Round5: KEM and PKE based on (Ring) Learning with Rounding

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2 Cover Sheet

Name of the proposed cryptosystem:	The proposed cryptosystem is called *Round5*. Round5 consists of a key-encapsulation mechanism (KEM) named *r5_cpa_kem*, and a public-key encryption (PKE) scheme named *r5_cca_pke*.
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2 Algorithm Specifications

This submission proposes Round5 that consists of algorithms for key encapsulation mechanisms, namely r5_cpa_kem and r5_cca_pke, and the public-key encryption scheme r5_cca_pke. Round5's r5_cpa_kem algorithm uses Round5's IND-CPA secure parameter sets. Round5's r5_cca_kem and r5_cca_pke algorithms require Round5's IND-CCA secure parameter sets.

The proposed algorithms fall under the category of lattice-based cryptography. Round5 is a merger of the submissions Round2 [15, 16] and HILA5 [94, 96]. Like with Round2, the security relies on the General Learning With Rounding (GLWR) problem, which allows for a unified design for instantiations based on Learning with Rounding (LWR) or Ring Learning with Rounding (RLWR). In some of its parameter sets, Round5 uses an error-correcting code based on the one from HILA5 to decrease the decryption failure probability, and thus, achieve smaller keys and better performance.

The submission is structured as follows:

- Section 2.1 reviews the design rationale of Round5.
- Section 2.2 contains preliminaries and explains notation.
- Section 2.3 defines the General Learning with Rounding problem.
- Section 2.4 and Figure 1 detail the Round5 algorithms and building blocks in a formal way. Section 2.4.7 detail the parameter sets.

  The Round5 cryptosystem proposes a unified scheme that can be configured to fit the needs of different applications. This specification details 18 main parameters sets: six ring parameter sets with error correction, six ring parameter sets without error correction, and six non-ring parameter sets. Each set of six parameter sets is IND-CPA and IND-CCA secure and for NIST security levels 1, 3 and 5. The IND-CPA secure parameter sets are provided in Tables 4, 5 and 6. These parameter sets can be used with r5_cpa_kem. Tables 8, 9 and 10summarize the IND-CCA secure parameter sets that can be used with r5_cca_kem and r5_cca_pke.

  Round5 has three additional "specific use-case" parameter sets with the only purpose of demonstrating the flexibility of Round5 and its applicability to a number of diverse, specialized usage scenarios. These parameter sets can be found in Tables 7 and 11.
- Section 2.5 contains information on the Known Answer Test Values.
- Section 2.6 and Figure 2 show that the Round5 family of algorithms stems from a provable secure design. More details can be found in Appendix A.
- Section 2.7 analyzes the concrete security of Round5 from the perspective of best known attacks.

- Section 2.8 reviews the correctness of Round5, in particular, it contains an analysis of the probability of a decapsulation or decryption error.
- Section 2.9 describes the various parameter sets and their performance. Section2.9.4 describes various countermeasures against side-channel attacks. In Appendix B, it is detailed how a parameter required for such a countermeasure has been computed.
- Section 2.10 discusses advantages and limitations of Round5.
- Section 2.11 details Round5 from an implementation perspective, including the specification of the bit ordering, of hash functions, and of functions used for generating randomness.

2.1 Design Rationale

Round5's design rationale is characterized by 3 features: a) a unified design; b) design choices for optimized performance; c) ring choice.

2.1.1 A Unified Design

A key feature of Round5 is that it has been designed so that it can be instantiated with the Learning With Rounding (LWR) problem and the Ring Learning With Rounding (RLWR) problem in a seamless and unified way. This is done by defining the General LWR problem, on which Round5 is based, that can instantiate LWR or RLWR depending on the input parameters. The reasons behind this choice are as follows:

Round5 is adaptive and can be applied to multiple environments. On the one hand, LWR-based algorithms are required in environments in which performance is less of an issue, but security is the priority. In those cases, it is often preferred to not have an additional ring structure (as in ideal lattices [79, 61]). On the other hand, RLWR-based algorithms achieve the best performance in terms of bandwidth and computation so they are better suited for constrained environments with stricter bandwidth requirements, e.g., due to the complexity of message fragmentation or small MTUs. It is possible to derive especially small parameter sets applicable to IoT scenarios, or non-ring parameter sets with balanced or unbalanced public-key and ciphertext sizes.

