
    $c_i \leftarrow \mathsf{ParEval}(\mathsf{k}_i, \mathsf{rnd})$ $\forall i \in [K]$
  if $b = 1$ **then**
    $(c_i)_{i\in[K]} \leftarrow \mathcal{S}\left(\mathsf{pk}, (\mathsf{sk}_i)_{i\in\mathcal{C}}, L_{\mathsf{Query}}[\mathsf{id}]\right)$
  $L_{\mathsf{Share}}[\mathsf{id}] \coloneqq (y_i)_{i\in[K]}$
parse $(c_i)_{i\in[K]} \leftarrow L_{\mathsf{Share}}[\mathsf{id}]$
return c_k

Fig. 6: Security experiment for dPRF. Gray code for the Q-bounded security described in Remark 3.

$\mathsf{Setup}(1^\lambda)$

return $\emptyset$

$\mathsf{Share}(\mathsf{k})$

parse $\mathbf{r} \leftarrow \mathsf{k}$
$\mathbf{R} \leftarrow\!\$\ \mathcal{R}_q^{t\times n} : \mathbf{v}_0^\intercal \mathbf{R} = \mathbf{r}^\intercal$
$(\mathbf{s}_k)_{k\in[K]} = \mathbf{S} \leftarrow \mathbf{VR}$
for $k \in [K]$
  $\mathsf{k}_k \coloneqq \mathbf{s}_k \in \mathcal{R}_q^n$
return $(\mathsf{k}_1, \ldots, \mathsf{k}_K)$

$\mathsf{KGen}(\mathsf{pp})$

$\mathbf{r} \leftarrow\!\$\ \mathcal{R}_q^n$
$\mathsf{k} \coloneqq \mathbf{r}$
return k

$\mathsf{ParEval}(\mathsf{k}_k, x)$

parse $(\mathbf{s}_k, \mathbf{y}) \leftarrow (\mathsf{k}_k, x)$
$c_k \coloneqq \left\lfloor \mathbf{s}_k^\intercal \mathbf{y} \right\rceil_p$
return y_k

$\mathsf{Eval}(\mathsf{k}, x)$

parse $(\mathbf{r}, \mathbf{y}) \leftarrow (\mathsf{k}, x)$
$c \coloneqq \left\lfloor \left\lfloor \xi \cdot \mathbf{r}^\intercal \mathbf{y} \right\rceil_p \right\rceil_u$
return c

$\mathsf{Rec}(T, (c_k)_{k\in T})$

$c' \leftarrow \mathbf{v}_0^\intercal \cdot \mathbf{V}_T^{-1} \cdot \xi \cdot (c_k)_{k\in T} \bmod q$
$c \coloneqq \left\lfloor c' \right\rceil_u$
return c

Fig. 7: dPRF construction $\Pi_{\mathsf{DPRF}}[\Xi]$ where Ξ is a ξ-subtractive set of size K. $\mathbf{V} \in \mathcal{R}^{K\times t}$ denotes the Vandermonde matrix with entries in Ξ.

Construction. Let $u, p, q \in \mathbb{N}$ with $u \le p \le q$. Define $\lfloor\cdot\rceil_p : \mathcal{R}_q \to \mathcal{R}_p$ to be the modulus switching operation. More precisely, fix a basis of $\mathcal{R}$, typically the power basis $\{\zeta^i : i \in \mathbb{Z}_\varphi\}$, and write $x \in \mathcal{R}_q$ in its balanced representation, i.e. $x = \sum_{i\in\mathbb{Z}_\varphi} x_i \cdot \zeta^i$ where $x_i \in \mathbb{Z} \cap [-q/2, q/2)$. We have $\lfloor x \rceil_p \coloneqq \sum_{i\in\mathbb{Z}_\varphi} x'_i \cdot \zeta^i$, where $x'_i \coloneqq \left\lfloor \frac{p}{q} \cdot x_i \right\rceil \bmod p \in \mathbb{Z} \cap [-p/2, p/2)$ and the rounding is performed over $\mathbb{Z}$. The operation $\lfloor\cdot\rceil_p$ naturally extends to $\mathcal{R}_q$-modules by viewing elements as $\mathcal{R}_q$ vectors and performing $\lfloor\cdot\rceil_p$ coordinate-wise.

Let $\Xi \subset \mathcal{R}$ with $|\Xi| = K$ be a ξ-subtractive set. The distributed weak pseudorandom function PRF construction $\Pi_{\mathsf{DPRF}}[\Xi]$ is described in Figure 7.

Theorem 5 (Correctness for Random Inputs). *If* $2(\rho(t)\cdot\sqrt{\varphi t}+3)u/p \le \mathsf{negl}(\lambda)$*, where* $\rho(t)$ *is the recovery-expansion factor of* Ξ*, then* Π_{DPRF} *is correct for random inputs.*

The proof is in Appendix C.

Theorem 6 (Security). *Let* $\mathsf{params} = ((\mathcal{R}, n, m, q, \mathcal{D}_{\mathtt{A}}, \mathcal{D}_{\mathtt{x}}, \chi), (t, K, \Xi))$ *be thLWE parameters (where* $\mathcal{D}_{\mathtt{x}}$ *can be arbitrary and is not used),* $\varphi \ge \omega(\log\lambda)$*, and* $(2\xi\chi\sqrt{\varphi}+1)p/q \le \mathsf{negl}(\lambda)$*. Then, the construction* Π_{DPRF} *is a secure distributed weak pseudorandom function under the* $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ *assumption.*

The proof is (almost) a direct reduction to the $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ assumption (before, the output of the Eval and $\mathsf{ParEval}$ algorithms need to be modified to include small errors, and this is where the constraint on q/p is used): the security experiments oracles EvalO and ChalO, and $\mathsf{ParEvalO}$ are simulated via the assumption oracle GenLWE and $\mathsf{ShareLWE}$ respectively. The detailed proof is in Appendix C.

Remark 3. If the number of queries $|L_{\mathsf{Query}}|$ an adversary can make in the security experiment is bounded by Q (formally given in gray in Fig. 6), the same proof from above shows that the scheme is simulation secure under the $(0, Q)$-bounded $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ assumption. Note that $|L_{\mathsf{Query}}| \le Q$ restricts both the numbers of (challenge/non-challenge) input and their partial evaluation queries.

7 Parameter Selection

We suggest candidate parameters for our tPKE scheme Pilvi and the corresponding ciphertext and partial decryption sizes for demonstrative purposes. We pick $\mathcal{R}$ to be the cyclotomic ring of conductor $\mathfrak{f} = 512$, i.e. degree $\varphi = 256$. To support $K \in \{8, 16, 32\}$ users, we use the subset $\Xi = \{1, \zeta_K, \ldots, \zeta_K^{K-1}\}$ of the subtractive set constructed in Lemma 3 where $\zeta_K = \zeta_{\mathfrak{f}}^{\mathfrak{f}/K}$.

For our performance estimation, we use empirically computed values of ρ and γ instead of the upper bounds given in Lemma 3. Recall that ρ and γ are quantities obtained by maximising over all possible t- and $(t-1)$-subsets of Ξ, respectively. Since exhaustively checking all subsets of Ξ is computationally infeasible, we use the heuristic that ρ (resp. γ) attain its maximum for the first t (resp. $t-1$) roots of unity. Exhaustively verified this heuristic for some small cases (e.g. $2 \le t < K = \mathfrak{f} = 8$) and checked probabilistically for some other cases. We also note that, by experiment, ρ and γ first grow exponentially in t for roughly $t \le K/2$ and then drop exponentially for $t > K/2$. That is, their values are small for values of t close to 0 or K and are maximised at around $t = K/2$.

Summarising Theorems 1, 3 and 4, to achieve both correctness and security, we set $\mathcal{D}_{\mathtt{A}}$ to be uniform over $\mathcal{R}_q^{n\times m}$, $\mathcal{D}_{\mathtt{x}} = D_{\mathcal{R},\sigma_{\mathtt{x}}}^m$, and we require the parameters $\mathcal{R}, n, m, q, t, K, Q = Q_{\mathtt{ISIS}}, \sigma_{\mathtt{x}}, \beta_{\mathtt{x}}, \chi, \chi_1^*, \chi_2^*, \gamma, \rho$ (and $Q_{\mathtt{LWE}} = 0$ not used) to satisfy the following constraints:

- (Theorem 1, LWE to th-\$-LWE) χ, χ_1^*, χ_2^* are such that:
  - $\chi_1^* \ge \sqrt{2}\cdot\eta_\epsilon(\mathcal{R}^m)$, $\chi_2^* \ge \sqrt{2}\cdot\eta_\epsilon(\mathcal{R}^Q)$ for $\epsilon = 2^{-\lambda}$, $\beta_{\mathtt{x}} = \sigma_{\mathtt{x}}\sqrt{\varphi m}$,
  - $\chi \gtrsim 2\gamma\cdot(\beta_{\mathtt{x}}\cdot\sqrt{Q}+1)\cdot\chi_1^*$,
  - $\chi \gtrsim 2\gamma\cdot\chi_2^*$.
- (Theorem 3, Correctness) $q > 4\chi\sqrt{\varphi}\cdot(\xi\cdot\beta_{\mathtt{x}}\sqrt{m}+\sqrt{t}\cdot\rho)$, and
- (Theorem 4, Security) the following LWE problems are 2^λ-hard:
  1. $\mathsf{LWE}^{(1)} = \mathsf{LWE}_{\mathcal{R},n,m,q,\chi_1^*}$,
  2. $\mathsf{LWE}^{(2)} = \mathsf{LWE}_{\mathcal{R},m,Q,q,\chi_2^*,\mathcal{D}_{\mathtt{x}}^Q}$, estimated by $\mathsf{LWE}_{\mathcal{R},m/\log_{\sigma_{\mathtt{x}}} q,Q,q,\chi_2^*}$,
  3. $\mathsf{LWE}^{(3)} = \mathsf{LWE}_{\mathcal{R},m-n-L,n+L,q,\sigma_{\mathtt{x}},D_{\mathcal{R},\sigma_{\mathtt{x}}}}$.

To simplify the constraints, we set $m = 2n + L$ and $\chi_1^* = \sigma_{\mathtt{x}}$ so that $\mathsf{LWE}^{(1)}$ and $\mathsf{LWE}^{(3)}$ are roughly equally hard. Our next goal is to let χ be minimal and χ_1^*, χ_2^* be maximal such that the above constraints are satisfied. Practically, let $\sigma_{\mathtt{x}} = \sqrt{2\varphi m\cdot\ln(2^\lambda\cdot 2\varphi m)/\pi}$. Expressing in terms of $\sigma_{\mathtt{x}}$, we let

$$\chi_1^* = \sigma_{\mathtt{x}}, \qquad \chi_2^* = (\beta_{\mathtt{x}}\cdot\sqrt{Q}+1)\cdot\sigma_{\mathtt{x}}, \qquad \chi = 2\gamma(\beta_{\mathtt{x}}\cdot\sqrt{Q}+1)\cdot\sigma_{\mathtt{x}}.$$

$Q\backslash t$	2	3	4	5	6	7
0	(7.5, 1.3)	(8.0, 1.3)	(8.2, 1.4)	(8.6, 1.4)	(8.6, 1.4)	(8.5, 1.4)
1	(14.0, 1.7)	(14.7, 1.8)	(14.8, 1.9)	(17.5, 1.9)	(17.5, 1.9)	(17.4, 1.9)
2^{32}	(22.8, 2.3)	(26.2, 2.4)	(26.4, 2.4)	(27.2, 2.5)	(27.2, 2.5)	(27.1, 2.5)
2^{60}	(35.8, 2.8)	(36.9, 2.8)	(37.2, 2.9)	(38.1, 2.9)	(38.1, 2.9)	(38.0, 2.9)

Table 2: Sizes $(|\mathsf{ctxt}|, |\mathsf{pd}_k|)$ in KB of Pilvi for $K = 8$ users.

$Q\backslash t$	2	4	6	8	10	12	15
0	(7.6, 1.3)	(8.5, 1.4)	(11.0, 1.6)	(11.2, 1.6)	(13.4, 1.7)	(11.4, 1.6)	(10.8, 1.5)
1	(14.1, 1.8)	(17.3, 1.9)	(18.6, 2.1)	(21.1, 2.1)	(21.8, 2.2)	(21.5, 2.1)	(18.4, 2.0)
2^{32}	(23.0, 2.3)	(27.0, 2.5)	(31.2, 2.6)	(31.7, 2.6)	(32.4, 2.7)	(32.1, 2.7)	(31.0, 2.6)
2^{60}	(36.0, 2.8)	(37.9, 2.9)	(42.9, 3.1)	(43.4, 3.1)	(47.6, 3.2)	(43.8, 3.1)	(42.6, 3.0)

Table 3: Sizes $(|\mathsf{ctxt}|, |\mathsf{pd}_k|)$ in KB of Pilvi for $K = 16$ users.

Substituting χ into the lower bound of q, we obtain:

$$\begin{aligned} q &> 4\chi\sqrt{\varphi} \cdot (\xi \cdot \beta_{\mathtt{x}}\sqrt{m} + \sqrt{t} \cdot \rho) \\ &\approx \begin{cases} 8\gamma\sqrt{\varphi}\sigma_{\mathtt{x}} \cdot (\xi \cdot \sigma_{\mathtt{x}}\sqrt{\varphi}m + \sqrt{t} \cdot \rho) & Q = 0 \\ 8\gamma\varphi\sqrt{mQ}\sigma_{\mathtt{x}}^2 \cdot (\xi \cdot \sigma_{\mathtt{x}}\sqrt{\varphi}m + \sqrt{t} \cdot \rho) & Q > 0. \end{cases} \end{aligned}$$

Our strategy (detailed in Appendix D.2) of selecting parameters is as follows: Fix the target threshold t, the maximum number of users K, an initial module rank n, and the maximum number of partial decryption queries Q. The choice of K fixes the subtractive set Ξ, which in turn fixes the expansion factors ρ and γ. Set $m = 2n + L$. Pick $\sigma_{\mathtt{x}}, \beta_{\mathtt{x}}, \chi, \chi_1^*, \chi_2^*, q$ as described above. Use the Lattice Estimator [APS15][16] to check if $\mathsf{LWE}^{(i)}$ are sufficiently hard for $i \in \{1, 2, 3\}$. If any check fails, repeat with a larger n.

In Tables 2 to 4, we report some feasible parameters and the corresponding ciphertext and partial decryption sizes for Pilvi. In particular, we consider the following parameter regimes: conductor $\mathfrak{f} = 512$, degree $\varphi = 256$, bit-security level $\lambda \geq 128$, maximum number of users $K \in \{8, 16, 32\}$, maximum number $Q \in \{0, 1, 2^{32}, 2^{60}\}$ of partial decryption queries (counting distinct ciphertexts), varying recovery threshold $t \in [2 : K - 1]$, LWE secret dimensions n and $m = 2n + L$, modulus size q, message length 256 bits (i.e. $L = 256/\varphi$), ciphertext size $|\mathsf{ctxt}| = (n + L)\varphi \log q$, and partial decryption size $|\mathsf{pd}_k| = L\varphi \log q$.

In Table 5, we compare efficiency metrics of our scheme, in terms of ciphertext and partial decryption share sizes, against tPKE constructions from [BS23, MS25, BFM+25]. We report various instantiations of Pilvi, and similarly include the most relevant parameters we could extract from the other works. All details can be found in Table 5; in what follows, we provide a textual overview of the main comparisons.

A key feature of Pilvi is its ability to support any threshold $t < K$ and a maximum number of users K of modest magnitude, while keeping the size of partial decryption shares small. Compared to [BS23], the size of the partial decryption shares in all instantiations of Pilvi scale well even as K increases and for $t \approx K/2$, remaining single-digit KB across all instantiations. In contrast, while [BS23] achieves excellent efficiency when $t = K$, the decryption share size grows to above 100 MB for $t \approx K/2$.

The construction of [MS25] only limits to K-out-of-K sharing but not any $t < K$ threshold, and is proven secure in a restrictive model, where the size of the corrupt set is necessarily maximal and no partial decryption queries are allowed. Nevertheless, their scheme achieves the most efficient performance among the compared works, with ciphertext and partial decryption share sizes of 1.5 KB and 0.3 KB, respectively.

Lastly, the scheme of [BFM+25] is the least efficient in terms of sizes among the compared schemes. We note, however, that [BFM+25] specifically thresholdises fully homomorphic encryption (FHE) but not basic PKE.

[16] Commit `5ba00f5` of https://github.com/malb/lattice-estimator/.

$Q\backslash t$	2	4	8	16	24	28	31
0	(7.7, 1.3)	(10.4, 1.5)	(14.6, 1.8)	(18.8, 2.1)	(18.3, 2.0)	(14.7, 1.8)	(11.6, 1.7)
1	(14.2, 1.8)	(17.9, 2.0)	(25.6, 2.3)	(31.1, 2.6)	(30.5, 2.5)	(25.9, 2.4)	(21.6, 2.2)
2^{32}	(25.6, 2.3)	(27.6, 2.5)	(37.1, 2.9)	(43.6, 3.1)	(42.9, 3.1)	(37.4, 2.9)	(32.3, 2.7)
2^{60}	(36.2, 2.8)	(41.8, 3.0)	(49.7, 3.3)	(57.1, 3.6)	(56.3, 3.5)	(50.0, 3.3)	(44.1, 3.1)

Table 4: Sizes ($|\mathsf{ctxt}|, |\mathsf{pd}_k|$) in KB of Pilvi for $K = 32$ users.

Reference	Parameter Set	$\lvert\mathcal{C}\rvert$	t	K	Q_{nc}	Q	q	$\lvert\mathsf{ctxt}\rvert$	$\lvert\mathsf{pd}_k\rvert$
[BS23, Tab. 2]	TKyber1024	$\leq$	2	2	1	0	2^{23}	2.9	0.7
	TKyber1024	$\leq$	2	2	1	0	2^{24}	3.0	0.8
	TKyber1024	$\leq$	10	10	1	0	2^{25}	3.1	0.8
	TKyber1280	$\leq$	6	10	1	0	2^{29}	4.5	114.2
	TKyber1536	$\leq$	11	20	10	0	2^{36}	6.8	101.5 MB
	TKyber1792	$\leq$	2	2	2^{32}	0	2^{39}	8.5	1.2
[BS23, Tab. 3]	TKyber1024	$\leq$	2	2	1	0	2^{15}	1.9	0.5
	TKyber1024	$\leq$	2	2	2	0	2^{16}	2.0	0.5
	TKyber1024	$\leq$	3	3	1	0	2^{15}	1.9	0.5
[MS25]		$=$	8263	8263	0	0	2^{16}	1.5	0.3
[BFM+25, Tab. 2, Fig. 4]		$=$	10	30	0	0	2^{122}	125.1	> 100
		$=$	160	480	0	0	2^{776}	3.1 MB	> 3 MB
This work	Pilvi1792-2-8-1	$\leq$	2	8	1		2^{56}	14.0	1.7
	Pilvi2048-6-8-1	$\leq$	6	8	1		2^{63}	17.5	1.9
	Pilvi2304-10-16-1	$\leq$	10	16	1		2^{70}	21.8	2.2
	Pilvi2816-16-32-1	$\leq$	16	32	1		2^{84}	31.1	2.6
	Pilvi3072-2-8-x60	$\leq$	2	8	2^{60}		2^{89}	35.8	2.8
	Pilvi3072-6-8-x60	$\leq$	6	8	2^{60}		2^{94}	38.1	2.9
	Pilvi3584-10-16-x60	$\leq$	10	16	2^{60}		2^{102}	47.6	3.2
	Pilvi3840-16-32-x60	$\leq$	16	32	2^{60}		2^{115}	57.1	3.6

Table 5: Ciphertext and partial decryption share sizes in KB for (at least) 128-bit security and (at least) 256-bit messages. The number e.g. 1792, 2048 after a parameter set name indicates the LWE dimension i.e. φn. '$\leq$' and '$=$' in the $|\mathcal{C}|$ column denote whether security is proven for $\leq t-1$ or exactly $t-1$ corrupt parties. The parameter t here denotes the recovery threshold, while t is used in [BS23] to denote the corruption threshold. For Pilvi, K denotes the maximum of users, e.g. a scheme with $(t, K) = (2, 8)$ can support 2-out-of-2 threshold decryption. Q_{nc} and Q denote the maximum number of partial decryption queries for **non-challenge** and challenge ciphertexts respectively, where the numbers for Pilvi are for both types combined.

We highlight once more that among all constructions in Table 5, Pilvi is the only one that allow partial decryption queries on challenge ciphertexts, it thus achieves a stronger security notion than the rest and a fair comparison of the parameters is challenging.

Finally, we remark that while using the degree $\varphi = 256$ ring will likely result in faster running times (with benchmark left as future work), it limits the flexibility of parameter choices and often make our instantiations much more secure than the targetted 128-bit security. This is because increasing the module rank n by 1 already implies an increase in LWE secret dimension (over $\mathbb{Z}$) by 256. We therefore expect that more fine-grained parameter optimisations will further shrink the ciphertext and partial decryption share sizes.

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A Reductions from LWE to th-$-LWE

We present formal reductions from LWE to th-$-LWE. This section is structured as follows. In Appendix A.1 we recall existing lemmas from the literature useful for our reductions. In Appendix A.2, we provide the proofs of Lemmas 2 to 3 concerning expansion factors of two subtractive sets. In Appendix A.3, we prove additional lemmas on Vandermonde Matrices, which will be useful for proving the random unauthorised shares property of th-$-LWE. In Appendix A.4, we prove a computational indistinguishability lemma which will become the core of our main reductions from LWE to th-LWE. Using all of the above, in Appendices A.5 and A.6 we provide two reductions from LWE to th-$-LWE. The first assumes a bounded number of adversarial queries, but can be instantiated with a polynomial modulus. The second allows an unbounded number of queries, but requires a super-polynomial modulus.