Round5 reduces code analysis and maintenance since the unified scheme definitions of r5_cpa_kem, r5_cca_kem and r5_cca_pke instantiate different underlying problems, LWR and RLWR, with the same code.

The unified design enables a migration strategy from ring-based schemes to non-ring schemes from day one of deployment. This makes sure that if vulnerabilities in ring-based problems were to be found in future, then an alternative secure solution would already be available and could be deployed directly. Indeed, a series of results [43, 42, 25] and most recently [87] indicate that Ideal Approximate-SVP [104], a problem typically considered to justify the hardness of the Ring-LWE problem may be a weaker problem than Approximate-SVP for

arbitrary lattices. Although this still does not call into question the hardness of Ring-LWE or Ring-LWR, it does raise a need to be conservative and offer competitive alternatives that do not rely on the hardness of lattice problems on structured lattices.

2.1.2 Design choices for optimized performance

Round5's design aims at optimizing performance.

- The usage of GLWR, i.e., LWR and RLWR, rather than their LWE counterparts, leads to lower bandwidth requirements in Round5, since fewer bits need to be transmitted per coefficient.
- Rounding avoids sampling of noise, and thus reduces the amount of random data to be generated. The generation of noise may be vulnerable to both implementation errors and side-channel attacks, see [91],[64] and the references therein, which is a further advantage of not having to generate noise samples.
- Round5 relies on a definition of GLWR with sparse ternary secrets. This simplifies implementation and reduces the probability of decryption/decapsulation errors.
- The ring instantiation of Round5 relies on the RLWR problem over the cyclotomic ring $\mathbb{Z}_q[x]/\Phi_{n+1}(x)$ with $n+1$ prime. This problem is well studied: there exist reductions [20] from the RLWE problem [79] to RLWR, and the former is well-studied for the ring in question. Operations over this ring can be mapped to an NTRU [61] ring $\mathbb{Z}_q[x]/(x^{n+1}-1)$ to improve performance.
- For some of its parameter sets, Round5 uses an f-bit error correcting block code XEf to decrease the failure probability, see Section 2.4.1. The code is built using the same strategy as codes used by TRUNC8 [96] (2-bit correction) and HILA5 [95] (5-bit correction). The main advantage of XEf codes is that they avoid table look-ups and conditions altogether, and are therefore resistant to timing attacks. The usage of XEf requires performing the ciphertext computations in the NTRU ring and requires sparse ternary secrets that are balanced, i.e., contain equally many ones as minus ones. This leads to independent bit failures so that error correction can be applied (Section 2.4.1).
- The moduli q and p are powers of two. This simplifies the implementation of the rounding function, as it can be realized by ignoring the least significant bits. Similarly, the modular computations can be realized by ignoring the most significant bits.
- Preventing pre-computation attacks requires refreshing the master public parameter $\boldsymbol{A}$. However, this can be computationally costly, in particular in the case of LWR. Round5 provides several alternatives for efficiently refreshing $\boldsymbol{A}$ that are applicable to different use cases.

2.1.3 The Choice of the Ring

In the literature, a common choice of the ring to instantiate an RLWE or RLWR scheme is $\mathbb{Z}_q[x]/\Phi_{2n}(x)$ where n is a power of two, so that the $2n$-th cyclotomic polynomial $\Phi_{2n}(x) = x^n + 1$. Examples of RLWE/RLWR key exchange schemes based on the above ring are [30] and [9]. However, requiring that n be a power of two severly the choice of n: it has to be a power of two, and it has to be at least 512 for the proper security level so that the underlying lattice problem is hard to solve in practice. While having $n = 512$ sometimes does not deliver the target security level, the $n = 1024$ choice would be considered an overkill. A sweet spot is $n \approx 700$, which was a common choice made by many proposals, including Kyber [31], NTRUEncrypt [61], NTRU-KEM [66] and more.