A.1 Existing Utility Lemmas

Lemma 6 (Adapted from [Ban93, Lemma 1.5]). *For any $m \in \mathbb{N}$, $\chi > 0$,*

$$\Pr\left[\|\mathbf{x}\| > \chi\sqrt{m\varphi} \;\middle|\; \mathbf{x} \hookleftarrow\$\; D^m_{\mathcal{R},\chi}\right] \leq 2^{-m\varphi}.$$

Lemma 7 (Noise Flooding [GKPV10]). *Let $n \in \mathbb{N}$. For any real $\chi > \omega(\sqrt{\log n})$, and any $\mathbf{c} \in \mathcal{R}^n$, it holds $\mathsf{SD}(D_{\mathcal{R}^n,\chi}, D_{\mathcal{R}^n,\chi} + \mathbf{c}) \leq \|\mathbf{c}\|/\chi$. In particular, if $\chi \geq \lambda^{\omega(1)} \cdot \|\mathbf{c}\|$, one has $D_{\mathcal{R}^n,\chi} \approx_s D_{\mathcal{R}^n,\chi} + \mathbf{c}$.*

A.2 Proof of Lemmas 2 and 3

Lemma 2. *Let $\mathbf{V} \in \mathcal{K}^{t\times t}$ be the Vandermonde matrix of the set $\{\mu_1, \ldots, \mu_t\} \subset \mathcal{K}$. It holds that $\left\|\mathbf{V}^{-1}\right\| \leq \sqrt{t}\max_\ell \max_{i\in[t]} \prod_{j\in[t],j\neq i} \frac{1+|\sigma_\ell(\mu_j)|}{|\sigma_\ell(\mu_j-\mu_i)|}$ where ℓ ranges over all φ embeddings σ_ℓ from $\mathcal{K}$ to $\mathbb{C}$.*

Proof. We observe that

$$\begin{aligned}
\left\|\mathbf{V}^{-1}\right\|^2 &= \max_{\mathbf{x}} \frac{\left\|\mathbf{V}^{-1}\mathbf{x}\right\|^2}{\|\mathbf{x}\|^2} = \max_{\mathbf{x}} \frac{\sum_\ell \left\|\sigma_\ell(\mathbf{V}^{-1})\sigma_\ell(\mathbf{x})\right\|^2}{\sum_\ell \|\sigma_\ell(\mathbf{x})\|^2} \\
&\leq \max_{\mathbf{x}} \frac{\sum_\ell \left\|\sigma_\ell(\mathbf{V}^{-1})\right\|^2 \|\sigma_\ell(\mathbf{x})\|^2}{\sum_\ell \|\sigma_\ell(\mathbf{x})\|^2} \\
&\leq \max_\ell \left\|\sigma_\ell(\mathbf{V}^{-1})\right\|^2 \leq \max_\ell\ t \cdot \left\|\sigma_\ell(\mathbf{V}^{-1})\right\|_\infty^2
\end{aligned}$$

where ℓ ranges over all φ embeddings σ_ℓ from $\mathcal{K}$ to $\mathbb{C}$ and $\sigma_\ell(\mathbf{V}_T^{-1})$ denotes applying σ_ℓ on $\mathbf{V}_T^{-1}$ element-wise. By [Gau62, Theorem 3.1],

$$\left\|\sigma_\ell(\mathbf{V}^{-1})\right\|_\infty \leq \max_{i\in[t]} \prod_{j\in[t],j\neq i} \frac{1+|\sigma_\ell(\mu_j)|}{|\sigma_\ell(\mu_j-\mu_i)|}.$$ □

Lemma 3. *Let $\mathcal{R} = \mathbb{Z}[\zeta]$ be the cyclotomic ring with conductor $\mathfrak{f}$. The set $\Xi = \left\{1, \zeta, \ldots, \zeta^{\mathfrak{f}-1}\right\}$ is ξ-subtractive for $\xi = \xi(t) = \mathfrak{f}$, or $\xi(t) = 2^{\lceil \log t \rceil}$ if $\mathfrak{f}$ is a power of 2. It has the quality $\rho(t) \leq \xi \cdot t\left(\frac{\mathfrak{f}}{2\sqrt{2}}\right)^{t-1}$ and $\gamma(t) \leq \xi \cdot t\sqrt{K}\left(\frac{\mathfrak{f}}{2\sqrt{2}}\right)^{t-1}$. Furthermore, if $\mathfrak{f}$ is a power of 2, then $\xi = 2^{\lceil \log t \rceil}$.*

Proof. We first analyse the slack $\xi(t)$ of Ξ. The case where $\mathfrak{f}$ is a power of 2 follows from Lemma 1. Below we consider general $\mathfrak{f}$. Fix any t-subset $T = \{\zeta^{i_j} : j \in [t]\}$ of Ξ. Each entry in the j-th row of $\mathbf{V}_T^{-1}$ can be expressed as a fraction with denominator given by $\prod_{k\in[t]\setminus\{j\}}(\zeta^{i_j} - \zeta^{i_k})$. Multiplying each factor in the denominator by ζ^{-i_j}, we obtain the expression $\prod_{k\in[t]\setminus\{j\}}(1 - \zeta^{i_k - i_j})$. We claim that $\prod_{i=1}^{\mathfrak{f}-1}(1-\zeta^i) = \mathfrak{f}$ and so the above

expression divides $\mathfrak{f}$. To show this claim, consider the polynomial $(X^{\mathfrak{f}}-1)/(X-1) = \sum_{j=0}^{\mathfrak{f}-1} X^j = \prod_{i=1}^{\mathfrak{f}-1}(X-\zeta^i)$ and evaluate at $X=1$.

In the rest we analyse the quality of Ξ. Let $\mu_i = \zeta^i$ where $i \in [K]$. For any T, let $\mathbf{v}_i$ denote the column of $\mathbf{V}_T$ indexed by $\mu_i = \zeta^i$. Clearly, $\left\|\zeta^i\right\|_\infty = 1$.

For bounding $\left\|\mathbf{V}_T^{-1}\right\|$, by Lemma 2, it suffices to upper bound $|\sigma_\ell(\mu_j)|$ and lower bound $|\sigma_\ell(\mu_j - \mu_i)|$ for $\ell \in \mathbb{Z}_{\mathfrak{f}}^\times$ and distinct $\mu_i, \mu_j \in T$. Fix some $\mu_i \in T$. For any other $\mu_j \in T$, it holds that

$$|\sigma_\ell(\mu_j)| = |\zeta^j| = 1$$

and

$$\mu_j - \mu_i = \zeta^j - \zeta^i = \zeta^i(\zeta^{j-i} - 1),$$
$$|\sigma_\ell(\zeta^j - \zeta^i)| = |\zeta^j - \zeta^i| = |\zeta^{j-i} - 1| \geq \frac{4\sqrt{2}}{\mathfrak{f}}$$

where the last inequality is obtained by lower-bounding the length of any chord in the unit circle with angle $2\pi/\mathfrak{f} \leq \pi/2$ (see e.g. [KLNO24, Lemma 2] for a proof). Therefore, by Lemma 2,

$$\left\|\mathbf{V}_T^{-1}\right\| \leq \sqrt{t} \cdot \max_{i\in[t]} \prod_{j\in[t], j\neq i} \frac{\mathfrak{f}}{2\sqrt{2}} = \sqrt{t}\left(\frac{\mathfrak{f}}{2\sqrt{2}}\right)^{t-1} \qquad \square$$

A.3 Additional Lemmas on Vandermonde Matrix

For any subset $\mathcal{C} \subseteq_{<t} [K]$, let T^* be an arbitrary fixed (only dependent on $\mathcal{C}$) t-subset of $[0, K]$ containing 0, i.e. $\mathcal{C} \cup \{0\} \subseteq T^* \subseteq_t [0, K]$. For example, if $|\mathcal{C}| = t-1$, then $T^* = \mathcal{C} \cup \{0\}$. We use the convention that $\mathbf{V}_{T^*} = \begin{bmatrix} \mathbf{v}_0^\intercal \\ \mathbf{V}_{T^*\setminus(\{0\}\cup\mathcal{C})} \\ \mathbf{V}_{\mathcal{C}} \end{bmatrix}$, i.e. the row corresponding to the virtual user 0 is located on top, followed by the rows for $T^* \setminus (\{0\} \cup \mathcal{C})$ and then $\mathcal{C}$. We observe that the matrix $\mathbf{V}_{T^*}$ specified above has several convenient properties.

1. For any subset $\mathcal{C} \subseteq_{<t} [K]$, define $\mathbf{T}_{\mathcal{C}} \coloneqq \xi \cdot \mathbf{V}_{T^*}^{-1} \in \mathcal{R}^{t\times t}$, and write $\mathbf{T}_{\mathcal{C}} = \left(\mathbf{T}_{\mathcal{C}}^{\perp}\ \mathbf{T}_{\mathcal{C}}^{\vee}\right)$, where $\mathbf{T}_{\mathcal{C}}^{\perp} \in \mathcal{R}^{t\times\tilde{t}}, \mathbf{T}_{\mathcal{C}}^{\vee} \in \mathcal{R}^{t\times|\mathcal{C}|}$ where $\tilde{t} \coloneqq t - |\mathcal{C}|$. Note that

$$\underbrace{\begin{pmatrix} \mathbf{v}_0^\intercal \\ \mathbf{V}_{T^*\setminus(\{0\}\cup\mathcal{C})} \\ \mathbf{V}_{\mathcal{C}} \end{pmatrix}}_{\mathbf{V}_{T^*}} \underbrace{\left(\mathbf{T}_{\mathcal{C}}^{\perp}\ \mathbf{T}_{\mathcal{C}}^{\vee}\right)}_{\mathbf{T}_{\mathcal{C}} \coloneqq \mathbf{V}_{T^*}^{-1}} = \xi \cdot \underbrace{\begin{bmatrix} 1 & & \\ & \mathbf{I}_{\tilde{t}-1} & \\ & & \mathbf{I}_{|\mathcal{C}|} \end{bmatrix}}_{\mathbf{I}_t}. \tag{2}$$

   In particular, we have $\mathbf{V}_{\mathcal{C}} \cdot \mathbf{T}_{\mathcal{C}}^{\vee} = \xi \cdot \mathbf{I}_{|\mathcal{C}|}$ and $\mathbf{V}_{\mathcal{C}} \cdot \mathbf{T}_{\mathcal{C}}^{\perp} = \mathbf{0}_{|\mathcal{C}|\times\tilde{t}}$. In other words, $\xi^{-1} \cdot \mathbf{T}_{\mathcal{C}}^{\vee}$ and $\xi^{-1} \cdot \mathbf{T}_{\mathcal{C}}^{\perp}$ are $\mathcal{K}$-bases of the (right-)dual and (right-)kernel of $\mathbf{V}_{\mathcal{C}}$ respectively. Furthermore, it holds that $\mathbf{v}_0^\intercal \cdot \mathbf{T}_{\mathcal{C}}^{\perp} = (1, 0, \ldots, 0)^\intercal$, the first unit vector of dimension $\tilde{t}$.
2. Letting $\bar{\mathbf{T}}_{\mathcal{C}}^{\perp} \coloneqq \mathbf{T}_{\mathcal{C}}^{\perp} \begin{pmatrix} \mathbf{0}_{1\times(t-1)} \\ \mathbf{I}_{\tilde{t}-1} \end{pmatrix} \in \mathcal{R}^{t\times(\tilde{t}-1)}$, i.e. $\bar{\mathbf{T}}_{\mathcal{C}}^{\perp}$ is obtained by removing the first column of $\mathbf{T}_{\mathcal{C}}^{\perp}$, then we have

$$\begin{pmatrix} \mathbf{V}_{\{0\}\cup\mathcal{C}} \\ \mathbf{V}_{T^*\setminus(\{0\}\cup\mathcal{C})} \end{pmatrix} \bar{\mathbf{T}}_{\mathcal{C}}^{\perp} = \xi \cdot \begin{bmatrix} \mathbf{0}_{(|\mathcal{C}|+1)\times(\tilde{t}-1)} \\ \mathbf{I}_{\tilde{t}-1} \end{bmatrix}.$$

   In particular, $\bar{\mathbf{T}}_{\mathcal{C}}^{\perp}$ is the $\mathcal{K}$-basis of the (right-)kernel of $\mathbf{V}_{\{0\}\cup\mathcal{C}}$.

Concerning the matrix $\bar{\mathbf{T}}_{\mathcal{C}}^{\perp}$ constructed in the second property above, we arrive at the following useful lemmas.

Lemma 8. *$\xi^{-1} \cdot \bar{\mathbf{T}}_{\mathcal{C}}^{\perp}$ is an $\mathcal{R}$-basis of the (right-)kernel of $\mathbf{V}_{\{0\}\cup\mathcal{C}}$. That is, for all $\mathbf{f} \in \mathcal{R}^t$ satisfying $\mathbf{V}_{\{0\}\cup\mathcal{C}} \cdot \mathbf{f} = \mathbf{0}$, there exists $\mathbf{c} \in \mathcal{R}^{\tilde{t}}$ such that $\mathbf{f} = \xi^{-1} \cdot \bar{\mathbf{T}}_{\mathcal{C}}^{\perp} \cdot \mathbf{c}$.*

Proof. Fix arbitrary $\mathbf{f} \in \mathcal{R}^t$ satisfying $\mathbf{V}_{\{0\}\cup\mathcal{C}} \cdot \mathbf{f} = \mathbf{0}$. Since $\bar{\mathbf{T}}_{\mathcal{C}}^{\perp}$ is a $\mathcal{K}$-basis of the (right-)kernel of $\mathbf{V}_{\{0\}\cup\mathcal{C}}$, there exists $\mathbf{c}' \in \mathcal{K}^{\tilde{t}}$ such that $\mathbf{f} = \bar{\mathbf{T}}_{\mathcal{C}}^{\perp} \cdot \mathbf{c}'$. Write $\mathbf{c}' = \xi^{-1} \cdot \mathbf{c}$ for some $\mathbf{c} \in \mathcal{K}^{\tilde{t}}$, so that $\mathbf{f} = \xi^{-1}\bar{\mathbf{T}}_{\mathcal{C}}^{\perp} \cdot \mathbf{c}$. Then $\mathbf{V}_{T^*\setminus(\{0\}\cup\mathcal{C})} \cdot \mathbf{f} = \mathbf{V}_{T^*\setminus(\{0\}\cup\mathcal{C})} \cdot \bar{\mathbf{T}}_{\mathcal{C}}^{\perp} \cdot \mathbf{c}' = \xi \cdot \mathbf{I}_{\tilde{t}-1} \cdot \mathbf{c}' = \xi \cdot \mathbf{c}' = \mathbf{c}$, where the second equality holds by construction of $\bar{\mathbf{T}}_{\mathcal{C}}^{\perp}$. Since $\mathbf{f}, \mathbf{V}_{T^*\setminus(\{0\}\cup\mathcal{C})}$ consist of $\mathcal{R}$ elements, so is $\mathbf{c}$. □

Lemma 9. *Let q be coprime with ξ. Let $\mathcal{C}, \mathcal{J} \subseteq [K]$ be disjoint. If $|\mathcal{J} \cup \mathcal{C}| < t$, then the columns of $\mathbf{V}_{\mathcal{J}} \cdot \bar{\mathbf{T}}_{\mathcal{C}}^{\perp}$ generate $\mathcal{R}_q^{|\mathcal{J}|}$.*

Proof. In this proof, we index the dimensions of $\mathcal{R}^{|\mathcal{J}|}$ by elements of $\mathcal{J}$.

First we show that, for each $j \in \mathcal{J}$, the j-th unit vector is spanned by the columns of $\xi^{-1} \cdot \mathbf{V}_{\mathcal{J}}\bar{\mathbf{T}}_{\mathcal{C}}^{\perp}$ with coefficients taken in $\mathcal{R}$. Let $\mathbf{F} = (\ldots, \mathbf{f}_j, \ldots)_{j\in\mathcal{J}} \in \mathcal{R}^{t\times|\mathcal{J}|}$ be satisfying

$$\begin{pmatrix} \mathbf{V}_{\{0\}\cup\mathcal{C}} \\ \mathbf{V}_{\mathcal{J}} \end{pmatrix} \cdot \mathbf{F} = \begin{pmatrix} \mathbf{0}_{t\times|\mathcal{J}|} \\ \mathbf{I}_{|\mathcal{J}|} \end{pmatrix},$$

that is, each $\mathbf{f}_j$ is the coefficient of the degree-$(t-1)$ polynomial f_j satisfying $f_j(\mu_i) = 0$ for all $i \in (\{0\}\cup\mathcal{J}\cup\mathcal{C})\setminus\{j\}$ and $f_j(\mu_j) = 1$, which must exist since $\{\mu_i : i \in [K]\}$ is ξ-subtractive and $|\mathcal{J}\cup\mathcal{C}| < t$. Note that each $\mathbf{f}_j$ is in the $\mathcal{R}$-column-span of $\xi^{-1} \cdot \bar{\mathbf{T}}_{\mathcal{C}}^{\perp}$ by Lemma 8. Therefore, there exists $\mathbf{C} \in \mathcal{R}^{\tilde{t}\times|\mathcal{J}|}$ such that

$$\xi^{-1} \cdot \mathbf{V}_{\mathcal{J}} \cdot \bar{\mathbf{T}}_{\mathcal{C}}^{\perp} \cdot \mathbf{C} = \mathbf{V}_{\mathcal{J}} \cdot \mathbf{F} = \mathbf{I}_{|\mathcal{J}|}.$$

Now since q and ξ are coprime, we have $\xi^{-1} \in \mathcal{R}_q$, thus $\mathbf{I}_{|\mathcal{J}|}$ is in the $\mathcal{R}_q$-span of $\mathbf{V}_{\mathcal{J}} \cdot \bar{\mathbf{T}}_{\mathcal{C}}^{\perp}$. □

A.4 Proof of Lemma 5

For a matrix $\mathbf{A}$, we denote by $\mathsf{rvec}(\mathbf{A})$ the row-vectorisation of $\mathbf{A}$, i.e. stacking the rows of $\mathbf{A}$ adjacent to one another horizontally. For matrices $\mathbf{A}, \mathbf{B}, \mathbf{C}$ of appropriate dimensions, it holds that

$$\mathsf{rvec}(\mathbf{ABC}) = \mathsf{rvec}(\mathbf{B})(\mathbf{A}^{\mathsf{T}} \otimes \mathbf{C}). \tag{3}$$

Proof (of Lemma 5). Applying Eq. (3) to the matrices $\mathbf{B}, \mathbf{C}$ in the LHS distribution, we have

$$\begin{aligned}
\mathsf{rvec}(\mathbf{B}) &= \mathsf{rvec}(\mathbf{N}\mathbf{S}_0\mathbf{A} + \mathbf{E}_B) \\
&= \mathsf{rvec}(\mathbf{S}_0) \cdot (\mathbf{N}^{\mathsf{T}} \otimes \mathbf{A}) + \mathsf{rvec}(\mathbf{E}_B) \\
&= \mathsf{rvec}(\mathbf{S}_0) \cdot (\mathbf{I}_{t_0} \otimes \mathbf{A})(\mathbf{N}^{\mathsf{T}} \otimes \mathbf{I}_m) + \mathsf{rvec}(\mathbf{E}_B), \\
\mathsf{rvec}(\mathbf{C}) &= \mathsf{rvec}(\mathbf{M} \begin{bmatrix} \mathbf{S}_0 \\ \mathbf{S}_1 \\ \mathbf{S}_2 \end{bmatrix} \mathbf{A}\mathbf{X} + \mathbf{E}_C) \\
&= (\mathsf{rvec}(\mathbf{S}_0), \mathsf{rvec}(\mathbf{S}_1), \mathsf{rvec}(\mathbf{S}_2)) \cdot (\mathbf{M}^{\mathsf{T}} \otimes \mathbf{A}\mathbf{X}) + \mathsf{rvec}(\mathbf{E}_C) \\
&= (\mathsf{rvec}(\mathbf{S}_0), \mathsf{rvec}(\mathbf{S}_1)) \cdot (\mathbf{M}_{0,1}^{\mathsf{T}} \otimes \mathbf{A}\mathbf{X}) + \mathsf{rvec}(\mathbf{E}_C) + \mathsf{rvec}(\mathbf{S}_2) \cdot (\mathbf{M}_2^{\mathsf{T}} \otimes \mathbf{A}\mathbf{X}) \\
&= (\mathsf{rvec}(\mathbf{S}_0), \mathsf{rvec}(\mathbf{S}_1)) \cdot (\mathbf{I}_{t_0+t_1} \otimes \mathbf{A})(\mathbf{M}_{0,1}^{\mathsf{T}} \otimes \mathbf{X}) + \mathsf{rvec}(\mathbf{E}_C) + \mathsf{rvec}(\mathbf{S}_2) \cdot (\mathbf{M}_2^{\mathsf{T}} \otimes \mathbf{A}\mathbf{X}),
\end{aligned}$$

where for both $\mathsf{rvec}(\mathbf{B})$ and $\mathsf{rvec}(\mathbf{C})$, in the last equality we use the mixed-product property of the Kronecker product. Similarly, applying Eq. (3) to the matrices $\mathbf{B}, \mathbf{C}$ in the RHS distribution, we have

$$\begin{aligned}
\mathsf{rvec}(\mathbf{B}) &= \mathsf{rvec}(\mathbf{N}\bar{\mathbf{S}}_0\mathbf{I}_m + \mathbf{E}_B) = \mathsf{rvec}(\bar{\mathbf{S}}_0) \cdot (\mathbf{N}^{\mathsf{T}} \otimes \mathbf{I}_m) + \mathsf{rvec}(\mathbf{E}_B), \\
\mathsf{rvec}(\mathbf{C}) &= \mathsf{rvec}(\mathbf{M} \begin{bmatrix} \bar{\mathbf{S}}_0 \\ \bar{\mathbf{S}}_1 \\ \mathbf{S}_2\mathbf{A} \end{bmatrix} \mathbf{X} + \mathbf{E}_C)
\end{aligned}$$

$$
\begin{aligned}
&= (\mathsf{rvec}(\bar{\mathbf{S}}_0), \mathsf{rvec}(\bar{\mathbf{S}}_1), \mathsf{rvec}(\mathbf{S}_2\mathbf{A})) \cdot (\mathbf{M}^{\mathsf{T}} \otimes \mathbf{X}) + \mathsf{rvec}(\mathbf{E}_C) \\
&= (\mathsf{rvec}(\bar{\mathbf{S}}_0), \mathsf{rvec}(\bar{\mathbf{S}}_1)) \cdot (\mathbf{M}_{0,1}^{\mathsf{T}} \otimes \mathbf{X}) + \mathsf{rvec}(\mathbf{E}_C) + \mathsf{rvec}(\mathbf{S}_2\mathbf{A}) \cdot (\mathbf{M}_2^{\mathsf{T}} \otimes \mathbf{X}) \\
&= (\mathsf{rvec}(\bar{\mathbf{S}}_0), \mathsf{rvec}(\bar{\mathbf{S}}_1)) \cdot (\mathbf{M}_{0,1}^{\mathsf{T}} \otimes \mathbf{X}) + \mathsf{rvec}(\mathbf{E}_C) + \mathsf{rvec}(\mathbf{S}_2)(\mathbf{I}_{t_2} \otimes \mathbf{A}) \cdot (\mathbf{M}_2^{\mathsf{T}} \otimes \mathbf{X}) \\
&= (\mathsf{rvec}(\bar{\mathbf{S}}_0), \mathsf{rvec}(\bar{\mathbf{S}}_1)) \cdot (\mathbf{M}_{0,1}^{\mathsf{T}} \otimes \mathbf{X}) + \mathsf{rvec}(\mathbf{E}_C) + \mathsf{rvec}(\mathbf{S}_2) \cdot (\mathbf{M}_2^{\mathsf{T}} \otimes \mathbf{A}\mathbf{X})
\end{aligned}
$$

where in the last line we use the mixed-product property of the Kronecker product. In both expressions, the matrix $\mathbf{S}_2$ is only involved in the last additive term of $\mathsf{rvec}(\mathbf{C})$ which is identical. Therefore, to show the lemma statement, it suffices to show that

$$
\begin{pmatrix} \mathbf{A},\ \mathsf{rvec}(\mathbf{S}_0) \cdot (\mathbf{I}_{t_0} \otimes \mathbf{A})(\mathbf{N}^{\mathsf{T}} \otimes \mathbf{I}_m) + \mathsf{rvec}(\mathbf{E}_B) \\ (\mathsf{rvec}(\mathbf{S}_0), \mathsf{rvec}(\mathbf{S}_1)) \cdot (\mathbf{I}_{t_0+t_1} \otimes \mathbf{A})(\mathbf{M}_{0,1}^{\mathsf{T}} \otimes \mathbf{X}) + \mathsf{rvec}(\mathbf{E}_C) \end{pmatrix} \approx_c \begin{pmatrix} \mathbf{A},\ \mathsf{rvec}(\bar{\mathbf{S}}_0) \cdot (\mathbf{N}^{\mathsf{T}} \otimes \mathbf{I}_m) + \mathsf{rvec}(\mathbf{E}_B) \\ (\mathsf{rvec}(\bar{\mathbf{S}}_0), \mathsf{rvec}(\bar{\mathbf{S}}_1)) \cdot (\mathbf{M}_{0,1}^{\mathsf{T}} \otimes \mathbf{X}) + \mathsf{rvec}(\mathbf{E}_C) \end{pmatrix},
$$

or equivalently

$$
\begin{pmatrix} \mathbf{A},\ \mathbf{b}^{\mathsf{T}} = \mathbf{s}_0^{\mathsf{T}} \cdot (\mathbf{I}_{t_0} \otimes \mathbf{A})(\mathbf{N}^{\mathsf{T}} \otimes \mathbf{I}_m) + \mathbf{e}_b^{\mathsf{T}} \\ \mathbf{c}^{\mathsf{T}} = (\mathbf{s}_0^{\mathsf{T}}, \mathbf{s}_1^{\mathsf{T}}) \cdot (\mathbf{I}_{t_0+t_1} \otimes \mathbf{A})(\mathbf{M}_{0,1}^{\mathsf{T}} \otimes \mathbf{X}) + \mathbf{e}_c^{\mathsf{T}} \end{pmatrix} \approx_c \begin{pmatrix} \mathbf{A},\ \mathbf{b}^{\mathsf{T}} = \bar{\mathbf{s}}_0^{\mathsf{T}} \cdot (\mathbf{N}^{\mathsf{T}} \otimes \mathbf{I}_m) + \mathbf{e}_b^{\mathsf{T}} \\ \mathbf{c}^{\mathsf{T}} = (\bar{\mathbf{s}}_0^{\mathsf{T}}, \bar{\mathbf{s}}_1^{\mathsf{T}}) \cdot (\mathbf{M}_{0,1}^{\mathsf{T}} \otimes \mathbf{X}) + \mathbf{e}_c^{\mathsf{T}} \end{pmatrix} \bmod q \tag{4}
$$

where $\mathbf{s}_0 \leftarrow\!\$\ \mathcal{R}_q^{nt_0}$, $\mathbf{s}_1 \leftarrow\!\$\ \mathcal{R}_q^{nt_1}$, $\bar{\mathbf{s}}_0 \leftarrow\!\$\ \mathcal{R}_q^{mt_0}$, $\bar{\mathbf{s}}_1 \leftarrow\!\$\ \mathcal{R}_q^{mt_1}$ are uniform, $\mathbf{A} \leftarrow\!\$\ \mathcal{D}_{\mathtt{A}}$, and $\mathbf{e}_b \leftarrow\!\$\ D_{\mathcal{R},\chi}^{r_N m}$, $\mathbf{e}_c \leftarrow\!\$\ D_{\mathcal{R},\chi}^{r_M Q}$.

To show the claimed indistinguishability under the first set of parameters, we will show that Eq. (4) holds under the $\mathsf{LLWE}_{\mathcal{R},n(t_0+t_1),m(t_0+t_1),k,q,\bar{\chi},\chi,\mathcal{L},\mathcal{D}^*}$ assumption (Definition 3), with parameters

$$
\begin{aligned}
&k \coloneqq r_N m + r_M Q, \qquad \bar{\chi}, \chi \text{ s.t. } \beta = \chi \cdot \sqrt{(2\eta_\epsilon(\mathcal{R}^m)^2 + (\chi^*)^2)^{-1} - \bar{\chi}^{-2}}, \\
&\mathcal{L}^* = \left\{ \mathbf{Z} \in \mathcal{R}^{m(t_0+t_1) \times k} : \|\mathbf{Z}\| \le \beta \right\}, \qquad \mathcal{D}^* \coloneqq (\mathbf{I}_{t_0+t_1} \otimes \mathcal{D}_{\mathtt{A}}).
\end{aligned}
$$

Then, the claim follows from noting that:

- the $\mathsf{LLWE}_{\mathcal{R},n(t_0+t_1),m(t_0+t_1),k,q,\bar{\chi},\chi,\mathcal{L}^*,\mathcal{D}^*}$ assumption is implied by the $\mathsf{LLWE}_{\mathcal{R},n,m,k,q,\bar{\chi},\chi,\mathcal{L},\mathcal{D}_{\mathtt{A}}}$ assumption with $\mathcal{L} = \left\{ \mathbf{Z} \in \mathcal{R}^{m \times k} : \|\mathbf{Z}\| \le \beta \right\}$ by a standard hybrid argument, formally shown in Proposition 1 below,
- the $\mathsf{LLWE}_{\mathcal{R},n,m,k,q,\bar{\chi},\chi,\mathcal{L},\mathcal{D}_{\mathtt{A}}}$ assumption is then implied by the $\mathsf{LWE}_{\mathcal{R},n,m,q,\chi^*,\mathcal{D}_{\mathtt{A}}}$ assumption under the stated constraints, which follows from Lemma 4.

Suppose towards contradiction there is a PPT $\mathcal{A}$ that distinguishes the distributions in Eq. (4) with non-negligible probability. We construct a reduction $\mathcal{B}$ against the $\mathsf{LLWE}_{\mathcal{R},n(t_0+t_1),m(t_0+t_1),k,q,\bar{\chi},\chi,\mathcal{L}^*,\mathcal{D}^*}$ problem as follows.

- Receive from the LLWE challenger a matrix $\mathbf{I}_{t_0+t_1} \otimes \mathbf{A}$.
- Let $\mathbf{Z}_b \coloneqq \begin{pmatrix} \mathbf{N}^{\mathsf{T}} \\ \mathbf{0} \end{pmatrix} \otimes \mathbf{I}_m$ and $\mathbf{Z}_c \coloneqq \mathbf{M}_{0,1}^{\mathsf{T}} \otimes \mathbf{X}$. Reply with $\mathbf{Z} \coloneqq (\mathbf{Z}_b, \mathbf{Z}_c)$.
- Receive from the LLWE challenger $(\bar{\mathbf{b}}, \mathbf{l})$. Parse $\mathbf{l}^{\mathsf{T}} = (\mathbf{l}_b^{\mathsf{T}}, \mathbf{l}_c^{\mathsf{T}})$.
- Let $\mathbf{b}^{\mathsf{T}} \coloneqq \bar{\mathbf{b}}^{\mathsf{T}} \cdot \mathbf{Z}_b - \mathbf{l}_b^{\mathsf{T}}$ and $\mathbf{c}^{\mathsf{T}} \coloneqq \bar{\mathbf{b}}^{\mathsf{T}} \cdot \mathbf{Z}_c - \mathbf{l}_c^{\mathsf{T}} \bmod q$.
- Pass $(\mathbf{A}, \mathbf{b})$ to $\mathcal{A}$ and return whatever $\mathcal{A}$ returns.

We analyse the output of $\mathcal{B}$. First we note that the leakage vector $\mathbf{l}$ received by $\mathcal{B}$ is

$$
\begin{aligned}
\mathbf{l}^{\mathsf{T}} = (\mathbf{l}_b^{\mathsf{T}}, \mathbf{l}_c^{\mathsf{T}}) = \bar{\mathbf{e}}^{\mathsf{T}}(\mathbf{Z}_b, \mathbf{Z}_c) + (\mathbf{e}_b^{\mathsf{T}}, \mathbf{e}_c^{\mathsf{T}}) &= \bar{\mathbf{e}}^{\mathsf{T}} \left(\begin{pmatrix} \mathbf{N}^{\mathsf{T}} \\ \mathbf{0} \end{pmatrix} \otimes \mathbf{I}_m,\ \mathbf{M}_{0,1}^{\mathsf{T}} \otimes \mathbf{X} \right) + (\mathbf{e}_b^{\mathsf{T}}, \mathbf{e}_c^{\mathsf{T}}) \\
&\equiv \bar{\mathbf{e}}^{\mathsf{T}} \left(\begin{pmatrix} \mathbf{N}^{\mathsf{T}} \\ \mathbf{0} \end{pmatrix} \otimes \mathbf{I}_m,\ \mathbf{M}_{0,1}^{\mathsf{T}} \otimes \mathbf{X} \right) - (\mathbf{e}_b^{\mathsf{T}}, \mathbf{e}_c^{\mathsf{T}})
\end{aligned}
$$

for some error $\bar{\mathbf{e}} \leftarrow\!\$\ D_{\mathcal{R},\bar{\chi}}^{m(t_0+t_1)}$ and $\begin{pmatrix} \mathbf{e}_b \\ \mathbf{e}_c \end{pmatrix} \leftarrow\!\$\ D_{\mathcal{R},\chi}^{r_N m + r_M Q}$. The $\equiv$ sign, i.e. equivalence in distribution, holds since Gaussian over $\mathcal{R}$ is symmetric around zero.

If $\mathcal{B}$ is interacting with experiment 0 of the LLWE problem, then $\bar{\mathbf{b}}^\mathsf{T} = (\mathbf{s}_0^\mathsf{T}, \mathbf{s}_1^\mathsf{T}) \cdot (\mathbf{I}_{t_0+t_1} \otimes \mathbf{A}) + \bar{\mathbf{e}}^\mathsf{T} \bmod q$. Therefore the outputs of $\mathcal{B}$ are

$$\begin{aligned}
\mathbf{b}^\mathsf{T} &\equiv \left((\mathbf{s}_0^\mathsf{T}, \mathbf{s}_1^\mathsf{T}) \cdot (\mathbf{I}_{t_0+t_1} \otimes \mathbf{A}) + \bar{\mathbf{e}}^\mathsf{T}\right) \mathbf{Z}_b - (\bar{\mathbf{e}}^\mathsf{T}\mathbf{Z}_b - \mathbf{e}_b^\mathsf{T}) \bmod q \\
&= (\mathbf{s}_0^\mathsf{T}, \mathbf{s}_1^\mathsf{T}) \cdot (\mathbf{I}_{t_0+t_1} \otimes \mathbf{A})\mathbf{Z}_b + \mathbf{e}_b^\mathsf{T} \bmod q \\
&= (\mathbf{s}_0^\mathsf{T}, \mathbf{s}_1^\mathsf{T}) \cdot (\mathbf{I}_{t_0+t_1} \otimes \mathbf{A})(\begin{pmatrix}\mathbf{N}^\mathsf{T} \\ \mathbf{0}\end{pmatrix} \otimes \mathbf{I}_m) + \mathbf{e}_b^\mathsf{T} \bmod q \\
&= (\mathbf{s}_0^\mathsf{T}, \mathbf{s}_1^\mathsf{T}) \cdot (\mathbf{I}_{t_0+t_1} \otimes \mathbf{A})(\begin{pmatrix}\mathbf{I}_{t_0} \\ \mathbf{0}\end{pmatrix} \otimes \mathbf{I}_m)(\mathbf{N}^\mathsf{T} \otimes \mathbf{I}_m) + \mathbf{e}_b^\mathsf{T} \bmod q \\
&= (\mathbf{s}_0^\mathsf{T}, \mathbf{s}_1^\mathsf{T}) \cdot (\begin{pmatrix}\mathbf{I}_{t_0} \\ \mathbf{0}\end{pmatrix} \otimes \mathbf{I}_n)(\mathbf{I}_{t_0} \otimes \mathbf{A})(\mathbf{N}^\mathsf{T} \otimes \mathbf{I}_m) + \mathbf{e}_b^\mathsf{T} \quad = \mathbf{s}_0^\mathsf{T} \cdot (\mathbf{I}_{t_0} \otimes \mathbf{A})(\mathbf{N}^\mathsf{T} \otimes \mathbf{I}_m) + \mathbf{e}_b^\mathsf{T} \bmod q,
\end{aligned}$$

where in the last two lines we use the mixed-product property of the Kronecker product, and

$$\begin{aligned}
\mathbf{c}^\mathsf{T} &\equiv \left((\mathbf{s}_0^\mathsf{T}, \mathbf{s}_1^\mathsf{T}) \cdot (\mathbf{I}_{t_0+t_1} \otimes \mathbf{A}) + \bar{\mathbf{e}}^\mathsf{T}\right) \mathbf{Z}_c - (\bar{\mathbf{e}}^\mathsf{T}\mathbf{Z}_c - \mathbf{e}_c^\mathsf{T}) \bmod q \\
&= (\mathbf{s}_0^\mathsf{T}, \mathbf{s}_1^\mathsf{T}) \cdot (\mathbf{I}_{t_0+t_1} \otimes \mathbf{A})\mathbf{Z}_c + \mathbf{e}_c^\mathsf{T} \bmod q \\
&= (\mathbf{s}_0^\mathsf{T}, \mathbf{s}_1^\mathsf{T}) \cdot (\mathbf{I}_{t_0+t_1} \otimes \mathbf{A})(\mathbf{M}_{0,1}^\mathsf{T} \otimes \mathbf{X}) + \mathbf{e}_c^\mathsf{T} \bmod q,
\end{aligned}$$

identical to the LWE samples in the LHS distribution in Eq. (4).

Else, if $\mathcal{B}$ is interacting with experiment 1 of the LLWE problem, then $\bar{\mathbf{b}}^\mathsf{T}$ is uniformly random. Therefore the outputs of $\mathcal{B}$ are

$$\begin{aligned}
\mathbf{b}^\mathsf{T} &\equiv \bar{\mathbf{b}}^\mathsf{T}\mathbf{Z}_b - (\bar{\mathbf{e}}^\mathsf{T}\mathbf{Z}_b - \mathbf{e}_b^\mathsf{T}) = (\bar{\mathbf{b}} - \bar{\mathbf{e}})^\mathsf{T}\mathbf{Z}_b + \mathbf{e}_b^\mathsf{T} \equiv \bar{\mathbf{s}}^\mathsf{T} \cdot (\begin{pmatrix}\mathbf{N}^\mathsf{T} \\ \mathbf{0}\end{pmatrix} \otimes \mathbf{I}_m) + \mathbf{e}_b^\mathsf{T} = \bar{\mathbf{s}}_0^\mathsf{T} \cdot (\mathbf{N}^\mathsf{T} \otimes \mathbf{I}_m) + \mathbf{e}_b^\mathsf{T} \bmod q, \\
\mathbf{c}^\mathsf{T} &\equiv \bar{\mathbf{b}}^\mathsf{T}\mathbf{Z}_c - (\bar{\mathbf{e}}^\mathsf{T}\mathbf{Z}_c - \mathbf{e}_c^\mathsf{T}) = (\bar{\mathbf{b}} - \bar{\mathbf{e}})^\mathsf{T}\mathbf{Z}_c + \mathbf{e}_c^\mathsf{T} \equiv \bar{\mathbf{s}}^\mathsf{T} \cdot (\mathbf{M}_{0,1}^\mathsf{T} \otimes \mathbf{X}) + \mathbf{e}_c^\mathsf{T} \bmod q
\end{aligned}$$

for some uniformly random $\bar{\mathbf{s}} = \begin{pmatrix}\bar{\mathbf{s}}_0 \\ \bar{\mathbf{s}}_1\end{pmatrix} \hookleftarrow \mathcal{R}_q^{m(t_0+t_1)}$, identical to the LWE samples in the RHS distribution in Eq. (4). The second $\equiv$ holds because $\bar{\mathbf{b}}$, therefore also $\bar{\mathbf{b}} - \bar{\mathbf{e}}$, is uniformly randomly distributed.

Finally, the matrix $\mathbf{Z}$ chosen by $\mathcal{B}$ is admissible since the norm of $\mathbf{Z}$ is bounded by

$$\begin{aligned}
\|\mathbf{Z}\| &= \left\| \left(\begin{pmatrix}\mathbf{N}^\mathsf{T} \\ \mathbf{0}\end{pmatrix} \otimes \mathbf{I}_m,\ \mathbf{M}_{0,1}^\mathsf{T} \otimes \mathbf{X} \right) \right\| \\
&\leq \left\| \begin{pmatrix}\mathbf{N}^\mathsf{T} \\ \mathbf{0}\end{pmatrix} \otimes \mathbf{I}_m \right\| + \left\| \mathbf{M}_{0,1}^\mathsf{T} \otimes \mathbf{X} \right\| \quad \leq \|\mathbf{N}\| + \|\mathbf{M}_{0,1}\|\|\mathbf{X}\| \quad \leq \beta,
\end{aligned}$$

where we use the inequalities $\|(\mathbf{A}, \mathbf{B})\| \leq \|\mathbf{A}\| + \|\mathbf{B}\|$ and $\|\mathbf{A} \otimes \mathbf{B}\| \leq \|\mathbf{A}\|\|\mathbf{B}\|$ for any matrices $\mathbf{A}, \mathbf{B}$. The claim follows.

To show the claimed indistinguishability under the second set of parameters, we directly show that Eq. (4) holds under the $\mathsf{LWE}_{\mathcal{R},n,m,q,\chi^*,\mathcal{D}_\mathbb{A}}$ assumption. We make the following sequence of hybrids (with mod q implicit and changes highlighted):

$$\begin{aligned}
&\text{LHS} \\
&= \left(\mathbf{A},\quad \mathbf{s}_0^\mathsf{T} \cdot (\mathbf{I}_{t_0} \otimes \mathbf{A})(\mathbf{N}^\mathsf{T} \otimes \mathbf{I}_m) + \mathbf{e}_b^\mathsf{T},\quad (\mathbf{s}_0^\mathsf{T}, \mathbf{s}_1^\mathsf{T}) \cdot (\mathbf{I}_{t_0+t_1} \otimes \mathbf{A})(\mathbf{M}_{0,1}^\mathsf{T} \otimes \mathbf{X}) + \mathbf{e}_c^\mathsf{T}\right) \\
&= \left(\mathbf{A},\quad (\hat{\mathbf{s}}_1^\mathsf{T}, \ldots, \hat{\mathbf{s}}_{t_0}^\mathsf{T}) \cdot (\mathbf{I}_{t_0} \otimes \mathbf{A})(\mathbf{N}^\mathsf{T} \otimes \mathbf{I}_m) + \mathbf{e}_b^\mathsf{T},\quad (\hat{\mathbf{s}}_1^\mathsf{T}, \ldots, \hat{\mathbf{s}}_{t_0+t_1}^\mathsf{T}) \cdot (\mathbf{I}_{t_0+t_1} \otimes \mathbf{A})(\mathbf{M}_{0,1}^\mathsf{T} \otimes \mathbf{X}) + \mathbf{e}_c^\mathsf{T}\right) \\
&\quad /\!/ \text{ express } \mathbf{s}_0 \text{ and } \mathbf{s}_1 \text{ as concatenation of uniform } \hat{\mathbf{s}}_i \hookleftarrow \mathcal{R}_q^n \\
&= \left(\mathbf{A},\quad (\hat{\mathbf{s}}_1^\mathsf{T}\mathbf{A}, \ldots, \hat{\mathbf{s}}_{t_0}^\mathsf{T}\mathbf{A}) \cdot (\mathbf{N}^\mathsf{T} \otimes \mathbf{I}_m) + \mathbf{e}_b^\mathsf{T},\quad (\hat{\mathbf{s}}_1^\mathsf{T}\mathbf{A}, \ldots, \hat{\mathbf{s}}_{t_0+t_1}^\mathsf{T}\mathbf{A}) \cdot (\mathbf{M}_{0,1}^\mathsf{T} \otimes \mathbf{X}) + \mathbf{e}_c^\mathsf{T}\right) \\
&\approx_s \left(\mathbf{A},\quad \left(\hat{\mathbf{s}}_1^\mathsf{T}\mathbf{A}+\hat{\mathbf{e}}_1^\mathsf{T}, \ldots, \hat{\mathbf{s}}_{t_0}^\mathsf{T}\mathbf{A}\right) \cdot (\mathbf{N}^\mathsf{T} \otimes \mathbf{I}_m) + \mathbf{e}_b^\mathsf{T},\quad \left(\hat{\mathbf{s}}_1^\mathsf{T}\mathbf{A}+\hat{\mathbf{e}}_1^\mathsf{T}, \ldots, \hat{\mathbf{s}}_{t_0+t_1}^\mathsf{T}\mathbf{A}\right) \cdot (\mathbf{M}_{0,1}^\mathsf{T} \otimes \mathbf{X}) + \mathbf{e}_c^\mathsf{T}\right) \qquad (5) \\
&\quad /\!/ \text{ where } \hat{\mathbf{e}}_1 \hookleftarrow D_{\mathcal{R},\chi^*}^m
\end{aligned}$$

$$
\begin{aligned}
&\approx_c \left(\mathbf{A},\quad \left(\bar{\mathbf{s}}_1^{\mathsf{T}},\ \hat{\mathbf{s}}_2^{\mathsf{T}}\mathbf{A},\ldots,\hat{\mathbf{s}}_{t_0}^{\mathsf{T}}\mathbf{A}\right)\cdot(\mathbf{N}^{\mathsf{T}}\otimes\mathbf{I}_m)+\mathbf{e}_b^{\mathsf{T}},\quad \left(\bar{\mathbf{s}}_1^{\mathsf{T}},\ \tilde{\mathbf{s}}_2^{\mathsf{T}}\mathbf{A},\ldots,\hat{\mathbf{s}}_{t_0+t_1}^{\mathsf{T}}\mathbf{A}\right)\cdot(\mathbf{M}_{0,1}^{\mathsf{T}}\otimes\mathbf{X})+\mathbf{e}_c^{\mathsf{T}}\right) \qquad (6)\\
&\quad /\!/ \text{ swap } \hat{\mathbf{s}}_1^{\mathsf{T}}\mathbf{A}+\hat{\mathbf{e}}_1^{\mathsf{T}} \text{ to uniform } \tilde{\mathbf{s}}_1 \leftarrow\!\$\ \mathcal{R}_q^m\\
&\quad \vdots\\
&\approx_c \left(\mathbf{A},\quad (\tilde{\mathbf{s}}_1^{\mathsf{T}},\ldots,\tilde{\mathbf{s}}_{t_0}^{\mathsf{T}})\cdot(\mathbf{N}^{\mathsf{T}}\otimes\mathbf{I}_m)+\mathbf{e}_b^{\mathsf{T}},\quad (\tilde{\mathbf{s}}_1^{\mathsf{T}},\ldots,\tilde{\mathbf{s}}_{t_0+t_1}^{\mathsf{T}})\cdot(\mathbf{M}_{0,1}^{\mathsf{T}}\otimes\mathbf{X})+\mathbf{e}_c^{\mathsf{T}}\right) \quad /\!/ \ \tilde{\mathbf{s}}_i \leftarrow\!\$\ \mathcal{R}_q^m \text{ all uniform}\\
&= \left(\mathbf{A},\quad \bar{\mathbf{s}}_0^{\mathsf{T}}\cdot(\mathbf{N}^{\mathsf{T}}\otimes\mathbf{I}_m)+\mathbf{e}_b^{\mathsf{T}},\quad (\bar{\mathbf{s}}_0^{\mathsf{T}},\bar{\mathbf{s}}_1^{\mathsf{T}})\cdot(\mathbf{M}_{0,1}^{\mathsf{T}}\otimes\mathbf{X})+\mathbf{e}_c^{\mathsf{T}}\right)\\
&\quad /\!/ \text{ express } (\tilde{\mathbf{s}}_1^{\mathsf{T}},\ldots,\tilde{\mathbf{s}}_{t_0}^{\mathsf{T}}) \text{ and } (\tilde{\mathbf{s}}_1^{\mathsf{T}},\ldots,\tilde{\mathbf{s}}_{t_0+t_1}^{\mathsf{T}}) \text{ as uniform } \bar{\mathbf{s}}_0^{\mathsf{T}} \text{ and } (\bar{\mathbf{s}}_0^{\mathsf{T}},\bar{\mathbf{s}}_1^{\mathsf{T}})\\
&= \text{RHS}.
\end{aligned}
$$

In the above, the $\vdots$ refers to looping the hops in Eqs. (5) and (6) (which are for index $i=1$) through all $i\in[t_0+t_1]$. That is, for each i, introduce an error $\hat{\mathbf{e}}_i \leftarrow\!\$\ D^m_{\mathcal{R},\chi^*}$, then swap $\hat{\mathbf{s}}_i^{\mathsf{T}}\mathbf{A}+\hat{\mathbf{e}}_i^{\mathsf{T}} \bmod q$ to a uniform $\tilde{\mathbf{s}}_i \leftarrow\!\$\ \mathcal{R}_q^m$.