The following observations can be made:

- Kyber [31] uses three RLWE instances, each of dimension 256, to achieve $n = 768$ in total. This still limits the choice of n as it has to be a multiple of 256.
- NTRUEncrypt uses the reduction polynomial $x^n - 1$ which is slightly different from a cyclotomic ring, although the NTRU problem remains hard for this ring, the decisional RLWE problem over this ring seems to be easy [93].

This leads us to use as reduction polynomial the $(n+1)$-th cyclotomic polynomial $\Phi_{n+1}(x) = x^n + \cdots + x + 1$ with $n + 1$ a prime as in NTRU-KEM [66]. With this reduction polynomial, there is a wide range of n to choose from, for various security levels. In addition, as shown in [86], decisional RLWE over this ring remains hard for any modulus; this gives us confidence in the underlying design and security of Round5. Note that although operating over the same ring as the NTRU-KEM scheme, Round5 achieves better performance because its key generation algorithm is significantly faster than the NTRU key generation algorithm.

In addition, since decisional RLWE is hard over a prime cyclotomic ring with any modulus [86], we can use any modulus that optimizes our performance. Common choices of the modulus are

- A number theoretical transform (NTT) friendly prime number, such as 12289 in [9] (note that NTT is not compatible with rounding operations naively);
- A composite number that fits in a data type for modern computers, such as $2^{32} - 1$ in [30];
- A power of two that makes modulo operations and integer multiplications efficient, such as 2^{11} in NTRUEncrypt [61].

In our proposal, we consider a prime cyclotomic polynomial ring with a modulus q that is a power of two such that the Φ_{n+1} is irreducible modulo two. As Φ_{n+1} then is irreducible modulo q, the ring $\mathbb{Z}_q[x]/\Phi_{n+1}(x)$ does not have

any proper subrings. This choice allows for a smooth implementation of the ring and non-ring cases in the unified scheme. All coefficients of our polynomials and matrices are integers modulo q less than 2^{16}. That is, each coefficient fits in a `uint16_t` type. For intermediate values during computations, overflows can be ignored, as overflown bits are "mod-ed out" once the element is lifted back to $\mathbb{Z}_q$. In particular, when multiplying two `uint16_t` elements, only the lower 16 bits of the product need to be computed; the higher 16 bits have no effect on the final result.

The use of a composite modulus in [30], as well as the result from [86] suggest that the particular modulus does not have much effect on the hardness of the problem; the size of the modulus is more important from this point of view. Consequently, any modulus of similar size should deliver a similar security level, and therefore depending on the use case we choose the one that is the most efficient.

We finally remark that in the parameter sets of Round5 that use error correction, operations on one component of the ciphertext, as well as decryption, use reduction modulo $x^{n+1} - 1$. The reason for doing so, as explained in Section 2.8, is to avoid correlated errors, which would make error correction much less effective.

2.2 Preliminaries

For each positive integer a, we denote the set $\{0, 1, \ldots, a-1\}$ by $\mathbb{Z}_a$. For a set A, we denote by $a \xleftarrow{\$} A$ that a is drawn uniformly from A. If χ is a probability distribution, then $a \leftarrow \chi$ means that a is drawn at random according to the probability distribution χ. Logarithms are in base 2, unless specified otherwise.

Modular reductions. For a positive integer α and $x \in \mathbb{Q}$, we define $\{x\}_\alpha$ as the unique element x' in the interval $(-\alpha/2, \alpha/2]$ satisfying $x' \equiv x \pmod{\alpha}$. Moreover, we define $\langle x \rangle_\alpha$ as the unique element x' in the interval $[0, \alpha)$ for which $x \equiv x' \pmod{\alpha}$.