Each of the $\approx_s$ holds by noise-flooding (Lemma 7), which uses the guarantees that $\|\hat{\mathbf{e}}_i\| \le \chi^*\sqrt{m}$ with overwhelming probability by standard tail bound (Lemma 6), and

$$
\begin{aligned}
\lambda^{\omega(1)}\cdot\left\|(\mathbf{0}^{\mathsf{T}},\hat{\mathbf{e}}_i^{\mathsf{T}},\mathbf{0}^{\mathsf{T}})\cdot(\mathbf{N}^{\mathsf{T}}\otimes\mathbf{I}_m)\right\| &\le \lambda^{\omega(1)}\cdot\chi^*\sqrt{m}\cdot\left\|\mathbf{N}^{\mathsf{T}}\right\| < \chi,\\
\lambda^{\omega(1)}\cdot\left\|(\mathbf{0}^{\mathsf{T}},\hat{\mathbf{e}}_i^{\mathsf{T}},\mathbf{0}^{\mathsf{T}})\cdot(\mathbf{M}_{0,1}^{\mathsf{T}}\otimes\mathbf{X})\right\| &\le \lambda^{\omega(1)}\cdot\chi^*\sqrt{m}\cdot\left\|\mathbf{M}_{0,1}^{\mathsf{T}}\right\|\|\mathbf{X}\| < \chi.
\end{aligned}
$$

Each of the $\approx_c$ follows directly from the $\mathsf{LWE}_{\mathcal{R},n,m,q,\chi^*,\mathcal{D}_{\mathtt{A}}}$ assumption.

Proposition 1. *Let $\mathcal{R},n,m,k,q,\bar{\chi},\chi,\mathcal{D}_{\mathtt{A}}$ be parametrised by λ, where $\mathcal{D}_{\mathtt{A}}$ is a distribution over $\mathcal{R}_q^{n\times m}$. Let $t\in\mathsf{poly}(\lambda)$, $\mathcal{L}=\left\{\mathbf{Z}\in\mathcal{R}^{m\times k}:\|\mathbf{Z}\|\le\beta\right\}$, and $\mathcal{L}^*=\left\{\mathbf{Z}\in\mathcal{R}^{mt\times k}:\|\mathbf{Z}\|\le\beta\right\}$, define the distribution $\mathcal{D}^*=\mathbf{I}_t\times\mathcal{D}_{\mathtt{A}}$. Let*

$$
\mathsf{params}=(\mathcal{R},n,m,k,q,\bar{\chi},\chi,\mathcal{L},\mathcal{D}_{\mathtt{A}}),\qquad \mathsf{params}^*=(\mathcal{R},nt,mt,k,q,\bar{\chi},\chi,\mathcal{L}^*,\mathcal{D}^*).
$$

If the $\mathsf{LLWE}_{\mathsf{params}}$ assumption holds, then the $\mathsf{LLWE}_{\mathsf{params}^*}$ assumption holds.

Proof. We observe that in the $\mathsf{LLWE}_{\mathsf{params}^*}$ experiment, LWE samples w.r.t. a matrix $\mathbf{I}_t\otimes\mathbf{A}$ is same as t independent LWE samples w.r.t. $\mathbf{A}$, and the leakage vector $\mathbf{l}$ can be expressed as a sum of t leakages. We will make t hybrids, each swapping one of the t samples to random, assuming $\mathsf{LLWE}_{\mathsf{params}}$.

For each $i\in\{0,1,\ldots,t\}$, define the following i-th hybrid experiment:

$\mathsf{Exp}_i(1^\lambda)$

$\mathbf{A}\leftarrow\mathcal{D}_{\mathtt{A}}$

$\mathbf{Z}\leftarrow\mathcal{A}(\mathbf{A})$; **assert** $\mathbf{Z}\in\mathcal{L}^*$

for $k\in[t]$ **do** $\bar{\mathbf{e}}_k\leftarrow\!\$\ D^m_{\mathcal{R},\bar{\chi}}$

for $k\in[1,\ldots,i]$ **do** $\mathbf{b}_k\leftarrow\!\$\ \mathcal{R}_q^m$

for $k\in[i+1,\ldots,t]$ **do** $\mathbf{r}_k\leftarrow\!\$\ \mathcal{R}_q^n$; $\mathbf{b}_k^{\mathsf{T}}\coloneqq\mathbf{r}_k^{\mathsf{T}}\mathbf{A}+\bar{\mathbf{e}}_k^{\mathsf{T}} \bmod q$

$\mathbf{b}^{\mathsf{T}}\coloneqq(\mathbf{b}_1^{\mathsf{T}},\ldots,\mathbf{b}_k^{\mathsf{T}})$; $\bar{\mathbf{e}}^{\mathsf{T}}\coloneqq(\bar{\mathbf{e}}_1^{\mathsf{T}},\ldots,\bar{\mathbf{e}}_t^{\mathsf{T}})$

parse $\begin{pmatrix}\mathbf{Z}_1\\ \vdots\\ \mathbf{Z}_t\end{pmatrix}\leftarrow\mathbf{Z}$; $\mathbf{e}\leftarrow\!\$\ D^k_{\mathcal{R},\chi}$; $\mathbf{l}^{\mathsf{T}}\coloneqq\sum_{k\in[t]}\bar{\mathbf{e}}_k^{\mathsf{T}}\cdot\mathbf{Z}_k+\mathbf{e}^{\mathsf{T}}$

return $\mathcal{A}(\mathbf{b},\mathbf{l})$

It is direct to verify that the 0-th hybrid is identical to the $\mathsf{LLWE}_{\mathsf{params}^*}$ experiment 0, as

$$
\begin{aligned}
\mathbf{b}^{\mathsf{T}} &= (\mathbf{r}_1^{\mathsf{T}}\mathbf{A}+\bar{\mathbf{e}}_1^{\mathsf{T}},\ \ldots,\ \mathbf{r}_t^{\mathsf{T}}\mathbf{A}+\bar{\mathbf{e}}_t^{\mathsf{T}}) = (\mathbf{r}_1^{\mathsf{T}},\ldots,\mathbf{r}_t^{\mathsf{T}})(\mathbf{I}_t\otimes\mathbf{A})+\bar{\mathbf{e}}^{\mathsf{T}} \bmod q,\\
\mathbf{l}^{\mathsf{T}} &= \textstyle\sum_{k\in[t]}\bar{\mathbf{e}}_k^{\mathsf{T}}\cdot\mathbf{Z}_k+\mathbf{e}^{\mathsf{T}} = \bar{\mathbf{e}}^{\mathsf{T}}\cdot\mathbf{Z}+\mathbf{e}^{\mathsf{T}},
\end{aligned}
$$

and the t-th hybrid is identical to the $\mathsf{LLWE}_{\mathsf{params}^*}$ experiment 1. In the rest we show the $(i-1)$-th and i-th hybrids are computationally indistinguishable under the $\mathsf{LLWE}_{\mathsf{params}}$ assumption, for each $i \in [t]$.

Fix any $i \in [t]$. Given any PPT $\mathcal{A}$ against distinguishing the $(i-1)$-th and i-th hybrids, we construct a PPT $\mathcal{B}$ against $\mathsf{LLWE}_{\mathsf{params}}$. Let $\mathcal{B}$ proceed as follows:

- Receive $\mathbf{A}$ from the $\mathsf{LLWE}_{\mathsf{params}}$ challenger. Pass $\mathbf{A}$ to $\mathcal{A}$, receive from which $\mathbf{Z}$. Assert $\mathbf{Z} \in \mathcal{L}^*$.
- Parse $\begin{pmatrix} \mathbf{Z}_1 \\ \vdots \\ \mathbf{Z}_t \end{pmatrix} \leftarrow \mathbf{Z}$. Send $\mathbf{Z}_i$ to the $\mathsf{LLWE}_{\mathsf{params}}$ challenger, receive the challenge $(\mathbf{b}_i, \mathbf{l}_i)$.
- For each $k \in [1, \ldots, t] \setminus \{i\}$, sample $\bar{\mathbf{e}}_k \leftarrow\!\$\ D^m_{\mathcal{R},\bar{\chi}}$, let $\mathbf{l}_k^\intercal \coloneqq \bar{\mathbf{e}}_k^\intercal \cdot \mathbf{Z}_k$.
- For each $k \in [1, \ldots, i-1]$, sample random $\mathbf{b}_k \leftarrow\!\$\ \mathcal{R}_q^m$.
- For each $k \in [i+1, \ldots, t]$, sample random $\mathbf{r}_k \leftarrow\!\$\ \mathcal{R}_q^n$, set $\mathbf{b}_k^\intercal \coloneqq \mathbf{r}_k^\intercal \mathbf{A} + \bar{\mathbf{e}}_k^\intercal \bmod q$.
- Set $\mathbf{b}^\intercal \coloneqq (\mathbf{b}_1^\intercal, \ldots, \mathbf{b}_k^\intercal)$ and $\mathbf{l} \coloneqq \sum_{k\in[t]} \mathbf{l}_k$. Send $(\mathbf{b}, \mathbf{l})$ to $\mathcal{A}$, and return whatever it returns.

It is direct to see that $\mathcal{B}$ perfectly simulates the view of the $(i-1)$-th and the i-th hybrid to $\mathcal{A}$, if it interacts with the $\mathsf{LLWE}_{\mathsf{params}}$ experiment 0 and 1, respectively. In particular, either $\mathbf{b}_i^\intercal = \mathbf{r}_i^\intercal \mathbf{A} + \bar{\mathbf{e}}_i^\intercal \bmod q$ for random $\mathbf{r}_i \leftarrow\!\$\ \mathcal{R}_q^n$ and error $\bar{\mathbf{e}}_i \leftarrow\!\$\ D^m_{\mathcal{R},\bar{\chi}}$, or $\mathbf{b}_i^\intercal$ is uniformly random. In either case, $\mathbf{l}_i^\intercal = \bar{\mathbf{e}}_i^\intercal \mathbf{Z}_i + \mathbf{e}^\intercal$ for error $\mathbf{e} \leftarrow\!\$\ D^k_{\mathcal{R},\chi}$, hence the simulated leakage vector is

$$\mathbf{l}^\intercal = \textstyle\sum_{k\in[t]} \mathbf{l}_k^\intercal = \sum_{k\in[t]} \bar{\mathbf{e}}_k^\intercal \cdot \mathbf{Z}_k + \mathbf{e}^\intercal.$$

The matrix $\mathbf{Z}_i$ sent from $\mathcal{A}$ to the $\mathsf{LLWE}_{\mathsf{params}}$ challenger is admissible, i.e. $\mathbf{Z}_i \in \mathcal{L}$, since $\mathbf{Z} \in \mathcal{L}^*$ implies $\|\mathbf{Z}\| \le \beta$, and we always have $\|\mathbf{Z}_i\| \le \|\mathbf{Z}\| \le \beta$. □

□

A.5 Proof of Theorem 1

Proof. The statement follows from Lemmas 10 and 11, which we show below. The former says that under the stated conditions, the Threshold-LWE assumption holds under the $\mathsf{LWE}_{\mathcal{R},n,m+Q_{\mathtt{LWE}},q,\chi_1^*,\mathcal{D}_1}$ and $\mathsf{LWE}_{\mathcal{R},m,Q_{\mathtt{ISIS}},q,\chi_2^*,\mathcal{D}_2}$ assumptions. The latter says that the additional random unauthorised shares condition required by the Threshold-$-LWE assumption also holds. The theorem follows from putting the two together.

Lemma 10 (Poly-modulus LWE implies $(Q_{\mathtt{ISIS}}, Q_{\mathtt{LWE}})$-bounded th-LWE). *Let the parameters*

$$\mathsf{params} = ((\mathcal{R}, n, m, q, \mathcal{D}_{\mathtt{A}}, \mathcal{D}_{\mathbf{x}}, \chi), (t, K, \Xi))$$

and χ_1^*, χ_2^* be such that the constraints stated in Theorem 1 are satisfied. The $(Q_{\mathtt{ISIS}}, Q_{\mathtt{LWE}})$-bounded $\mathsf{thLWE}_{\mathsf{params}}$ assumption holds if the $\mathsf{LWE}_{\mathcal{R},n,m+Q_{\mathtt{LWE}},q,\chi_1^*,\mathcal{D}_1}$ and $\mathsf{LWE}_{\mathcal{R},m,Q_{\mathtt{ISIS}},q,\chi_2^*,\mathcal{D}_2}$ assumptions hold.

Proof. We recall some notation in Fig. 3:

- $\mathbf{R} \in \mathcal{R}_q^{t\times n}$ is a matrix with the i-th row (counting from 0) given by $\mathbf{r}_i^\intercal$. The top row is $\mathbf{r}_0^\intercal$ also written as $\mathbf{r}^\intercal$, which can be interpreted as the main LWE secret. The remaining rows can be interpreted as secret-sharing randomness.
- $\mathbf{v}_0^\intercal = (1, 0, \ldots, 0) \in \mathcal{R}^t$ is the first unit vector of dimension t. Note that $\mathbf{r}^\intercal = \mathbf{v}_0^\intercal \mathbf{R} \bmod q$.
- $\mathbf{V} \in \mathcal{R}^{K\times t}$ is the Vandermonde matrix defined by Ξ. Its i-th row (counting from 1) is denoted $\mathbf{v}_i^\intercal$.
- $\mathbf{S} = \mathbf{V}\mathbf{R} \bmod q \in \mathcal{R}_q^{K\times n}$, and its i-th row (counting from 1) is denoted $\mathbf{s}_i^\intercal$. For any $i \in [n]$, $\mathbf{s}_i$ can be interpreted as Shamir's secret shares of $\mathbf{r}$.
- For any subset $\mathcal{C} \subseteq [K]$, $\mathbf{V}_\mathcal{C} \in \mathcal{R}^{|\mathcal{C}|\times t}$ is the submatrix of $\mathbf{V}$ whose rows are indexed by $\mathcal{C}$. Similarly, $\mathbf{S}_\mathcal{C} \in \mathcal{R}_q^{|\mathcal{C}|\times n}$ is the submatrix of $\mathbf{S}$ whose rows are indexed by $\mathcal{C}$.

For any set $\mathcal{C} \subset [K]$ of corrupt parties with $|\mathcal{C}| < t$, we further define:

$\mathsf{Hyb}[D](1^\lambda)$

$L_{\mathsf{Query}}[\cdot] \coloneqq \emptyset;\ L_{\mathsf{Share}}[\cdot] \coloneqq \emptyset$

$\mathbf{A} \leftarrow\!\!\$\ \mathcal{D}_{\mathtt{A}};\quad \mathbf{X} \leftarrow\!\!\$\ \mathcal{D}_{\mathtt{x}}^{Q_{\mathtt{ISIS}}};\quad \mathbf{Y} \leftarrow\!\!\$\ \mathcal{R}_q^{n \times Q_{\mathtt{LWE}}}$

$\mathcal{C} \leftarrow \mathcal{A}(\mathbf{A})$; **assert** $|\mathcal{C}| < t$

$(\mathbf{b}, \mathbf{C}, \mathbf{D}, \mathbf{z}, \mathbf{S}_{\mathcal{C}}) \leftarrow D(\mathcal{C}, \mathbf{A}, \mathbf{X}, \mathbf{Y})$

parse $\mathbf{X} = (\mathbf{x}_i)_{i \in [Q_{\mathtt{ISIS}}]}$

parse $\mathbf{Y} = (\mathbf{y}_i)_{i \in [Q_{\mathtt{LWE}}]}$

parse $\mathbf{z} = (z_i)_{i \in [Q_{\mathtt{LWE}}]}$

parse $\left[\mathbf{C}\ \mathbf{D}\right] = \left[\mathbf{c}_1\ \ldots\ \mathbf{c}_{Q_{\mathtt{ISIS}}} \middle| \mathbf{d}_1\ \ldots\ \mathbf{d}_{Q_{\mathtt{LWE}}}\right]$

for $i \in [Q_{\mathtt{ISIS}}]:\ L_{\mathtt{ISIS}}[\mathbf{A}\mathbf{x}_i] \coloneqq \mathbf{c}_i$

for $i \in [Q_{\mathtt{LWE}}]:\ L_{\mathtt{LWE}}[\mathbf{y}_i] \coloneqq \mathbf{d}_i$

$b' \leftarrow \mathcal{A}^{\mathsf{HybLWE},\mathsf{HybISIS},\mathsf{ShareLWE},\mathsf{ShareISIS}}(\mathbf{b}, \mathbf{S}_{\mathcal{C}})$

return b'

$\mathsf{HybISIS}()$

On i-th query :

return $(\mathbf{x}_i, \mathbf{A}\mathbf{x}_i \bmod q)$

$\mathsf{HybLWE}()$

On i-th query :

return $(\mathbf{y}_i, z_i)$

Fig. 8: Hybrid experiment $\mathsf{Hyb}[D]$ parametrised by distribution D. $\mathsf{Hyb}[D_0]$ and $\mathsf{Hyb}[D_4]$ are functionally equivalent to $\mathsf{Real\text{-}thLWE}_{\mathsf{params},\mathcal{A},\mathcal{S}}$ and $\mathsf{Ideal\text{-}thLWE}_{\mathsf{params},\mathcal{A},\mathcal{S}}$ in Fig. 3 respectively. HybLWE plays the role of GenLWE and SimLWE. HybISIS plays the role of GenISIS and SimISIS. ShareLWE and ShareISIS are defined in Fig. 3.

- $\mathcal{H} \coloneqq [K] \setminus \mathcal{C}$ the set of honest (i.e. non-corrupt) parties, and
- $\mathbf{T}_{\mathcal{C}} \in \mathcal{R}^{t \times t}$ a matrix such that it holds $\xi^{-1} \cdot \mathbf{T}_{\mathcal{C}} \cdot \mathbf{V}_{T^*} = \mathbf{I}_t$ for some size-t set T^* satisfying $(\{0\} \cup \mathcal{C}) \subseteq T^* \subseteq [0, K]$. ($\mathbf{T}_{\mathcal{C}}$ is not unique given $\mathcal{C}$ and we may fix an arbitrary one.) Such $\mathbf{T}_{\mathcal{C}}$ is same as that in Eq. (2).

We begin with defining experiment $\mathsf{Hyb}[D]$ in Fig. 8, whose code depends on the distribution D. We also define the hybrid distributions D_i for $i \in \{0, 1, 2, 3, 4\}$ in Fig. 9. Below we overview $\mathsf{Hyb}[D_i]$ for $i \in \{0, 1, 2, 3, 4\}$.

$\mathsf{Hyb}[D_0]$. It can be verified by direct inspection that $\mathsf{Hyb}[D_0]$ is identical to $\mathsf{Real\text{-}thLWE}_{\mathsf{params},\mathcal{A},\mathcal{S}}$ defined in Fig. 3. In particular, in $\mathsf{Hyb}[D_0]$, we concatenate the oracle answers $\mathbf{x}$'s and $\mathbf{y}$'s into matrices $\mathbf{X}$ and $\mathbf{Y}$ respectively, and we concatenate the ShareISIS and ShareLWE oracle answers $\mathbf{c}$'s and $\mathbf{d}$'s into matrices $\mathbf{C}$ and $\mathbf{D}$ respectively.

$\mathsf{Hyb}[D_1]$. This is functionally equivalent to $\mathsf{Hyb}[D_0]$. Notice that the matrix $\mathbf{V}$ equals $\begin{bmatrix}\mathbf{V}_{\mathcal{H}} \\ \mathbf{V}_{\mathcal{C}}\end{bmatrix}$ by definition, thus the only differences between D_0 and D_1 is that we swap

$$\begin{bmatrix}\mathbf{v}_0^{\mathsf{T}} \\ \mathbf{V}\end{bmatrix}\mathbf{R} = \begin{bmatrix}\mathbf{v}_0^{\mathsf{T}} \\ \mathbf{V}_{\mathcal{H}} \\ \mathbf{V}_{\mathcal{C}}\end{bmatrix}\mathbf{R} \qquad \text{to} \qquad \left[\begin{array}{c|c|c} \xi & & \\ \hline \multicolumn{3}{c}{\mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}}} \\ \hline & & \xi\mathbf{I}_{\mathcal{C}} \end{array}\right]\begin{bmatrix}\mathbf{r}^{\mathsf{T}} \\ \mathbf{W} \\ \mathbf{S}_{\mathcal{C}}\end{bmatrix},$$

where on the RHS the matrix $\begin{bmatrix}\mathbf{r}^{\mathsf{T}} \\ \mathbf{W} \\ \mathbf{S}_{\mathcal{C}}\end{bmatrix}$ is uniform, and we recall $\mathbf{T}_{\mathcal{C}} \in \mathcal{R}^{t \times t}$ is such that it holds $\xi^{-1} \cdot \mathbf{T}_{\mathcal{C}} \cdot \mathbf{V}_{T^*} = \mathbf{I}_t$ for some size-t set T^* satisfying $(\{0\} \cup \mathcal{C}) \subseteq T^* \subseteq [K]$. To see that the two terms are functionally equivalent,

$D_0(\mathcal{C}, \mathbf{A}, \mathbf{X}, \mathbf{Y})$

$\mathbf{R} \leftarrow\!\$\ \mathcal{R}_q^{t\times n};\ \begin{bmatrix} \mathbf{e}^\mathsf{T} & * & \mathbf{e}_{\mathtt{LWE}}^\mathsf{T} \\ * & \mathbf{E}_{\mathtt{ISIS}} & \mathbf{E}_{\mathtt{LWE}} \end{bmatrix} \leftarrow\!\$\ D_{\mathcal{R},\chi}^{(1+K)\times(m+Q_{\mathtt{ISIS}}+Q_{\mathtt{LWE}})}$

$\begin{bmatrix}\mathbf{b}^\mathsf{T} & \mathbf{z}^\mathsf{T}\end{bmatrix} \coloneqq \mathbf{v}_0^\mathsf{T}\mathbf{R}\begin{bmatrix}\mathbf{A} & \mathbf{Y}\end{bmatrix} + \begin{bmatrix}\mathbf{e}^\mathsf{T} & \mathbf{e}_{\mathtt{LWE}}^\mathsf{T}\end{bmatrix} \bmod q \in \mathcal{R}_q^{m+Q_{\mathtt{LWE}}}$

$\begin{bmatrix}\mathbf{C} & \mathbf{D}\end{bmatrix} \coloneqq \mathbf{V}\mathbf{R}\begin{bmatrix}\mathbf{A}\mathbf{X} & \mathbf{Y}\end{bmatrix} + \begin{bmatrix}\mathbf{E}_{\mathtt{ISIS}} & \mathbf{E}_{\mathtt{LWE}}\end{bmatrix} \bmod q \in \mathcal{R}_q^{K\times(Q_{\mathtt{ISIS}}+Q_{\mathtt{LWE}})}$

$\mathbf{S}_\mathcal{C} \coloneqq \mathbf{V}_\mathcal{C}\mathbf{R} \bmod q \in \mathcal{R}_q^{\mathcal{C}\times n}$

return $(\mathbf{b}, \mathbf{C}, \mathbf{D}, \mathbf{z}, \mathbf{S}_\mathcal{C})$

$D_1(\mathcal{C}, \mathbf{A}, \mathbf{X}, \mathbf{Y})$

$\begin{bmatrix}\mathbf{r}^\mathsf{T} \\ \mathbf{W} \\ \mathbf{S}_\mathcal{C}\end{bmatrix} \leftarrow\!\$\ \mathcal{R}_q^{t\times n};\ \begin{bmatrix} \mathbf{e}^\mathsf{T} & * & \mathbf{e}_{\mathtt{LWE}}^\mathsf{T} \\ * & \mathbf{E}_{\mathtt{ISIS}} & \mathbf{E}_{\mathtt{LWE}} \end{bmatrix} \leftarrow\!\$\ D_{\mathcal{R},\chi}^{(1+K)\times(m+Q_{\mathtt{ISIS}}+Q_{\mathtt{LWE}})}$

$\begin{bmatrix}\mathbf{b}^\mathsf{T} & \mathbf{z}^\mathsf{T}\end{bmatrix} \coloneqq \xi\cdot\mathbf{r}^\mathsf{T}\begin{bmatrix}\mathbf{A} & \mathbf{Y}\end{bmatrix} + \begin{bmatrix}\mathbf{e}^\mathsf{T} & \mathbf{e}_{\mathtt{LWE}}^\mathsf{T}\end{bmatrix} \bmod q \in \mathcal{R}_q^{m+Q_{\mathtt{LWE}}}$

$\begin{bmatrix}\mathbf{C} & \mathbf{D}\end{bmatrix} \coloneqq \left[\begin{array}{c|c} \mathbf{V}_\mathcal{H}\cdot\mathbf{T}_\mathcal{C} & \\ \hline & \xi\mathbf{I}_\mathcal{C}\end{array}\right]\begin{bmatrix}\mathbf{r}^\mathsf{T} \\ \mathbf{W} \\ \mathbf{S}_\mathcal{C}\end{bmatrix}\begin{bmatrix}\mathbf{A} & \mathbf{Y}\end{bmatrix}\begin{bmatrix}\mathbf{X} & \\ & \mathbf{I}_{Q_{\mathtt{LWE}}}\end{bmatrix} + \begin{bmatrix}\mathbf{E}_{\mathtt{ISIS}} & \mathbf{E}_{\mathtt{LWE}}\end{bmatrix} \bmod q \in \mathcal{R}_q^{K\times(Q_{\mathtt{ISIS}}+Q_{\mathtt{LWE}})}$

return $(\mathbf{b}, \mathbf{C}, \mathbf{D}, \mathbf{z}, \mathbf{S}_\mathcal{C})$

$D_2(\mathcal{C}, \mathbf{A}, \mathbf{X}, \mathbf{Y})$

$\mathbf{S}_\mathcal{C} \leftarrow\!\$\ \mathcal{R}_q^{\mathcal{C}\times n};\ \begin{bmatrix}\mathbf{r}_m^\mathsf{T} & \mathbf{r}_{\mathtt{LWE}}^\mathsf{T} \\ \mathbf{W}_m & \mathbf{W}_{\mathtt{LWE}}\end{bmatrix} \leftarrow\!\$\ \mathcal{R}_q^{(t-|\mathcal{C}|)\times(m+Q_{\mathtt{LWE}})};\ \begin{bmatrix} \mathbf{e}^\mathsf{T} & * & \mathbf{e}_{\mathtt{LWE}}^\mathsf{T} \\ * & \mathbf{E}_{\mathtt{ISIS}} & \mathbf{E}_{\mathtt{LWE}} \end{bmatrix} \leftarrow\!\$\ D_{\mathcal{R},\chi}^{(1+K)\times(m+Q_{\mathtt{ISIS}}+Q_{\mathtt{LWE}})}$

$\begin{bmatrix}\mathbf{b}^\mathsf{T} & \mathbf{z}^\mathsf{T}\end{bmatrix} \coloneqq \xi\cdot\begin{bmatrix}\mathbf{r}_m^\mathsf{T} & \mathbf{r}_{\mathtt{LWE}}^\mathsf{T}\end{bmatrix} + \begin{bmatrix}\mathbf{e}^\mathsf{T} & \mathbf{e}_{\mathtt{LWE}}^\mathsf{T}\end{bmatrix} \bmod q \in \mathcal{R}_q^{m+Q_{\mathtt{LWE}}}$

$\begin{bmatrix}\mathbf{C} & \mathbf{D}\end{bmatrix} \coloneqq \left[\begin{array}{c|c} \mathbf{V}_\mathcal{H}\cdot\mathbf{T}_\mathcal{C} & \\ \hline & \xi\mathbf{I}_\mathcal{C}\end{array}\right]\begin{bmatrix}\mathbf{r}_m^\mathsf{T} & \mathbf{r}_{\mathtt{LWE}}^\mathsf{T} \\ \mathbf{W}_m & \mathbf{W}_{\mathtt{LWE}} \\ \mathbf{S}_\mathcal{C}\mathbf{A} & \mathbf{S}_\mathcal{C}\mathbf{Y}\end{bmatrix}\begin{bmatrix}\mathbf{X} & \\ & \mathbf{I}_{Q_{\mathtt{LWE}}}\end{bmatrix} + \begin{bmatrix}\mathbf{E}_{\mathtt{ISIS}} & \mathbf{E}_{\mathtt{LWE}}\end{bmatrix} \bmod q \in \mathcal{R}_q^{K\times(Q_{\mathtt{ISIS}}+Q_{\mathtt{LWE}})}$

return $(\mathbf{b}, \mathbf{C}, \mathbf{D}, \mathbf{z}, \mathbf{S}_\mathcal{C})$

$D_3(\mathcal{C}, \mathbf{A}, \mathbf{X}, \mathbf{Y})$

$\mathbf{S}_\mathcal{C} \leftarrow\!\$\ \mathcal{R}_q^{\mathcal{C}\times n};\ \begin{bmatrix}\mathbf{r}_m^\mathsf{T} & * & \mathbf{r}_{\mathtt{LWE}}^\mathsf{T} \\ * & \mathbf{W}_{\mathtt{ISIS}} & \mathbf{W}_{\mathtt{LWE}}\end{bmatrix} \leftarrow\!\$\ \mathcal{R}_q^{(t-|\mathcal{C}|)\times(m+Q_{\mathtt{ISIS}}+Q_{\mathtt{LWE}})};\ \begin{bmatrix} \mathbf{e}^\mathsf{T} & * & \mathbf{e}_{\mathtt{LWE}}^\mathsf{T} \\ * & \mathbf{E}_{\mathtt{ISIS}} & \mathbf{E}_{\mathtt{LWE}} \end{bmatrix} \leftarrow\!\$\ D_{\mathcal{R},\chi}^{(1+K)\times(m+Q_{\mathtt{ISIS}}+Q_{\mathtt{LWE}})}$

$\begin{bmatrix}\mathbf{b}^\mathsf{T} & \mathbf{z}^\mathsf{T}\end{bmatrix} \coloneqq \xi\cdot\begin{bmatrix}\mathbf{r}_m^\mathsf{T} & \mathbf{r}_{\mathtt{LWE}}^\mathsf{T}\end{bmatrix} + \begin{bmatrix}\mathbf{e}^\mathsf{T} & \mathbf{e}_{\mathtt{LWE}}^\mathsf{T}\end{bmatrix} \bmod q \in \mathcal{R}_q^{m+Q_{\mathtt{LWE}}}$

$\begin{bmatrix}\mathbf{C} & \mathbf{D}\end{bmatrix} \coloneqq \left[\begin{array}{c|c} \mathbf{V}_\mathcal{H}\cdot\mathbf{T}_\mathcal{C} & \\ \hline & \xi\mathbf{I}_\mathcal{C}\end{array}\right]\begin{bmatrix}\mathbf{r}_m^\mathsf{T}\mathbf{X} & \mathbf{r}_{\mathtt{LWE}}^\mathsf{T} \\ \mathbf{W}_{\mathtt{ISIS}} & \mathbf{W}_{\mathtt{LWE}} \\ \mathbf{S}_\mathcal{C}\mathbf{A}\mathbf{X} & \mathbf{S}_\mathcal{C}\mathbf{Y}\end{bmatrix} + \begin{bmatrix}\mathbf{E}_{\mathtt{ISIS}} & \mathbf{E}_{\mathtt{LWE}}\end{bmatrix} \bmod q \in \mathcal{R}_q^{K\times(Q_{\mathtt{ISIS}}+Q_{\mathtt{LWE}})}$

return $(\mathbf{b}, \mathbf{C}, \mathbf{D}, \mathbf{z}, \mathbf{S}_\mathcal{C})$

$D_4(\mathcal{C}, \mathbf{A}, \mathbf{X}, \mathbf{Y})$

$\mathbf{S}_\mathcal{C} \leftarrow\!\$\ \mathcal{R}_q^{\mathcal{C}\times n};\ \begin{bmatrix}\mathbf{W}_{\mathtt{ISIS}} & \mathbf{W}_{\mathtt{LWE}}\end{bmatrix} \leftarrow\!\$\ \mathcal{R}_q^{(t-|\mathcal{C}|)\times(Q_{\mathtt{ISIS}}+Q_{\mathtt{LWE}})};\ \begin{bmatrix} \mathbf{e}^\mathsf{T} & * & \mathbf{e}_{\mathtt{LWE}}^\mathsf{T} \\ * & \mathbf{E}_{\mathtt{ISIS}} & \mathbf{E}_{\mathtt{LWE}} \end{bmatrix} \leftarrow\!\$\ D_{\mathcal{R},\chi}^{(1+K)\times(m+Q_{\mathtt{ISIS}}+Q_{\mathtt{LWE}})}$

$\begin{bmatrix}\mathbf{b}^\mathsf{T} & \mathbf{z}^\mathsf{T}\end{bmatrix} \leftarrow\!\$\ \mathcal{R}_q^{m+Q_{\mathtt{LWE}}}$

$\begin{bmatrix}\mathbf{C} & \mathbf{D}\end{bmatrix} \coloneqq \left[\begin{array}{c|c} \mathbf{V}_\mathcal{H}\cdot\mathbf{T}_\mathcal{C} & \\ \hline & \xi\mathbf{I}_\mathcal{C}\end{array}\right]\begin{bmatrix}\xi^{-1}(\mathbf{b}-\mathbf{e})^\mathsf{T}\mathbf{X} & \xi^{-1}(\mathbf{z}-\mathbf{e}_{\mathtt{LWE}})^\mathsf{T} \\ \mathbf{W}_{\mathtt{ISIS}} & \mathbf{W}_{\mathtt{LWE}} \\ \mathbf{S}_\mathcal{C}\mathbf{A}\mathbf{X} & \mathbf{S}_\mathcal{C}\mathbf{Y}\end{bmatrix} + \begin{bmatrix}\mathbf{E}_{\mathtt{ISIS}} & \mathbf{E}_{\mathtt{LWE}}\end{bmatrix} \bmod q \in \mathcal{R}_q^{K\times(Q_{\mathtt{ISIS}}+Q_{\mathtt{LWE}})}$

return $(\mathbf{b}, \mathbf{C}, \mathbf{D}, \mathbf{z}, \mathbf{S}_\mathcal{C})$

Fig. 9: Core distributions D_0, D_1, D_2, D_3 and D_4.

$\mathsf{Ideal\text{-}thLWE}_{\mathsf{params},\mathcal{A},\mathcal{S}}(1^\lambda)$

$L_{\mathtt{LWE}}[\cdot] \coloneqq \emptyset;\ L_{\mathtt{ISIS}}[\cdot] \coloneqq \emptyset$
$\mathbf{A} \leftarrow\!\$\ \mathcal{D}_{\mathtt{A}}$
$\mathcal{C} \leftarrow \mathcal{A}(\mathbf{A});$ **assert** $|\mathcal{C}| < t$
$\mathbf{S}_{\mathcal{C}} \leftarrow\!\$\ \mathcal{R}_q^{\mathcal{C}\times n}$
$\mathbf{b} \leftarrow\!\$\ \mathcal{R}_q^m$
$\mathsf{st} \leftarrow \mathcal{S}_{\mathsf{Init}}(\mathbf{A}, \mathbf{b}, \mathbf{S}_{\mathcal{C}})$
$b' \leftarrow \mathcal{A}^{\mathsf{SimISIS},\mathsf{SimLWE},\mathsf{ShareISIS},\mathsf{ShareLWE}}(\mathbf{b}, \mathbf{S}_{\mathcal{C}})$
assert $|L_{\mathtt{ISIS}}| \le Q_{\mathtt{ISIS}}$
assert $|L_{\mathtt{LWE}}| \le Q_{\mathtt{LWE}}$
return b'

$\mathsf{ShareISIS}(\mathbf{y}, k \in [K])$

parse $\mathbf{c} \leftarrow L_{\mathtt{ISIS}}[\mathbf{y}] \in \mathcal{R}_q^K$
return c_k

$\mathsf{SimISIS}()$

$\mathbf{x} \leftarrow\!\$\ \mathcal{D}_{\mathtt{x}};\quad \mathbf{y} \coloneqq \mathbf{A}\mathbf{x} \bmod q$
$(\mathbf{c}, \mathsf{st}) \leftarrow \mathcal{S}_{\mathsf{ISIS}}(\mathbf{x}, \mathsf{st})$
$L_{\mathtt{ISIS}}[\mathbf{y}] = \mathbf{c}$
return $(\mathbf{x}, \mathbf{y})$

$\mathsf{SimLWE}()$

$\mathbf{y} \leftarrow\!\$\ \mathcal{R}_q^n$
$(z, \mathbf{d}, \mathsf{st}) \leftarrow \mathcal{S}_{\mathsf{LWE}}(\mathbf{y}, \mathsf{st})$
$L_{\mathtt{LWE}}[\mathbf{y}] = \mathbf{d}$
return $(\mathbf{y}, z)$

$\mathsf{ShareLWE}(\mathbf{y}, k \in [K])$

parse $\mathbf{d} \leftarrow L_{\mathtt{LWE}}[\mathbf{y}] \in \mathcal{R}_q^K$
return d_k

$\mathcal{S}_{\mathsf{Init}}(\mathbf{A}, \mathbf{b}, \mathbf{S}_{\mathcal{S}})$

$\mathbf{e} \leftarrow\!\$\ D_{\mathcal{R},\chi}^m;\ \hat{\mathbf{b}} \coloneqq \xi^{-1}(\mathbf{b} - \mathbf{e})$
return $\mathsf{st} \coloneqq (\mathbf{A}, \mathbf{b}, \mathbf{S}_{\mathcal{S}}, \hat{\mathbf{b}})$

$\mathcal{S}_{\mathsf{ISIS}}(\mathbf{x}, \mathsf{st})$

$\mathbf{w}_{\mathtt{ISIS}} \leftarrow\!\$\ \mathcal{R}_q^{t-|\mathcal{C}|};\ \mathbf{e}_{\mathtt{ISIS}} \leftarrow\!\$\ D_{\mathcal{R},\chi}^K$
$\mathbf{c} \coloneqq \left[\begin{array}{c|c|c} \mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}} & & \\ \hline & & \xi\mathbf{I}_{\mathcal{C}} \end{array}\right] \begin{bmatrix} \hat{\mathbf{b}}^{\mathsf{T}}\mathbf{x} \\ \mathbf{w}_{\mathtt{ISIS}} \\ \mathbf{S}_{\mathcal{C}}\mathbf{A}\mathbf{x} \end{bmatrix} + \mathbf{e}_{\mathtt{ISIS}} \bmod q$
return $(\mathbf{c}, \mathsf{st})$

$\mathcal{S}_{\mathsf{LWE}}(\mathbf{y}, \mathsf{st})$

$\mathbf{w}_{\mathtt{LWE}} \leftarrow\!\$\ \mathcal{R}_q^{t-|\mathcal{C}|};\ z \leftarrow\!\$\ \mathcal{R}_q$
$e_{\mathtt{LWE}} \leftarrow\!\$\ D_{\mathcal{R},\chi};\ \mathbf{e}_{\mathtt{LWE}} \leftarrow\!\$\ D_{\mathcal{R},\chi}^K$
$\mathbf{d} \coloneqq \left[\begin{array}{c|c|c} \mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}} & & \\ \hline & & \xi\mathbf{I}_{\mathcal{C}} \end{array}\right] \begin{bmatrix} \xi^{-1}(z - e_{\mathtt{LWE}}) \\ \mathbf{w}_{\mathtt{LWE}} \\ \mathbf{S}_{\mathcal{C}}\mathbf{y} \end{bmatrix} + \mathbf{e}_{\mathtt{LWE}} \bmod q$
return $(z, \mathbf{d}, \mathsf{st})$

Fig. 10: Ideal experiment with simulator $\mathcal{S} = (\mathcal{S}_{\mathsf{Init}}, \mathcal{S}_{\mathsf{ISIS}}, \mathcal{S}_{\mathsf{LWE}})$, equivalent to $\mathsf{Hyb}[D_4]$.

we denote $\bar{\mathcal{C}} \coloneqq T^* \setminus (\{0\} \cup \mathcal{C})$ and notice

$$\begin{bmatrix} \mathbf{v}_0^{\mathsf{T}} \\ \mathbf{V} \end{bmatrix} \mathbf{R} = \begin{bmatrix} \mathbf{v}_0^{\mathsf{T}} \\ \mathbf{V}_{\mathcal{H}} \\ \mathbf{V}_{\mathcal{C}} \end{bmatrix} \mathbf{R} = \left[\begin{array}{c|c|c} 1 & & \\ \hline \xi^{-1} \cdot \mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}} & & \\ \hline & & \mathbf{I}_{\mathcal{C}} \end{array}\right] \underbrace{\begin{bmatrix} \mathbf{v}_0^{\mathsf{T}} \\ \mathbf{V}_{\bar{\mathcal{C}}} \\ \mathbf{V}_{\mathcal{C}} \end{bmatrix}}_{\mathbf{V}_{T^*}} \mathbf{R} \equiv \left[\begin{array}{c|c|c} \xi & & \\ \hline \mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}} & & \\ \hline & & \xi\mathbf{I}_{\mathcal{C}} \end{array}\right] \underbrace{\begin{bmatrix} \mathbf{v}_0^{\mathsf{T}} \\ \mathbf{V}_{\bar{\mathcal{C}}} \\ \mathbf{V}_{\mathcal{C}} \end{bmatrix}}_{\mathbf{V}_{T^*}} \mathbf{R} \equiv \left[\begin{array}{c|c|c} \xi & & \\ \hline \mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}} & & \\ \hline & & \xi\mathbf{I}_{\mathcal{C}} \end{array}\right] \underbrace{\begin{bmatrix} \mathbf{r}^{\mathsf{T}} \\ \mathbf{W} \\ \mathbf{S}_{\mathcal{C}} \end{bmatrix}}_{\text{uniform}},$$

where the first $=$ is by definition of $\mathbf{V}$, the second $=$ holds since $\xi^{-1} \cdot \mathbf{T}_{\mathcal{C}} \cdot \mathbf{V}_{T^*} = \mathbf{I}_t$, the first $\equiv$ holds since q is co-prime with ξ and therefore both $\mathbf{R}$ and $\xi\mathbf{R}$ are uniformly distributed, and the last $\equiv$ holds since $\mathbf{V}_{T^*} \in \mathcal{R}^{t\times t}$ is a bijective map.

$\mathsf{Hyb}[D_2]$. We swap the matrices $\begin{bmatrix}\mathbf{b}^{\mathsf{T}} \\ \mathbf{z}^{\mathsf{T}}\end{bmatrix}$ and $\begin{bmatrix}\mathbf{C} \\ \mathbf{D}\end{bmatrix}$ from

$$\xi \cdot \mathbf{r}^{\mathsf{T}} \begin{bmatrix}\mathbf{A} & \mathbf{Y}\end{bmatrix} + \begin{bmatrix}\mathbf{e}^{\mathsf{T}} & \mathbf{e}_{\mathtt{LWE}}^{\mathsf{T}}\end{bmatrix} \bmod q \quad \text{and} \quad \left[\begin{array}{c|c|c} \mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}} & & \\ \hline & & \xi\mathbf{I}_{\mathcal{C}} \end{array}\right] \begin{bmatrix} \mathbf{r}^{\mathsf{T}} \\ \mathbf{W} \\ \mathbf{S}_{\mathcal{C}} \end{bmatrix} \begin{bmatrix}\mathbf{A} & \mathbf{Y}\end{bmatrix} \begin{bmatrix}\mathbf{X} & \\ & \mathbf{I}_{Q_{\mathtt{LWE}}}\end{bmatrix} + \begin{bmatrix}\mathbf{E}_{\mathtt{ISIS}} & \mathbf{E}_{\mathtt{LWE}}\end{bmatrix} \bmod q$$

to

$$\xi \cdot \begin{bmatrix}\mathbf{r}_m^{\mathsf{T}} & \mathbf{r}_{\mathtt{LWE}}^{\mathsf{T}}\end{bmatrix} + \begin{bmatrix}\mathbf{e}^{\mathsf{T}} & \mathbf{e}_{\mathtt{LWE}}^{\mathsf{T}}\end{bmatrix} \bmod q \quad \text{and} \quad \left[\begin{array}{c|c|c} \mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}} & & \\ \hline & & \xi\mathbf{I}_{\mathcal{C}} \end{array}\right] \begin{bmatrix} \mathbf{r}_m^{\mathsf{T}} & \mathbf{r}_{\mathtt{LWE}}^{\mathsf{T}} \\ \mathbf{W}_m & \mathbf{W}_{\mathtt{LWE}} \\ \mathbf{S}_{\mathcal{C}}\mathbf{A} & \mathbf{S}_{\mathcal{C}}\mathbf{Y} \end{bmatrix} \begin{bmatrix}\mathbf{X} & \\ & \mathbf{I}_{Q_{\mathtt{LWE}}}\end{bmatrix} + \begin{bmatrix}\mathbf{E}_{\mathtt{ISIS}} & \mathbf{E}_{\mathtt{LWE}}\end{bmatrix} \bmod q$$

respectively, where $\mathbf{r}_m, \mathbf{r}_{\mathtt{LWE}}, \mathbf{W}_m, \mathbf{W}_{\mathtt{LWE}}$ are uniformly random. Applying Lemma 5, we have $\mathsf{Hyb}[D_1] \approx_c \mathsf{Hyb}[D_2]$ under the $\mathsf{LWE}_{\mathcal{R},n,m+Q_{\mathtt{LWE}},q,\chi_1^*,\mathcal{D}_1}$ assumption where $\mathcal{D}_1 = \mathcal{D}_{\mathtt{A}} \times \mathcal{R}_q^{n\times Q_{\mathtt{LWE}}}$ (corresponding to the distribution of $\begin{bmatrix}\mathbf{A} & \mathbf{Y}\end{bmatrix}$). To see that Lemma 5 can be applied, set $\mathbf{N} = \xi$, $\mathbf{M} = \left[\begin{array}{c|c|c} \mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}} & & \\ \hline & & \xi\mathbf{I}_{\mathcal{C}} \end{array}\right]$ and $\mathbf{M}_{0,1}$ the submatrix with the last $|\mathcal{C}|$ columns removed, the dimension parameters are $r_M = K, r_N = t_0 = 1, t_1 = t - |\mathcal{C}| - 1, t_2 = |\mathcal{C}|$. The norm bound constraint in the first parameter set of Lemma 5 is satisfied, since

$$\|\mathbf{N}\| + \|\mathbf{M}_{0,1}\| \cdot \left\| \begin{bmatrix}\mathbf{X} & \\ & \mathbf{I}_{Q_{\mathtt{LWE}}}\end{bmatrix} \right\| \le \xi + \|\mathbf{M}_{0,1}\| \cdot (\|\mathbf{X}\| + \|\mathbf{I}_{Q_{\mathtt{LWE}}}\|) \le \xi + \gamma \cdot (\beta_{\mathtt{x}} \cdot \sqrt{Q_{\mathtt{ISIS}}} + 1),$$

where we recall $\gamma \geq \left\|\mathbf{V} \cdot \mathbf{V}_{T^*}^{-1}\right\| \geq \|\mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}}\|$.