Rounding. For $x \in \mathbb{Q}$, we denote by $\lfloor x \rfloor$ and $\lfloor x \rceil$ rounding downwards to the next integer and rounding to the closest integer (with rounding up in case of a tie) respectively. For positive integers a, b and $h \in \mathbb{Q}$, the rounding function $\mathrm{R}_{a \to b,h}$ is defined as

$$\mathrm{R}_{a \to b,h}(x) = \left\langle \left\lfloor \frac{b}{a}(x+h) \right\rfloor \right\rangle_b . \tag{1}$$

If $h = \frac{a}{2b}$, then $\mathrm{R}_{a \to b,h}(x) = \langle \lfloor \frac{b}{a} x \rceil \rangle_b$. This special case of rounding will be used in the underlying problem for Round5, so the following notation will come in handy: for positive integers a, b, the function $\mathrm{R}_{a \to b}$ is defined as

$$\mathrm{R}_{a \to b} = \mathrm{R}_{a \to b, a/2b}. \tag{2}$$

Ring choice. Let $n+1$ be prime. The $(n+1)$-th cyclotomic polynomial $\Phi_{n+1}(x)$ then equals $x^n + x^{n-1} + \cdots + x + 1$. We denote the polynomial ring $\mathbb{Z}[x]/\Phi_{n+1}(x)$ by $\mathcal{R}_n$. When n equals 1, then $\mathcal{R}_n = \mathbb{Z}$. For each positive integer a, we write $\mathcal{R}_{n,a}$ for $\mathbb{Z}_a[x]/\Phi_{n+1}(x)$. We call a polynomial in $\mathcal{R}_n$ *ternary* if all its coefficients are 0, 1 or -1. Throughout this document, regular font letters denote elements from $\mathcal{R}_n$, and bold lowercase letters represent vectors with coefficients in $\mathcal{R}_n$. All vectors are column vectors. Bold uppercase letters are matrices. The transpose of a vector $\boldsymbol{v}$ or a matrix $\boldsymbol{A}$ is denoted by $\boldsymbol{v}^T$ or $\boldsymbol{A}^T$. A vector or matrix of polynomials, in which all polynomial entries have all their coefficients equal to 1, is denoted by $\boldsymbol{j}$ or $\boldsymbol{J}$, respectively.

Distributions. For each $v \in \mathcal{R}_n$, the **Hamming weight** of v is defined as its number of non-zero coefficients. The Hamming weight of a vector in $\mathcal{R}_n^k$ equals the sum of the Hamming weighs of its components. We denote with $\mathcal{H}_{n,k}(h)$ the set of all vectors $\boldsymbol{v} \in \mathcal{R}_n^k$ of ternary polynomials of Hamming weight h, where $h \leq nk$. By considering the coefficients of a polynomial in $\mathcal{R}_n$ as a vector of length n, a polynomial in $\mathcal{H}_{n,k}(h)$ corresponds to a ternary vector of length nk with non-zeros in h positions, so that $\mathcal{H}_{n,k}(h)$ has $\binom{nk}{h}2^h$ elements. When $k = 1$, we omit it from the notation, and $\mathcal{H}_n(h)$ denotes the set of all ternary polynomials in $\mathcal{R}_n$ of Hamming weight h, corresponding to the set of all vectors $\boldsymbol{v} \in \{-1, 0, 1\}^n$ with Hamming weight h.

Secret keys consist of matrices that contain (column) vectors in $\mathcal{H}_{n,k}(h)$. Functions f_R and f_S are used to generate secrets from a seed in the encryption (Algorithm 2) and decryption (Algorithm 3), respectively.

2.3 The General Learning With Rounding Problem

The problem underlying the security of Round5 is the **General Learning With Rounding (GLWR) problem** formally defined as follows:

Definition 2.3.1 (General LWR (GLWR))**.** *Let d, n, p, q be positive integers such that $q \geq p \geq 2$, and $n \in \{1, d\}$. Let $\mathcal{R}_{n,q}$ be a polynomial ring, and let D_s be a probability distribution on $\mathcal{R}_{n,q}^{d/n}$*

The search version of the GLWR problem $\mathtt{sGLWR}_{d,n,m,q,p}(D_s)$ is as follows: given m samples of the form $R_{q\to p}(\boldsymbol{a}_i^T \boldsymbol{s})$ with $\boldsymbol{a}_i \in \mathcal{R}_{n,q}^{d/n}$ and a fixed $\boldsymbol{s} \leftarrow D_s$, recover $\boldsymbol{s}$.