$\mathsf{Hyb}[D_3]$. We swap the matrix $\mathbf{C}$ from

$$\left[\begin{array}{c|c} \mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}} & \\ & \xi \mathbf{I}_{\mathcal{C}} \end{array}\right] \begin{bmatrix} \mathbf{r}_m^{\intercal} \\ \mathbf{W}_m \\ \mathbf{S}_{\mathcal{C}}\mathbf{A} \end{bmatrix} \mathbf{X} + \mathbf{E}_{\mathtt{ISIS}} \bmod q \qquad \text{to} \qquad \left[\begin{array}{c|c} \mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}} & \\ & \xi \mathbf{I}_{\mathcal{C}} \end{array}\right] \begin{bmatrix} \mathbf{r}_m^{\intercal}\mathbf{X} \\ \mathbf{W}_{\mathtt{ISIS}} \\ \mathbf{S}_{\mathcal{C}}\mathbf{A}\mathbf{X} \end{bmatrix} + \mathbf{E}_{\mathtt{ISIS}} \bmod q$$

where $\mathbf{W}_{\mathtt{ISIS}}$ is uniformly random. Applying Lemma 5, we have that $\mathsf{Hyb}[D_2] \approx_c \mathsf{Hyb}[D_3]$ under the $\mathsf{LWE}_{\mathcal{R},m,Q_{\mathtt{ISIS}},q,\chi_2^*,\mathcal{D}_{\mathbf{x}}^{Q_{\mathtt{ISIS}}}}$ assumption. To invoke Lemma 5, we interpret $\mathbf{X} = \mathbf{X} \cdot \mathbf{I}_{Q_{\mathtt{ISIS}}}$, consider the same matrix $\mathbf{M}$ defined in the previous hop, let $\mathbf{M}_{0,1}$ be the middle block column of $\mathbf{M}$ and $\mathbf{M}_2$ be the remaining columns, let $\mathbf{N}$ be empty, the dimension parameters are $r_M = K, r_N = t_0 = 0, t_1 = t - |\mathcal{C}| - 1, t_2 = 1 + |\mathcal{C}|$. (To align with the representation in Lemma 5, permute the rows and columns of the above matrices, so that $\mathbf{r}_m^{\intercal}$ and $\mathbf{S}_{\mathcal{C}}\mathbf{A}$ are the bottom block row.) To see that the norm bound constraint in the first parameter set of Lemma 5 is satisfied, observe

$$\|\mathbf{M}_{0,1}\| \cdot \|\mathbf{I}_{Q_{\mathtt{ISIS}}}\| \leq \gamma.$$

$\mathsf{Hyb}[D_4]$. This is functionally equivalent to $\mathsf{Hyb}[D_3]$. We rewrite the vectors $\mathbf{b} = \xi\mathbf{r}_m + \mathbf{e} \bmod q$ and $\mathbf{r}_m \leftarrow\!\!\$\ \mathcal{R}_q^m$ in $\mathsf{Hyb}[D_3]$ as $\mathbf{b} \leftarrow\!\!\$\ \mathcal{R}_q^m$ and $\xi^{-1}(\mathbf{b} - \mathbf{e})$ in $\mathsf{Hyb}[D_4]$, similarly for the vectors $\mathbf{z}$ and $\mathbf{r}_{\mathtt{LWE}}$. This is a simple change of variables of uniformly random vectors, and clearly the two hybrids are identically distributed.

The proof is completed by observing that $\mathsf{Hyb}[D_4]$ is functionally equivalent to the ideal experiment $\mathsf{Ideal\text{-}thLWE}_{\mathsf{params},\mathcal{A},\mathcal{S}}$ defined in Fig. 3. The complete experiment with the code of the simulator $\mathcal{S}$ is provided in Fig. 10. □

Lemma 11 (Random Unauthorised Shares). *Consider the* $\mathsf{Ideal\text{-}thLWE}_{\mathsf{params},\mathcal{A},\mathcal{S}}$ *experiment given in Fig. 10. Let*

$$\mathcal{V}_{\mathcal{A},\mathsf{Ideal\text{-}thLWE}}(1^\lambda) \coloneqq \left\{ \mathbf{A}, \mathbf{b}, \mathbf{S}_{\mathcal{C}}, \left(\mathbf{x}, \begin{array}{l} \mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}} = (c_{\mathbf{x},k})_{k \notin \mathcal{C}} \\ \mathbf{c}_{\mathbf{x},\bar{\mathcal{C}}} = (c_{\mathbf{x},k})_{k \in \mathcal{C}} \end{array} \right)_{\mathbf{x}}, \left(\mathbf{y}, \ z_{\mathbf{y}}, \begin{array}{l} \mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}} = (d_{\mathbf{y},k})_{k \notin \mathcal{C}} \\ \mathbf{d}_{\mathbf{y},\bar{\mathcal{C}}} = (d_{\mathbf{y},k})_{k \in \mathcal{C}} \end{array} \right)_{\mathbf{y}}, \mathsf{coins}_{\mathcal{A}} \right\}$$

be the view of $\mathcal{A}$ *in the* $\mathsf{Ideal\text{-}thLWE}$ *experiment. It holds that*

$$\mathcal{V}_{\mathcal{A},\mathsf{Ideal\text{-}thLWE}}(1^\lambda) \equiv \left\{ \begin{pmatrix} \mathbf{A}, \mathbf{b}, \mathbf{S}_{\mathcal{C}}, \\ \left(\mathbf{x}, \mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}}, \mathbf{c}_{\mathbf{x},\bar{\mathcal{C}}}\right)_{\mathbf{x}}, \\ \left(\begin{array}{c} \mathbf{y}, z_{\mathbf{y}}, \\ \mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}}, \mathbf{d}_{\mathbf{y},\bar{\mathcal{C}}} \end{array}\right)_{\mathbf{y}}, \\ \mathsf{coins}_{\mathcal{A}} \end{pmatrix} \;\middle|\; \begin{array}{l} \left\{ \mathbf{A}, \mathbf{b}, \mathbf{S}_{\mathcal{C}}, \left(\mathbf{x}, \begin{array}{c} \mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}} \\ \mathbf{c}_{\mathbf{x},\bar{\mathcal{C}}} \end{array} \right)_{\mathbf{x}}, \left(\mathbf{y}, \ z_{\mathbf{y}}, \begin{array}{c} \mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}} \\ \mathbf{d}_{\mathbf{y},\bar{\mathcal{C}}} \end{array} \right)_{\mathbf{y}}, \mathsf{coins}_{\mathcal{A}} \right\} \leftarrow \mathcal{V}_{\mathcal{A},\mathsf{Ideal\text{-}thLWE}}(1^\lambda) \\ \forall\ \mathbf{x}\ \mathbf{do} \\ \quad \mathbf{if}\ |\mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}}| + |\mathcal{C}| < t\ \mathbf{then}\ \mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}} \leftarrow\!\!\$\ \mathcal{R}_q^\ell \\ \forall\ \mathbf{y}\ \mathbf{do} \\ \quad \mathbf{if}\ |\mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}}| + |\mathcal{C}| < t\ \mathbf{then}\ z_{\mathbf{y}} \leftarrow\!\!\$\ \mathcal{R}_q;\ \mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}} \leftarrow\!\!\$\ \mathcal{R}_q^\ell \end{array} \right\}.$$

Proof. The simulator $\mathcal{S}_{\mathsf{Query}}$ in Fig. 10 computes each share vector as

$$\mathbf{c}_{\mathbf{x}} = \left[\begin{array}{c|c} \mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}} & \\ & \xi \mathbf{I}_{\mathcal{C}} \end{array}\right] \begin{bmatrix} \hat{\mathbf{b}}^{\intercal}\mathbf{x} \\ \mathbf{w}_{\mathtt{ISIS}} \\ \mathbf{S}_{\mathcal{C}}\mathbf{A}\mathbf{x} \end{bmatrix} \bmod q, \qquad \mathbf{d}_{\mathbf{y}} = \left[\begin{array}{c|c} \mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}} & \\ & \xi \mathbf{I}_{\mathcal{C}} \end{array}\right] \begin{bmatrix} \xi^{-1}(z - e_{\mathtt{LWE}}) \\ \mathbf{w}_{\mathtt{LWE}} \\ \mathbf{S}_{\mathcal{C}}\mathbf{y} \end{bmatrix} \bmod q,$$

where $z \leftarrow\!\!\$\ \mathcal{R}_q$, $\mathbf{w}_{Q_{\mathtt{ISIS}}} \leftarrow\!\!\$\ \mathcal{R}_q^{t-|\mathcal{C}|}$ and $\mathbf{w}_{Q_{\mathtt{LWE}}} \leftarrow\!\!\$\ \mathcal{R}_q^{t-|\mathcal{C}|}$ are uniformly random.

For any set $\bar{\mathcal{H}} \subseteq \mathcal{H} = [K] \setminus \mathcal{C}$, the submatrix of $\mathbf{V}_{\mathcal{H}}\mathbf{T}_{\mathcal{C}}$ with rows indexed by $\bar{\mathcal{H}}$ is $\mathbf{V}_{\bar{\mathcal{H}}}\mathbf{T}_{\mathcal{C}}$. Write $\mathbf{V}_{\bar{\mathcal{H}}}\mathbf{T}_{\mathcal{C}} = \left[\mathbf{V}_{\bar{\mathcal{H}}}\mathbf{T}_{\mathcal{C}}^{\perp}, *\right] \in \mathcal{R}^{\mathcal{H} \times ((t-|\mathcal{C}|)+|\mathcal{C}|)}$. (Such $\mathbf{T}_{\mathcal{C}}^{\perp}$ is identical to that in Eq. (2).) Further denote by $\bar{\mathbf{T}}_{\mathcal{C}}^{\perp}$ the submatrix of $\mathbf{T}_{\mathcal{C}}^{\perp}$ with its first column removed.

The concerned shares $\mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}}$, $\mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}}$, corresponding to the shares queries on honest indices $\bar{\mathcal{H}} \subseteq \mathcal{H}$ by the adversary $\mathcal{A}$, are

$$\mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}} = \mathbf{V}_{\bar{\mathcal{H}}}\mathbf{T}_{\mathcal{C}} \begin{bmatrix} \hat{\mathbf{b}}^{\mathsf{T}}\mathbf{x} \\ \mathbf{w}_{\mathtt{ISIS}} \\ \mathbf{S}_{\mathcal{C}}\mathbf{A}\mathbf{x} \end{bmatrix} = \mathbf{V}_{\bar{\mathcal{H}}}\bar{\mathbf{T}}_{\mathcal{C}}^{\perp} \cdot \mathbf{w}_{\mathtt{ISIS}} + * \bmod q,$$
$$\mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}} = \mathbf{V}_{\bar{\mathcal{H}}}\mathbf{T}_{\mathcal{C}} \begin{bmatrix} \xi^{-1}(z - e_{\mathtt{LWE}}) \\ \mathbf{w}_{\mathtt{LWE}} \\ \mathbf{S}_{\mathcal{C}}\mathbf{y} \end{bmatrix} = \mathbf{V}_{\bar{\mathcal{H}}}\bar{\mathbf{T}}_{\mathcal{C}}^{\perp} \cdot \mathbf{w}_{\mathtt{LWE}} + * \bmod q.$$

Whenever $|\mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}}| = |\bar{\mathcal{H}}| < t - |\mathcal{C}|$, equivalently $|\bar{\mathcal{H}} \cup \mathcal{C}| < t$, the columns of $\mathbf{V}_{\bar{\mathcal{H}}}\bar{\mathbf{T}}_{\mathcal{C}}^{\perp}$ generates $\mathcal{R}_q^{|\bar{\mathcal{H}}|}$ by Lemma 9. Since $\mathbf{w}_{\mathtt{ISIS}}$ is uniformly random, we conclude so is $\mathbf{V}_{\bar{\mathcal{H}}}\bar{\mathbf{T}}_{\mathcal{C}}^{\perp} \cdot \mathbf{w}_{\mathtt{ISIS}} \bmod q$, therefore also $\mathbf{c}_{\mathbf{x},\bar{\mathcal{H}}}$.

Similarly, because of Lemma 9, whenever $|\mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}}| = |\bar{\mathcal{H}}| < t - |\mathcal{C}|$, $\mathbf{V}_{\bar{\mathcal{H}}}\bar{\mathbf{T}}_{\mathcal{C}}^{\perp} \cdot \mathbf{w}_{\mathtt{LWE}} \bmod q$ is uniformly random as $\mathbf{w}_{\mathtt{LWE}}$ is. Therefore so is $\mathbf{d}_{\mathbf{y},\bar{\mathcal{H}}}$. □

□

A.6 Proof of Theorem 2

Proof. The proof is almost identical to that of Theorem 1. The only differences are the hops from $\mathsf{Hyb}[D_1]$ to $\mathsf{Hyb}[D_2]$ and from $\mathsf{Hyb}[D_2]$ to $\mathsf{Hyb}[D_3]$, where for each of them we rely on Lemma 5 with its second set of parameters instead. We verify that the required parameter constraints are satisfied. Denote $\mathbf{M} = \left[\begin{array}{c|c} \mathbf{V}_{\mathcal{H}} \cdot \mathbf{T}_{\mathcal{C}} & \\ \hline & \xi\mathbf{I}_{\mathcal{C}} \end{array}\right]$.

For the hop from $\mathsf{Hyb}[D_1]$ to $\mathsf{Hyb}[D_2]$, we let $\mathbf{N} = \xi$, $\mathbf{M}_{0,1}$ the submatrix of $\mathbf{M}$ with the last $|\mathcal{C}|$ columns removed, and have that

$$\begin{aligned} &\lambda^{\omega(1)} \cdot \chi^* \sqrt{m} \cdot \max\left(\|\mathbf{N}\|^{\mathsf{T}},\ \left\|\mathbf{M}_{0,1}^{\mathsf{T}}\right\| \cdot \left\| \begin{bmatrix} \mathbf{X} \\ & \mathbf{I}_{Q_{\mathtt{LWE}}} \end{bmatrix} \right\| \right) \\ \leq\ &\lambda^{\omega(1)} \cdot \chi^* \sqrt{m} \cdot \max(\xi,\ \left\|\mathbf{M}_{0,1}^{\mathsf{T}}\right\| \cdot (\|\mathbf{X}\| + \|\mathbf{I}_{\mathtt{LWE}}\|)) \\ \leq\ &\lambda^{\omega(1)} \cdot \chi^* \sqrt{m} \cdot \max(\xi,\ \gamma \cdot (\beta_{\mathtt{x}}\sqrt{Q_{\mathtt{ISIS}}} + 1)) < \chi \end{aligned}$$

is satisfied by the constraint of Theorem 2, thus $\mathsf{Hyb}[D_1] \approx_c \mathsf{Hyb}[D_2]$ holds under the $\mathsf{LWE}_{\mathcal{R},n,m+Q_{\mathtt{LWE}},q,\chi^*,\mathcal{D}_1}$ assumption by Lemma 5, where $\mathcal{D}_1 = \mathcal{D}_{\mathtt{A}} \times \mathcal{R}_q^{Q_{\mathtt{LWE}}}$.

For the hop from $\mathsf{Hyb}[D_2]$ to $\mathsf{Hyb}[D_3]$, we let $\mathbf{N}$ be empty, $\mathbf{M}_{0,1}$ the submatrix of $\mathbf{M}$ consisting only its middle block column, and have that

$$\lambda^{\omega(1)} \cdot \chi^* \sqrt{Q_{\mathtt{ISIS}}} \cdot \left\|\mathbf{M}_{0,1}^{\mathsf{T}}\right\| \|\mathbf{I}_{Q_{\mathtt{ISIS}}}\| \leq \lambda^{\omega(1)} \cdot \chi^* \cdot \gamma \cdot \sqrt{Q_{\mathtt{ISIS}}} < \chi$$

is satisfied by the constraint of Theorem 2, thus $\mathsf{Hyb}[D_2] \approx_c \mathsf{Hyb}[D_3]$ holds under the $\mathsf{LWE}_{\mathcal{R},m,Q_{\mathtt{ISIS}},q,\chi^*,\mathcal{D}_{\mathtt{x}}^{Q_{\mathtt{ISIS}}}}$ assumption by Lemma 5. □

B Threshold PKE: Correctness and Security Proof

This is a continuation of Section 5. We present the correctness and security proofs.

Theorem 3 (Correctness). *Let $q > 4\chi\sqrt{\varphi} \cdot (\xi \cdot \beta_{\mathtt{x}}\sqrt{m} + \sqrt{t} \cdot \rho(t))$, where $\rho(t)$ is the recovery-expansion factor of Ξ, and $\beta_{\mathtt{x}} > 0$ is such that $\Pr(\|\mathbf{x}\| \leq \beta_{\mathtt{x}} | \mathbf{x} \leftarrow\!\$\ \mathcal{D}_{\mathtt{x}}) \geq 1 - \mathsf{negl}(\lambda)$. Then, Pilvi is correct.*

Proof. For honestly generated partial decryptions and ciphertexts, for each index $\ell \in [L]$ one has

$$\begin{aligned} \mathsf{pd}_\ell &= \mathbf{v}_0^{\mathsf{T}} \cdot \mathbf{V}_T^{-1} \cdot (\mathsf{pd}_{\ell,k})_{k \in T} \bmod q \\ &= \mathbf{v}_0^{\mathsf{T}} \cdot \mathbf{V}_T^{-1} \cdot (\mathbf{S}_T\mathbf{c}_0 + \mathbf{e}_{\ell,T}) \bmod q \quad /\!/\ \mathbf{S}_T\mathbf{c}_0 + \mathbf{e}_{\ell,T} \coloneqq (\mathbf{s}_{\ell,k}^{\mathsf{T}}\mathbf{c}_0 + e_{\ell,k})_{k \in T} \end{aligned}$$

$$= \mathbf{r}_\ell^\intercal \mathbf{c}_0 + \mathbf{v}_0^\intercal \cdot \mathbf{V}_T^{-1} \cdot \mathbf{e}_{\ell,T} \bmod q \quad /\!/\ \mathbf{r}_\ell^\intercal = \mathbf{v}_0^\intercal \mathbf{V}_T^{-1} \mathbf{S}_T \bmod q$$
$$= \mathbf{r}_\ell^\intercal \mathbf{A}\mathbf{x} + \mathbf{v}_0^\intercal \cdot \mathbf{V}_T^{-1} \cdot \mathbf{e}_{\ell,T} \bmod q \quad /\!/\ \mathbf{c}_0 = \mathbf{A}\mathbf{x} \bmod q$$

for recovery coefficients $\mathbf{v}_0^\intercal \mathbf{V}_T^{-1}$ and some error $\mathbf{v}_0^\intercal \cdot \mathbf{V}_T^{-1} \cdot \mathbf{e}_T$. From

$$\begin{aligned}
y_\ell &= (c_{\ell,1} - \mathsf{pd}_\ell) \cdot \xi \bmod q \\
&= \left(\mathbf{b}_\ell^\intercal \mathbf{x} + \xi^{-1} \cdot \mu_\ell \left\lfloor \frac{q}{2} \right\rfloor - \mathbf{r}_\ell^\intercal \mathbf{A}\mathbf{x} - \mathbf{v}_0^\intercal \cdot \mathbf{V}_T^{-1} \mathbf{e}_{\ell,T}\right) \cdot \xi \bmod q \\
&= \left((\mathbf{r}_\ell^\intercal \mathbf{A} + \mathbf{e}_\ell^\intercal)\mathbf{x} + \xi^{-1} \cdot \mu_\ell \left\lfloor \frac{q}{2} \right\rfloor - \mathbf{r}_\ell^\intercal \mathbf{A}\mathbf{x} - \mathbf{v}_0^\intercal \cdot \mathbf{V}_T^{-1} \mathbf{e}_{\ell,T}\right) \cdot \xi \bmod q \\
&= \left(\xi^{-1} \cdot \mu_\ell \left\lfloor \frac{q}{2} \right\rfloor + \mathbf{e}_\ell^\intercal \cdot \mathbf{x} - \mathbf{v}_0^\intercal \cdot \mathbf{V}_T^{-1} \mathbf{e}_{\ell,T}\right) \cdot \xi \bmod q \\
&= \mu \left\lfloor \frac{q}{2} \right\rfloor + \xi \cdot \mathbf{e}_\ell^\intercal \cdot \mathbf{x} - \mathbf{v}_0^\intercal \cdot (\xi \mathbf{V}_T^{-1}) \cdot \mathbf{e}_{\ell,T} \bmod q,
\end{aligned}$$

we deduce that decryption correctness for the ℓ-th message μ_ℓ follows from

$$\begin{aligned}
4 \cdot \left\| \xi \cdot \mathbf{e}_\ell^\intercal \cdot \mathbf{x} - \mathbf{v}_0^\intercal \cdot (\xi \mathbf{V}_T^{-1}) \cdot \mathbf{e}_{\ell,T} \right\| &\leq 4 \cdot (\xi \cdot \left\| \mathbf{e}_\ell^\intercal \cdot \mathbf{x} \right\| + \left\| \xi \mathbf{v}_0^\intercal \mathbf{V}_T^{-1} \right\| \| \mathbf{e}_{\ell,T} \|) \\
&\leq 4 \cdot (\xi \cdot \chi \sqrt{m\varphi} \cdot \beta_{\mathtt{x}} + \rho(t) \cdot \chi \sqrt{\varphi} \cdot \sqrt{t}) \\
&= 4\chi \sqrt{\varphi} \cdot (\xi \cdot \beta_{\mathtt{x}} \sqrt{m} + \sqrt{t} \cdot \rho(t)) < q,
\end{aligned}$$

where we recall $\rho(t)$ is the "recovery-expansion factor" of the subtractive set Ξ, and $\beta_{\mathtt{x}} > 0$ is such that $\Pr(\|\mathbf{x}\| \leq \beta_{\mathtt{x}} | \mathbf{x} \hookleftarrow\$\ \mathcal{D}_{\mathtt{x}}) \geq 1 - \mathsf{negl}(\lambda)$. Repeating the above analyse over all $\ell \in [L]$ messages concludes decryption correctness. □

Theorem 4 (Security). *Let $\mathcal{R}_q$ split into super-polynomial-size fields, q be prime, $\mathcal{D}_{\mathtt{A}}$ be the uniform distribution over $\mathcal{R}_q^{n \times m}$, and $\mathcal{D}_{\mathtt{x}} = D_{\mathcal{R},\sigma_{\mathtt{x}}}^m$ for some $\sigma_{\mathtt{x}} > 0$. For*

$$\begin{aligned}
\mathsf{params}_0 &= ((\mathcal{R}, n, m, q, \mathcal{D}_{\mathtt{A}}, \mathcal{D}_{\mathtt{x}}, \chi), (t, K, \Xi)), \\
\mathsf{params}_1 &= (\mathcal{R}, m - n - L, n + L, q, \sigma_{\mathtt{x}}, D_{\mathcal{R},\sigma_{\mathtt{x}}}).
\end{aligned}$$

Pilvi *is simulation secure under the* th-$-LWE$_{\mathsf{params}_0}$ *and* LWE$_{\mathsf{params}_1}$ *assumptions.*

Proof. We prove by a standard hybrid argument. Define the following hybrids:

- Hyb_0: Identical to $\mathsf{Exp}^0_{\Pi,\mathcal{A}}$.
- Hyb_i, for $i \in [L]$: Identical to $\mathsf{Exp}^{i-1}_{\Pi,\mathcal{A}}$ except that
  - the i-th component of the public key $\mathbf{b}_i$ is sampled uniformly at random, i.e., $\mathbf{b}_i \leftarrow \mathcal{R}_q^m$,
  - the i-th component of each reply to a partial decryption oracle query is replaced with the output of the SimISIS and ShareISIS algorithms, i.e., on an arbitrary index $k \in [K]$, for $\mathsf{st}_i = \mathcal{S}_{\mathsf{Init}}(\mathbf{A}, \mathbf{b}_i, \mathbf{S}_{i,\mathcal{C}}), \mathbf{x} \hookleftarrow\$\ \mathcal{D}_{\mathtt{x}}, \mathbf{y} = \mathbf{A}\mathbf{x} \bmod q, (\mathbf{c}_i, \mathsf{st}_i) \leftarrow \mathcal{S}_{\mathsf{ISIS}}(\mathbf{x}, \mathsf{st}_i)$ and $L_{\mathsf{ISIS}}[\mathbf{y}] = \mathbf{c}_i$, one returns $\mathsf{ShareISIS}(\mathbf{y}, k \in [K])$.
- Hyb_{L+1}: Identical to $\mathsf{Exp}^1_{\Pi,\mathcal{A}}$.

We show that Hyb_{i-1} and Hyb_i are computationally indistinguishable, for each $i \in [L]$, by providing a reduction to the th-$-LWE$_{\mathsf{params}}$ assumption. Let us define the reduction.

- It receives $\mathbf{A}$ from the thLWE challenger. It sets $\mathsf{pp} = \mathbf{A}$, sends it to $\mathcal{A}$.
- It receives $\mathcal{C} \subset_{<t} [K]$ from $\mathcal{A}$ and forwards it to thLWE challenger.
- It receives $(\mathbf{b}_i, (\mathbf{s}_{i,k})_{k \in \mathcal{C}})$ from the thLWE challenger.
- For $j = 1, \ldots, i-1$, it samples $\mathbf{b}_j \hookleftarrow\$\ \mathcal{R}_q^m, (\mathsf{sk}_{j,k})_{k \in \mathcal{C}} = \mathbf{S}_{j,\mathcal{C}} \hookleftarrow\$\ \mathcal{R}_q^{|\mathcal{C}| \times n}$ and sets $\mathsf{st}_j \leftarrow \mathcal{S}_{\mathsf{Init}}(\mathbf{A}, \mathbf{b}_j, \mathbf{S}_{\mathcal{C}})$.
- For $j = i+1, \ldots, L$, it samples $\mathbf{R}_j \hookleftarrow\$\ \mathcal{R}_q^{t \times n}, \mathbf{e}_j \hookleftarrow\$\ D_{\mathcal{R},\chi}^m$ and sets $\mathbf{r}_j^\intercal = \mathbf{v}_0^\intercal \mathbf{R}_j, \mathbf{b}_j^\intercal = \mathbf{r}_j^\intercal \mathbf{A} + \mathbf{e}_j^\intercal, (\mathbf{s}_{j,k})_{k \in [K]} = \mathbf{V}\mathbf{R}_j$.
- It sets $\mathsf{pk} = (\mathbf{A}, (\mathbf{b}_\ell)_{\ell \in [L]}), (\mathsf{sk}_k)_{k \in \mathcal{C}} = ((\mathbf{s}_{\ell,k})_{\ell \in [L]})_{k \in \mathcal{C}}$, and sends it to $\mathcal{A}$.
- It initialises lists $L_{\mathsf{Query}} \coloneqq \emptyset$; $L_{\mathsf{Share}} \coloneqq \emptyset$; $L_{\mathsf{Party}} \coloneqq \emptyset$; and $L^{(j)}_{\mathtt{ISIS}} \coloneqq \emptyset$ for $j \in [i-1]$

Next, we discuss how queries $\mathsf{EncO}, \mathsf{ChalO}, \mathsf{ParDecO}$ are dealt with.

- Queries $\mathsf{EncO}(\mathsf{id}, (\mu_\ell)_{\ell\in[L]})$: if $L_{\mathsf{Query}}[\mathsf{id}] = \emptyset$
  - it queries $\mathsf{GenISIS}/\mathsf{SimISIS}$ to the thLWE challenger to obtain $(\mathbf{x}, \mathbf{y})$,
  - for $j = 1, \ldots, i-1$, it computes $(\mathbf{c}_j, \mathsf{st}_j) \leftarrow \mathcal{S}_{\mathsf{ISIS}}(\mathbf{x}, \mathsf{st}_j)$ and lets $L^{(j)}_{\mathtt{ISIS}}[\mathbf{y}] = \mathbf{c}_j$,
  - for $j = i+1, \ldots, L$, it samples $\mathbf{e}_j \leftarrow\!\$\ D^K_{\mathcal{R},\chi}$, sets $\mathbf{c}_j \coloneqq \mathbf{V}\mathbf{R}_j\mathbf{y} + \mathbf{e}_j$ and lets $L^{(j)}_{\mathtt{ISIS}}[\mathbf{y}] = \mathbf{c}_j$,
  - it sets
$$\mathsf{ctxt} = (\mathbf{c}_0, (c_{\ell,1})_{\ell\in[L]}) \coloneqq (\mathbf{y}, (\mathbf{b}_\ell^\intercal\mathbf{x} + \xi^{-1}\cdot\mu_\ell\lfloor q/2\rfloor)_{\ell\in[L]})$$
    and $L_{\mathsf{Query}}[\mathsf{id}] \coloneqq (\mathsf{ctxt}, \mathbf{x})$.

  It then returns $L_{\mathsf{Query}}[\mathsf{id}]$ to $\mathcal{A}$.
- Queries $\mathsf{ChalO}(\mathsf{id}, (\mu_\ell)_{\ell\in[L]})$: if $L_{\mathsf{Query}}[\mathsf{id}] = \emptyset$
  - it queries $\mathsf{GenISIS}/\mathsf{SimISIS}$ to the thLWE challenger to obtain $(\mathbf{x}, \mathbf{y})$,
  - for $j = 1, \ldots, i-1$, it computes $(\mathbf{c}_j, \mathsf{st}_j) \leftarrow \mathcal{S}_{\mathsf{ISIS}}(\mathbf{x}, \mathsf{st}_j)$ and lets $L^{(j)}_{\mathtt{ISIS}}[\mathbf{y}] = \mathbf{c}_j$,
  - for $j = i+1, \ldots, L$, it samples $\mathbf{e}_j \leftarrow\!\$\ D^K_{\mathcal{R},\chi}$, sets $\mathbf{c}_j \coloneqq \mathbf{V}\mathbf{R}_j\mathbf{y} + \mathbf{e}_j$ and lets $L^{(j)}_{\mathtt{ISIS}}[\mathbf{y}] = \mathbf{c}_j$,
  - it sets
$$\mathsf{ctxt} = (\mathbf{c}_0, (c_{\ell,1})_{\ell\in[L]}) \coloneqq (\mathbf{y}, (\mathbf{b}_\ell^\intercal\mathbf{x} + \xi^{-1}\cdot\mu_\ell\lfloor q/2\rfloor)_{\ell\in[L]})$$
    and $L_{\mathsf{Query}}[\mathsf{id}] \coloneqq (\mathsf{ctxt}, \perp)$.

  It then returns $L_{\mathsf{Query}}[\mathsf{id}]$ to $\mathcal{A}$.
- Queries $\mathsf{ParDecO}(\mathsf{id}, k \in [K])$:
  - Assert $L_{\mathsf{Query}}[\mathsf{id}] \neq \emptyset$.
  - Add k to $L_{\mathsf{Party}}[\mathsf{id}]$.
  - Parses $(\mathsf{ctxt}, \mathsf{rnd}) \leftarrow L_{\mathsf{Query}}[\mathsf{id}]$. If $\mathsf{rnd} = \perp$, assert $|L_{\mathsf{Party}}[\mathsf{id}] \cup \mathcal{C}| < t$.
  - Parses $(\mathbf{c}_0, (c_{\ell,1})_{\ell\in[L]}) \leftarrow \mathsf{ctxt}$.
  - If $L_{\mathsf{Share}}[\mathsf{id}] = \emptyset$, then
    - for $h \in [K]$
      - for $j \in [L] \setminus \{i\}$, sets $\mathsf{pd}_{j,h} = (\mathbf{c}_j)_h$, where $\mathbf{c}_j \leftarrow L^{(j)}_{\mathtt{ISIS}}[\mathbf{c}_0]$
      - queries the $\mathsf{ShareISIS}$ oracle on input $(\mathbf{y}, h \in [K])$ and sets $\mathsf{pd}_{i,h} \leftarrow \mathsf{ShareISIS}(\mathbf{y}, h \in [K])$.
      - Set $\mathsf{pd}_h = (\mathsf{pd}_{\ell,h})_{\ell\in[L]}$,
    - Set $L_{\mathsf{Share}}[\mathsf{id}] = (\mathsf{pd}_h)_{h\in[K]}$.
  - Parse $(\mathsf{pd}_h)_{h\in[K]} \leftarrow L_{\mathsf{Share}}[\mathsf{id}]$.
  - Return pd_k to $\mathcal{A}$.

A routine check confirms that the reduction is perfectly simulating Hyb_{i-1} if $b = 0$, and Hyb_i if $b = 1$. Therefore, the computational indistinguishability between Hyb_{i-1} and Hyb_i follows from the $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ assumption.

To show the computational indistinguishability between Hyb_L and Hyb_{L+1}, we rely on the following facts about Hyb_L:

1. The matrix $\begin{bmatrix}\mathbf{A}\\ \mathbf{b}_1^\intercal\\ \vdots\\ \mathbf{b}_L^\intercal\end{bmatrix}$ is uniformly random.
2. By the pseudorandomness guarantee of the simulator $\mathcal{S}_{\mathsf{thLWE}}$ in the $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ assumption, the adversary's view is completely independent of the encryption randomness $\mathbf{x}$ of any challenge ciphertext, which take the form $(\mathbf{A}\mathbf{x}, \mathbf{b}_1^\intercal\mathbf{x} + \xi^{-1}\cdot\mu_1\lfloor q/2\rfloor, \ldots, \mathbf{b}_L^\intercal\mathbf{x} + \xi^{-1}\cdot\mu_L\lfloor q/2\rfloor)$.[17]

[17] Note that here we rely on the $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ assumption (instead of merely $\mathsf{th\text{-}LWE}_{\mathsf{params}}$), which assures that, in Hyb_L, partial decryptions of any challenge ciphertext are uniformly random in the eye of the adversary.

Since $\mathcal{R}_q$ splits into super-polynomial-size fields, $\begin{bmatrix} \mathbf{A} \\ \mathbf{b}_1^\intercal \\ \vdots \\ \mathbf{b}_L^\intercal \end{bmatrix}$ is primitive with overwhelming probability. It then follows that tuples of the form $(\mathbf{A}\mathbf{x}, \mathbf{b}_1^\intercal\mathbf{x}, \ldots, \mathbf{b}_L^\intercal\mathbf{x})$, where $\mathbf{x} \leftarrow\!\!\$\ \mathcal{D}_{\mathbf{x}}$, are pseudorandom under the $\mathsf{LWE}_{\mathcal{R},m-n-L,n+L,q,\sigma_{\mathbf{x}},D_{\mathcal{R},\sigma_{\mathbf{x}}}}$ assumption. Since there are only polynomially many such tuples, we conclude that Hyb_L and Hyb_{L+1} are computationally indistinguishable. □

C Distributed PRF: Correctness and Security Proof

This is a continuation of Section 6. We recall the definition, correctness and security of distributed PRFs and present correctness and security proof.

Syntax. A pseudorandom function PRF is a tuple of PPT algorithms $(\mathsf{Setup}, \mathsf{KGen}, \mathsf{Eval})$ defined over a key space $\mathcal{K}$, a message space $\mathcal{X}$, and an image space $\mathcal{Y}$.

- $\mathsf{pp} \leftarrow \mathsf{Setup}(1^\lambda)$: The setup algorithm generates the public parameters pp, which are implicitly input to all other algorithms.
- $\mathsf{k} \leftarrow \mathsf{KGen}(\mathsf{pp})$: The key generation algorithm outputs a key $\mathsf{k} \in \mathcal{K}$.
- $c \leftarrow \mathsf{Eval}(\mathsf{k} \in \mathcal{K}, x \in \mathcal{X})$: The deterministic function evaluation algorithm outputs an image $c \in \mathcal{Y}$.

The security of (weak) PRF guarantees that for any PPT adversary $\mathcal{A}$

$$\left| \begin{array}{l} \mathsf{Pr}_{\mathsf{pp}\leftarrow\mathsf{Setup}(1^\lambda),\mathsf{k}\leftarrow\mathsf{KGen}(\mathsf{pp})}\left[\mathcal{A}((x_i, \mathsf{Eval}(\mathsf{k}, x_i))_{i\in[Q]}) = 1\right] \\ - \mathsf{Pr}_{f\leftarrow\mathcal{Y}^{\mathcal{X}}}\left[\mathcal{A}((x_i, f(x_i))_{i\in[Q]}) = 1\right] \end{array} \right| \leq \mathsf{negl}(\lambda),$$

where $Q \in \mathsf{poly}(\lambda)$, $x_i \leftarrow\!\!\$\ \mathcal{X}$, and $\mathcal{Y}^{\mathcal{X}}$ denotes the set of all functions from $\mathcal{X} \to \mathcal{Y}$.

Remark 4 (Rounding). Observe that, for $x \leftarrow\!\!\$\ \mathbb{Z}_q$ and $e \in \mathbb{Z}$, with $|e| \leq B$, we have that $\lfloor x + e \rceil_p = \lfloor x \rceil_p$, except that with probability at most $(2B+1)p/q$: the reason is that $\lfloor x + e \rceil_p \neq \lfloor x \rceil_p$ only when x is within B of the nearest multiple of q/p. In this case, adding e might cause rounding to a different integer. The probability that $x \leftarrow\!\!\$\ \mathbb{Z}_q$ is within B of the nearest multiple of q/p is exactly $(2B+1)p/q$. The result extends to vectors by taking an union bound over the different coordinate. In particular, this implies that, for $x \leftarrow\!\!\$\ \mathcal{R}_q$ and $e \in \mathcal{R}$ with $\|e\|_{\mathtt{coeff},\infty} \leq B$, one has $\mathrm{Pr}_{x\leftarrow\mathcal{R}_q}[\lfloor x + e \rceil_p \neq \lfloor x \rceil_p] \leq (2B+1)\varphi p/q$.

Theorem 5 (Correctness for Random Inputs). *If $2(\rho(t) \cdot \sqrt{\varphi t} + 3)u/p \leq \mathsf{negl}(\lambda)$, where $\rho(t)$ is the recovery-expansion factor of Ξ, then Π_{DPRF} is correct for random inputs.*

Proof. Consider honest evaluations and partial evaluations of the PRF on a random input $\mathbf{y} \leftarrow\!\!\$\ \mathcal{R}_q^n$. On the one hand, one has

$$c = \mathsf{Eval}(\mathbf{r}, \mathbf{y}) = \lfloor \lfloor \xi \cdot \mathbf{r}^\intercal\mathbf{y} \rceil_p \rceil_u.$$

On the other hand, for any $k \in [K]$, it holds that

$$c_k = \mathsf{ParEval}(\mathbf{s}_k, \mathbf{y}) = \lfloor \mathbf{s}_k^\intercal\mathbf{y} \rceil_p.$$

Recall that, for $(c_k)_{k\in T}$, one has

$$\begin{aligned} c' &= \mathbf{v}_0^\intercal \cdot \mathbf{V}_T^{-1} \cdot \xi \cdot (c_k)_{k\in T} \\ &= \mathbf{v}_0^\intercal \cdot \mathbf{V}_T^{-1} \cdot \xi \cdot (\left\lfloor \mathbf{s}_k^\intercal\mathbf{y} \right\rceil_p)_{k\in T} \end{aligned}$$

For $k \in [T]$, let $\bar{c}'_k \in \mathcal{R}$ with norm $\leq q/p - 1$ be such that $\mathbf{s}_k^{\mathsf{T}}\mathbf{y} = q/p\lfloor \mathbf{s}_k^{\mathsf{T}}\mathbf{y}\rceil_p + \bar{c}'_k$, and similarly, let $\bar{c} \in \mathcal{R}$ of norm $\leq q/p - 1$ be such that $\xi \cdot \mathbf{r}^{\mathsf{T}}\mathbf{y} = q/p\lfloor \xi \cdot \mathbf{r}^{\mathsf{T}}\mathbf{y}\rceil_p + \bar{c}$, We have that

$$\begin{aligned}
\left\| \lfloor \xi \cdot \mathbf{r}^{\mathsf{T}}\mathbf{y}\rceil_p - \mathbf{v}_0^{\mathsf{T}} \cdot \mathbf{V}_T^{-1} \cdot \xi \cdot (\lfloor \mathbf{s}_k^{\mathsf{T}}\mathbf{y}\rceil_p)_{k\in T} \right\| &= \left\| \frac{p}{q}(\xi \cdot \mathbf{r}^{\mathsf{T}}\mathbf{y} - \bar{c}) - \frac{p}{q} \cdot \mathbf{v}_0^{\mathsf{T}} \cdot \mathbf{V}_T^{-1} \cdot \xi \cdot (\mathbf{s}_k^{\mathsf{T}}\mathbf{y} - \bar{c}'_k)_{k\in T} \right\| \\
&= \left\| \left(\mathbf{v}_0^{\mathsf{T}} \cdot \mathbf{V}_T^{-1} \cdot \xi \cdot \frac{p}{q}(\bar{c}'_k)_{k\in T} - \frac{p}{q}\bar{c} \right) \right\| \\
&\leq \left\| \mathbf{v}_0^{\mathsf{T}} \cdot \mathbf{V}_T^{-1} \cdot \xi \cdot \frac{p}{q}(\bar{c}'_k)_{k\in T} \right\| + \left\| \frac{p}{q}\bar{c} \right\| \\
&\leq \left\| \mathbf{v}_0^{\mathsf{T}} \cdot \mathbf{V}_T^{-1} \cdot \xi \right\| \cdot \left\| \frac{p}{q}(\bar{c}'_k)_{k\in T} \right\| + \left\| \frac{p}{q}\bar{c} \right\| \\
&\leq \rho(t) \cdot \sqrt{\varphi t} + 1
\end{aligned}$$

where we recall $\rho(t)$ is the "recovery-expansion factor" of the subtractive set Ξ. Using Remark 4, it follows that $c = \left\lfloor \lfloor \xi \cdot \mathbf{r}^{\mathsf{T}}\mathbf{y}\rceil_p \right\rceil_u = \lfloor \mathbf{v}_0^{\mathsf{T}} \cdot \mathbf{V}_T^{-1} \cdot \xi \cdot (c_k)_{k\in T}\rceil_u = \Pi_{\mathsf{DPRF}}.\mathsf{Rec}(T, (c_k)_{k\in T})$, except that with probability $(2(\rho(t) \cdot \sqrt{\varphi t} + 1) + 1)u/p = 2(\rho(t) \cdot \sqrt{\varphi t} + 3)u/p \leq \mathsf{negl}(\lambda)$ as required. □

Theorem 6 (Security). *Let* $\mathsf{params} = ((\mathcal{R}, n, m, q, \mathcal{D}_{\mathtt{A}}, \mathcal{D}_{\mathtt{x}}, \chi), (t, K, \Xi))$ *be thLWE parameters (where* $\mathcal{D}_{\mathtt{x}}$ *can be arbitrary and is not used),* $\varphi \geq \omega(\log \lambda)$*, and* $(2\xi\chi\sqrt{\varphi}+1)p/q \leq \mathsf{negl}(\lambda)$*. Then, the construction* Π_{DPRF} *is a secure distributed weak pseudorandom function under the* $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ *assumption.*

Proof. We start with defining the following sequence of hybrids:

- Hyb_0: This is the security experiment $\mathsf{WPRF\text{-}Exp}^0_{\Pi,\mathcal{A}}$.
- Hyb_1: This is identical to the previous hybrid, except for the following modifications made to the way the y_k's and y are produced by the $\mathsf{ParEvalO}$ and ChalO oracles:
  - When responding to $\mathsf{ParEvalO}$ queries, compute y_k as follows: Sample $f_k \leftarrow D_{\mathcal{R},\chi}$ and set $c_k \coloneqq \lfloor \mathbf{s}_k^{\mathsf{T}}\mathbf{y} + f_k \bmod q\rceil_p$.
  - When responding to EvalO and ChalO queries, compute y as follows: Sample $e \leftarrow D_{\mathcal{R},\chi}$ and set $c = \left\lfloor \lfloor \xi \cdot (\mathbf{r}^{\mathsf{T}}\mathbf{y} + e) \bmod q\rceil_p \right\rceil_u$.
- Hyb_2: Identical to $\mathsf{WPRF\text{-}Exp}^1_{\Pi,\mathcal{A}}$ except that challenge and non-challenge PRF values are simulated by a simulator which is analogous to the simulator in $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ assumption.
- Hyb_3: This is the security experiment $\mathsf{WPRF\text{-}Exp}^1_{\Pi,\mathcal{A}}$.

The fact that Hyb_0 and Hyb_1 are statistically indistinguishable readily follows from the fact that $(2\xi\chi\sqrt{\varphi} + 1)p/q \leq \mathsf{negl}(\lambda)$, where we used Lemma 6, Remark 4 and the fact that $\varphi \geq \omega(\log \lambda)$. That is, with overwhelming probability, the error terms introduced do not modify the distributions.

To show that Hyb_1 and Hyb_2 are computationally indistinguishable, similarly to what done in Theorem 4, we rely on the $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ assumption. The reduction works as follows

- It receives $\mathbf{A}$ from the thLWE challenger, ignores it, and sends $\mathsf{pp} = \emptyset$ to $\mathcal{A}$.
- It receives $\mathcal{C} \subset_{<t} [K]$ from $\mathcal{A}$ and forwards it to thLWE challenger.
- It receives $(\mathbf{b}, (\mathbf{s}_k)_{k\in\mathcal{C}})$ from the thLWE challenger. It sets $(\mathsf{k}_k)_{k\in\mathcal{C}} = (\mathbf{s}_k)_{k\in\mathcal{C}}$, and sends it to $\mathcal{A}$.
- It initialises lists $L_{\mathsf{Query}} \coloneqq \emptyset$; $L_{\mathsf{Share}} \coloneqq \emptyset$; $L_{\mathsf{Party}} \coloneqq \emptyset$

Next, we discuss how queries to $\mathsf{EvalO}, \mathsf{ChalO}, \mathsf{ParEvalO}$ are dealt with.

- Queries $\mathsf{EvalO}(\mathsf{id})$: If $L_{\mathsf{Query}}[\mathsf{id}] = \emptyset$, query $\mathsf{GenLWE/SimLWE}$ to the thLWE challenger to obtain $(\mathbf{y}, z)$. Set $c \coloneqq \left\lfloor \lfloor \xi \cdot z\rceil_p \right\rceil_u$ and $L_{\mathsf{Query}}[\mathsf{id}] \coloneqq (c, \mathbf{y}, 0)$. Return $L_{\mathsf{Query}}[\mathsf{id}]$ to $\mathcal{A}$.
- Queries $\mathsf{ChalO}(\mathsf{id})$: If $L_{\mathsf{Query}}[\mathsf{id}] = \emptyset$, query $\mathsf{GenLWE/SimLWE}$ to the thLWE challenger to obtain $(\mathbf{y}, z)$. Sets $c \coloneqq \left\lfloor \lfloor \xi \cdot z\rceil_p \right\rceil_u$ and $L_{\mathsf{Query}}[\mathsf{id}] \coloneqq (c, \mathbf{y}, 1)$. Return $L_{\mathsf{Query}}[\mathsf{id}]$ to $\mathcal{A}$.

– Queries $\mathsf{ParEvalO}(\mathsf{id}, k \in [K])$:
  - Assert $L_{\mathsf{Query}}[\mathsf{id}] \neq \emptyset$.
  - Adds k to $L_{\mathsf{Party}}[\mathsf{id}]$.
  - Parse $(c, \mathsf{rnd}, \texttt{is_chal}) \leftarrow L_{\mathsf{Query}}[\mathsf{id}]$. If $\texttt{is_chal}$, assert that $|L_{\mathsf{Party}}[\mathsf{id}] \cup \mathcal{C}| < t$.
  - If $L_{\mathsf{Share}}[\mathsf{id}] = \emptyset$, then for all $i \in [K]$, query $\mathsf{ShareLWE}(\mathsf{rnd}, i)$ to the thLWE challenger to obtain $\hat{c}_i$ and set $c_i = \lfloor \hat{c}_i \rceil_p$. Set $L_{\mathsf{Share}}[\mathsf{id}] = (c_i)_{i \in [K]}$.
  - Parse $(c_i)_{i \in [K]} \leftarrow L_{\mathsf{Share}}[\mathsf{id}]$. Return c_k to $\mathcal{A}$.

A routine check confirms that the reduction is perfectly simulating Hyb_1 if $b = 0$, and Hyb_2 if $b = 1$. Therefore, the computational indistinguishability between Hyb_1 and Hyb_2 follows from the $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ assumption.

Note that, in Hyb_2, the simulator would never be asked to generate more than $t-1$ partial evaluations for any challenge input $\mathbf{y}$. By the pseudorandomness guarantee of the $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ assumption, the PRF values z and partial evaluations c_k corresponding to challenge inputs are uniformly random. We can therefore revert the simulation except for these values and arrive at Hyb_3. In other words, the computational indistinguishability between Hyb_2 and Hyb_3 follows from the $\mathsf{th\text{-}\$\text{-}LWE}_{\mathsf{params}}$ assumption. □

Remark 5. In the hop from Hyb_2 to Hyb_3, if we use the simulator $\mathcal{S}$ constructed in Appendix A, then the knowledge of $\mathbf{b}$ is not needed to simulate responses to $\mathsf{ParEvalO}$. Therefore, we can rely on a slightly weaker assumption, i.e. $\mathsf{LWE}_{\mathcal{R},n,Q,q,\chi}$.

D Code

D.1 Subtractive Set Expansion Factors

The following script is also attached.

```
from lattice_lib.geometric_norms import canon_norm
from sage.all import CyclotomicField, is_prime_power, radical, matrix, vector, ceil, log, Combinations

def integral_test(L):
    for tuple in L:
        for entry in tuple:
            if not entry.is_integral():
                return False
    return True

class Subtractive_Set_Params:
    """
    Class of subtractive sets consisting of all roots of unity.

    Examples:
    >>> SS_512_8 = Subtractive_Set_Params(512,8)
    >>> SS_512_8.estimate_all()
    >>> SS_512_8.print_construction()

    conductor: 512
    cardinality: 8
    ==================
    t:  2, slack:  2, log_rho:  5.52, log_gamma:  7.29
    t:  3, slack:  4, log_rho:  6.67, log_gamma:  9.00
    t:  4, slack:  4, log_rho:  6.51, log_gamma:  9.63
    t:  5, slack:  8, log_rho:  7.00, log_gamma: 11.00
    t:  6, slack:  8, log_rho:  6.51, log_gamma: 10.98
    t:  7, slack:  8, log_rho:  6.00, log_gamma: 10.68
    t:  8, slack:  8, log_rho:  5.52, log_gamma: 10.14

    SS_512_8 = Subtractive_Set_Params(512,8)
    SS_512_8.rho = {2: 46, 3: 102, 4: 91, 5: 128, 6: 91, 7: 64, 8: 46}
    SS_512_8.gamma = {2: 157, 3: 512, 4: 790, 5: 2048, 6: 2024, 7: 1640, 8: 1131}


    >>> SS_512_16 = Subtractive_Set_Params(512,16)
    >>> SS_512_16.estimate_all()
    >>> SS_512_16.print_construction()

    conductor: 512
```

```
cardinality: 16
==================
t:  2, slack:  2, log_rho:  6.00, log_gamma:  7.79
t:  3, slack:  4, log_rho:  8.04, log_gamma:  9.79
t:  4, slack:  4, log_rho:  8.70, log_gamma: 11.33
t:  5, slack:  8, log_rho: 10.00, log_gamma: 13.72
t:  6, slack:  8, log_rho: 10.03, log_gamma: 14.77
t:  7, slack:  8, log_rho:  9.85, log_gamma: 15.50
t:  8, slack:  8, log_rho:  9.50, log_gamma: 15.92
t:  9, slack: 16, log_rho: 10.00, log_gamma: 17.07
t: 10, slack: 16, log_rho:  9.41, log_gamma: 16.95
t: 11, slack: 16, log_rho:  8.73, log_gamma: 16.58
t: 12, slack: 16, log_rho:  8.09, log_gamma: 15.97
t: 13, slack: 16, log_rho:  7.51, log_gamma: 15.20
t: 14, slack: 16, log_rho:  7.00, log_gamma: 14.26
t: 15, slack: 16, log_rho:  6.51, log_gamma: 13.09
t: 16, slack: 16, log_rho:  6.00, log_gamma: 12.08

SS_512_16 = Subtractive_Set_Params(512,16)
SS_512_16.rho = {2: 64, 3: 264, 4: 415, 5: 1024, 6: 1048, 7: 926, 8: 725, 9: 1024, 10: 678, 11: 425, 12:
    ↪ 272, 13: 182, 14: 128, 15: 91, 16: 64}
SS_512_16.gamma = {2: 222, 3: 887, 4: 2573, 5: 13489, 6: 27931, 7: 46211, 8: 62178, 9: 137811, 10: 126779,
    ↪ 11: 97717, 12: 64410, 13: 37604, 14: 19581, 15: 8735, 16: 4330}

>>> SS_512_32 = Subtractive_Set_Params(512,32)
>>> SS_512_32.estimate_all()
>>> SS_512_32.print_construction()

conductor: 512
cardinality: 32
==================
t:  2, slack:  2, log_rho:  6.51, log_gamma:  8.29
t:  3, slack:  4, log_rho:  9.51, log_gamma: 10.66
t:  4, slack:  4, log_rho: 11.14, log_gamma: 13.29
t:  5, slack:  8, log_rho: 13.40, log_gamma: 16.76
t:  6, slack:  8, log_rho: 14.37, log_gamma: 18.89
t:  7, slack:  8, log_rho: 15.10, log_gamma: 20.73
t:  8, slack:  8, log_rho: 15.63, log_gamma: 22.32
t:  9, slack: 16, log_rho: 16.98, log_gamma: 24.69
t: 10, slack: 16, log_rho: 17.17, log_gamma: 25.86
t: 11, slack: 16, log_rho: 17.23, log_gamma: 26.85
t: 12, slack: 16, log_rho: 17.17, log_gamma: 27.66
t: 13, slack: 16, log_rho: 17.01, log_gamma: 28.32
t: 14, slack: 16, log_rho: 16.74, log_gamma: 28.82
t: 15, slack: 16, log_rho: 16.39, log_gamma: 29.18
t: 16, slack: 16, log_rho: 15.96, log_gamma: 29.39
t: 17, slack: 32, log_rho: 16.46, log_gamma: 30.46
t: 18, slack: 32, log_rho: 15.90, log_gamma: 30.39
t: 19, slack: 32, log_rho: 15.28, log_gamma: 30.18
t: 20, slack: 32, log_rho: 14.61, log_gamma: 29.82
t: 21, slack: 32, log_rho: 13.89, log_gamma: 29.32
t: 22, slack: 32, log_rho: 13.13, log_gamma: 28.66
t: 23, slack: 32, log_rho: 12.34, log_gamma: 27.85
t: 24, slack: 32, log_rho: 11.53, log_gamma: 26.86
t: 25, slack: 32, log_rho: 10.72, log_gamma: 25.70
t: 26, slack: 32, log_rho:  9.95, log_gamma: 24.35
t: 27, slack: 32, log_rho:  9.23, log_gamma: 22.84
t: 28, slack: 32, log_rho:  8.58, log_gamma: 21.19
t: 29, slack: 32, log_rho:  8.00, log_gamma: 19.48
t: 30, slack: 32, log_rho:  7.51, log_gamma: 17.63
t: 31, slack: 32, log_rho:  7.00, log_gamma: 15.55
t: 32, slack: 32, log_rho:  6.51, log_gamma: 14.04

SS_512_32 = Subtractive_Set_Params(512,32)
SS_512_32.rho = {2: 91, 3: 730, 4: 2256, 5: 10839, 6: 21245, 7: 35211, 8: 50657, 9: 129047, 10: 147804, 11:
    ↪  154144, 12: 147906, 13: 131729, 14: 109725, 15: 86049, 16: 63908, 17: 90380, 18: 61141, 19: 39747,
    ↪  20: 24935, 21: 15154, 22: 8960, 23: 5175, 24: 2950, 25: 1689, 26: 992, 27: 601, 28: 384, 29: 256,
    ↪ 30: 182, 31: 128, 32: 91}
SS_512_32.gamma = {2: 314, 3: 1620, 4: 10040, 5: 111212, 6: 487228, 7: 1743554, 8: 5243422, 9: 27060293,
    ↪ 10: 60839847, 11: 120561796, 12: 212416686, 13: 334968081, 14: 475131734, 15: 608403489, 16:
    ↪ 705026090, 17: 1480831775, 18: 1410059967, 19: 1216825669, 20: 950300012, 21: 670002558, 22:
    ↪ 424947621, 23: 241308899, 24: 121959545, 25: 54507533, 26: 21452402, 27: 7485519, 28: 2392190, 29:
    ↪ 728794, 30: 203193, 31: 47844, 32: 16873}
"""

def __init__(self,f,g = None):
    """
```

```
    Generate a subtractive set in the f-th cyclotomic ring consisting of g-th roots of unity, where g
        ↪ divides f. By default, g = f.
    """
    if g == None:
        g = f
    assert g.divides(f)
    K = CyclotomicField(f)
    z = K.gen()
    self.f = f
    self.g = g
    self.K = K
    self.S = [(z**(f/g))**i for i in range(g)] ## Exclude 0
    # The slack (denoted by xi on paper) is a function of t such that the slack times the inverse of the
        ↪ Vandermonde matrix induced by any t-subset of S is integral.
    if is_prime_power(f):
        p = radical(f)
        self.slack = dict([(t,p**(ceil(log(t, p)))) for t in range(2,self.g+1)])
    else:
        self.slack = dict([(t,f) for t in range(2,self.g+1)])
    self.rho = {}
    self.gamma = {}

def estimate(self,t,mode='first',num_trials = 100):
    """
    Estimate the recovery-expansion factor rho(t) and inverse-expansion factor gamma(t) of the given
        ↪ subtractive set self.S for a given threshold t.
    There are 3 modes: 'first', 'random', and 'exhaust'.
    The 'first' mode uses the heuristics that picking the first t elements of the given subtractive set is
        ↪ the worst case.
    The 'random' mode samples num_trials many t-subsets.
    The 'exhaust' mode enumerates all t-subsets. WARNING: This takes time exponential in t.
    """
    assert t > 1
    assert t <= len(self.S)

    if mode == 'first':
        T_list = [range(t)]
    elif mode == 'random':
        T_list = [Combinations(len(self.S), t).random_element() for _ in range(num_trials)]
    else: # mode == 'exhaust'
        T_list = Combinations(len(self.S), t)

    for T in T_list:
        V_T = matrix.vandermonde(self.S)[T,:t]
        rec_coeff = self.slack[t] * (~V_T)[0]
        assert integral_test(rec_coeff)
        assert rec_coeff * V_T == vector([self.slack[t]] + [0 for _ in range(t-1)])
        candidate_rho = ceil(canon_norm(rec_coeff))
        if t not in self.rho or candidate_rho > self.rho[t]:
            self.rho[t] = candidate_rho

    if mode == 'first':
        T_list = [range(t-1)]
    elif mode == 'random':
        T_list = [Combinations(len(self.S), t-1).random_element() for _ in range(num_trials)]
    else: # mode == 'exhaust'
        T_list = Combinations(len(self.S), t-1)

    for T in T_list:
        V_S = matrix.vandermonde(self.S)[:,:t]
        V_T = matrix([1] + [0 for _ in range(t-1)]).stack(matrix.vandermonde(self.S)[T,:t])
        Z = self.slack[t] * V_S * ~V_T
        assert integral_test(Z)
        assert Z * V_T == self.slack[t] * V_S
        candidate_gamma = ceil(canon_norm(Z))
        if t not in self.gamma or candidate_gamma > self.gamma[t]:
            self.gamma[t] = candidate_gamma

def estimate_all(self,mode='first',num_trials=100):
    """
    Estimate the recovery-expansion factor rho(t) and inverse-expansion factor gamma(t) of the given
        ↪ subtractive set self.S for all values of t.
    """
    print(f'conductor: {self.f}')
    print(f'cardinality: {self.g}')
    print(f'====================')
    for t in range(2,self.g+1):
```

```
            self.estimate(t,mode,num_trials)
            print(f't: {t:2d}, slack: {self.slack[t]:2d}'
                  + f', log_rho: {log(self.rho[t],2).n():5.2f}'
                  + f', log_gamma: {log(self.gamma[t],2).n():5.2f}')
        print()

    def show(self):
        """
        Print the slack and expansion factors.
        """
        print(f'conductor: {self.f}')
        print(f'cardinality: {self.g}')
        print(f'====================')
        for t in range(2,self.g+1):
            print(f't: {t:2d}, slack: {self.slack[t]:2d}'
                  + f', log_rho: {log(self.rho[t],2).n():5.2f}'
                  + f', log_gamma: {log(self.gamma[t],2).n():5.2f}')
        print()

    def print_construction(self):
        print(f'SS_{self.f}_{self.g} = Subtractive_Set_Params({self.f},{self.g})')
        print(f'SS_{self.f}_{self.g}.rho = {self.rho}')
        print(f'SS_{self.f}_{self.g}.gamma = {self.gamma}')
```

D.2 Parameter Selection

The following script is also attached.

```
"""
This script estimates the parameters of the threshold PKE scheme Pilvi.
"""

from subtractive_set_estimate import *

from dataclasses import dataclass
import sys
sys.path.append('./lattice-estimator')

from estimator import LWE, ND
from estimator.nd import sigmaf,stddevf
from sage.all import var, log, ceil, floor, sqrt, Infinity, euler_phi, round, pi, n
import os

class HiddenPrints:
    def __enter__(self):
        self._original_stdout = sys.stdout
        sys.stdout = open(os.devnull, "w")

    def __exit__(self, exc_type, exc_val, exc_tb):
        sys.stdout.close()
        sys.stdout = self._original_stdout

@dataclass
class TPKEParams:
    """
    Dataclass for the parameters of the threshold PKE scheme Pilvi.
    """

    secpar: int # security level
    f: int # conductor
    n: int # module rank, height of matrix A
    m: int # width of matrix A
    q: int # modulus
    t: int # recovery threshold
    K: int # number of users
    ell: int # message dimension
    Q: int # number of partial decryption queries

    def __repr__(self):
        return f"TPKE( secpar: {self.secpar:3d}, f: {self.f:3d}, phi: {self.phi():3d}, n: {self.n:1d}, m: {self
            ↪ .m:1d}, q: 2^{ceil(log(self.q,2)):3d}, t: {self.t:1d}, K: {self.K:3d}, ell: {self.ell:1d}, Q: {
            ↪ self.printQ():3s}, (|ct|: {self.ct():5s}, |pd|: {self.pd():4s} )"

    def printQ(self):
        if self.Q < 100:
```

```
            return self.Q.str()
        else:
            return f'2^{round(log(self.Q,2))}'
    def phi(self):
        return euler_phi(self.f)

    def ct(self):
        # return ciphertext size in KB
        return f'{n((self.n + self.ell)* self.phi() * log(self.q,2) / (1<<13)):5.1f}'

    def pd(self):
        # return partial decryption size in KB
        return f'{n(self.ell * self.phi() * log(self.q,2) / (1<<13)):5.1f}'

def tpke_params(secpar, f, base_n, t, Xi, Q = 2**60, ratio_m = 2):

    """
    Compute the parameters of the threshold PKE scheme Pilvi.

    Parameters:
    - secpar: the minimum security parameter
    - f: the conductor of the cyclotomic field
    - base_n: the base value of the module rank n
    - t: the recovery threshold
    - Xi: a xi(t)-subtractive set
    - Q: the maximum number of partial decryption queries, default is 2^60
    - ratio_m: the matrix A will be of dimension n x m with m = ratio_m * n + ell where ell = ceil(2*secpar/phi
        ↪ ) is the plaintext dimension, default is 2

    Returns:
    - An instance of TPKEParams, describing the parameters of the threshold PKE scheme
    """

    phi = euler_phi(f)
    ell = ceil(2*secpar/phi) # plaintext dimension
    for n in range(base_n,max([2*base_n, 10]),1):
        m = ratio_m * n + ell
        slack = Xi.slack[t]
        rho = Xi.rho[t]
        gamma = Xi.gamma[t]
        sigma_x = sqrt(2 * phi * m * log(2 * phi * m * 2**secpar)/pi)    # upper bound of smoothing parameter
            ↪ of R^m in canonical embedding
        beta_x = sigma_x * sqrt(phi * m)
        chistar_1 = sigma_x
        chistar_2 = (beta_x * sqrt(Q) + 1) * sigma_x
        chimain = 2 * gamma * (beta_x * sqrt(Q) + 1) * sigma_x
        q = ceil( 4 * chimain * sqrt(phi) * (slack * beta_x * sqrt(m) + sqrt(t) * rho) )

        lwe1 = LWE.Parameters(
            n=phi*n, m = phi*m, q=q, Xs=ND.UniformMod(q), Xe=ND.DiscreteGaussian(stddevf(chistar_1))
        )
        lwe2 = LWE.Parameters(
            n=phi*n, m = phi*ceil(m/log(q,sigma_x)), q=q, Xs=ND.UniformMod(q), Xe=ND.DiscreteGaussian(stddevf(
                ↪ chistar_2))
        )
        lwe3 = LWE.Parameters(
            n=phi*(m-n-ell), m = phi*(n+ell), q=q, Xs=ND.DiscreteGaussian(stddevf(sigma_x)), Xe=ND.
                ↪ DiscreteGaussian(stddevf(sigma_x))
        )
        lwe_params = [ # comment out LWE instance if estimation is not needed
            lwe1,
            lwe2, # chistar_2 is so large that the cost of lwe2 is +Infinity
            lwe3, # hardness is set to be the same as lwe1
        ]

        with HiddenPrints():
            lwe_costs = []
            for lwe in lwe_params:
                costs = LWE.estimate(lwe, deny_list=("arora-gb", "bkw", "bdd_hyrbid", "bdd_mitm_hybrid"))
                lwe_costs += [costs]

        min_lwe_costs = []
        for costs in lwe_costs:
            min_cost = log(min(cost["rop"] for cost in costs.values()),2)
            min_cost = floor(min_cost) if min_cost < Infinity else Infinity
            min_lwe_costs += [min_cost]
```

```
        min_lwe_cost = min(min_lwe_costs)

        print(f'secpar: {min_lwe_costs}, n: {n}, q: 2^{ceil(log(q,2)):3d}')

        if (
            min_lwe_cost >= secpar
        ):
            tpke = TPKEParams(min_lwe_cost, f, n, m, q, t, Xi.g, ell, Q)
            print(f"{tpke}")
            return tpke

def gen_tpke_params(secpar, tns, f, Xi, Q = 2**60, ratio_m = 2):
    """
    Parameters:
    - secpar: the minimum security parameter
    - tns: a list of tuples (t, base_n), where t is the recovery threshold and base_n is the base value of the
        ↪ module rank n
    - f: the conductor of the cyclotomic field
    - Xi: a xi(t)-subtractive set
    - Q: the maximum number of partial decryption queries, default is 2^60
    - ratio_m: the matrix A will be of dimension n x m with m = ratio_m * n + ell where ell = ceil(2*secpar/phi
        ↪ ) is the plaintext dimension, default is 2

    Examples:
    >>> param_table = {}
    >>> SS_512_8 = Subtractive_Set_Params(512,8)
    >>> SS_512_8.rho = {2: 46, 3: 102, 4: 91, 5: 128, 6: 91, 7: 64, 8: 46}
    >>> SS_512_8.gamma = {2: 157, 3: 512, 4: 790, 5: 2048, 6: 2024, 7: 1640, 8: 1131}
    >>> tns = [
            (2, 4),
            (3, 4),
            (4, 4),
            (5, 4),
            (6, 4),
            (7, 4),
        ]
    >>> tpke_params_Q0 = gen_tpke_params(secpar = 128, tns = tns, f = 512, Xi = SS_512_8, Q = 0)
    >>> for tpke in tpke_params_Q0:
    >>>     param_table['0', tpke.t] = (tpke.secpar, tpke.n, ceil(log(tpke.q,2)), tpke.ct(), tpke.pd())
    """
    params = []
    for t, base_n in tns:
        print(f"=========================")
        print(f"t: {t}, K: {Xi.g}, Q: {Q if Q<100 else f'2^{round(log(Q,2))}'}")
        print(f"=========================")
        tpke = tpke_params(secpar=secpar, f=f, base_n=base_n, t=t, Xi=Xi, Q=Q, ratio_m=ratio_m)
        params += [tpke]
        if not tpke == None:
            n = tpke.n
        print("=====\n")
    return params
```