The decision version of the GLWR problem $\mathtt{dGLWR}_{d,n,m,q,p}(D_s)$ is to distinguish between the uniform distribution on $\mathcal{R}_{n,q}^{d/n} \times \mathcal{R}_{n,p}$ and the distribution $(\boldsymbol{a}_i, b_i = R_{q\to p}(\boldsymbol{a}_i^T \boldsymbol{s}))$ with $\boldsymbol{a}_i \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n}$ and a fixed $\boldsymbol{s} \leftarrow D_s$.

For brevity, when $D_s = \mathcal{U}\left(\mathcal{H}_{n,d/n}(h)\right)$, we denote $\mathtt{GLWR}_{d,n,m,q,p}\left(\mathcal{U}\left(\mathcal{H}_{n,d/n}(h)\right)\right)$ as $\mathtt{GLWR}_{\mathrm{spt}}$. When the secret distribution D_s is the uniform one over $\mathcal{R}_{n,q}^{d/n}$, it shall be omitted in the above problem notation.

Instantiating GLWR as LWR. When $n = 1$, the GLWR problem is equivalent to the LWR problem [20] with dimension d, large modulus q and rounding modulus p. Setting the distribution $D_s = \mathcal{U}(\mathcal{H}_{1,d}(h))$ further specializes the GLWR problem to the LWR problem with sparse-ternary secrets $\mathtt{LWR}_{\mathrm{spt}}$. In [40] it is claimed that the hardness of $\mathtt{LWR}_{\mathrm{spt}}$ can be obtained from that of LWE with similar secret distributions since the reduction from LWE to LWR is independent of the secret's distribution [26]. We extend this claim and make it explicit by proving that for appropriate parameters there exists a polynomial-time reduction from the (decision) Learning with Errors (LWE) problem with secrets chosen uniformly from $\mathbb{Z}_q^d$ and errors chosen from a Gaussian distribution D_α, to the decision version of $\mathtt{LWR}_{\mathrm{spt}}$. See Section A.7 and Theorem A.7.1 for more details.

Instantiating GLWR as RLWR. When $n = d > 1$ is such that $n + 1$ is prime, and $\mathcal{R}_{n,q} = \mathbb{Z}_q[x]/(\Phi_{n+1}(x))$ for the $n + 1$-th cyclotomic polynomial $\Phi_{n+1}(x) = 1 + x + \ldots + x^n$, the GLWR problem is equivalent to the RLWR problem with reduction polynomial $\Phi_{d+1}(x)$, dimension d, large modulus q and rounding modulus p. Setting $D_s = \mathcal{U}(\mathcal{H}_{d,1}(h))$ further specializes it to the RLWR problem with sparse-ternary secrets $\mathtt{RLWR}_{\mathrm{spt}}$.

Possible instantiation as Module Learning with Rounding (MLWR) The NIST submission CRYSTALS-Kyber [14] has as underlying problem the Module LWE (MLWE) problem [76]. In prior work [34], MLWE was first introduced as the General Learning with Errors problem, but only instantiated with the ring case and the non-ring cases. The NIST submission SABER [45] has the corresponding Module LWR(MLWR) problem as underlying hard problem. In both submissions, the rationale is that a single ring needs to be optimized, and that different security levels can be obtained by choosing a different module rank.

In contrast, Round5 can easily choose from many different possible rings $\mathcal{R}_{n,q}$. We note that if the GLWR condition $n \in \{1, d\}$ is relaxed by stipulating that n only needs to be a divisor of d, this would lead to the MLWR problem with module rank equal to d/n. In this configuration, it would be possible to vary over d, n and the moduli p, q and t, allowing for even a more fine-grained optimization.

2.4 Round5

Our proposal is called Round5. It includes an IND-CPA and IND-CCA secure parameter sets. We include the the IND-CPA parameter sets since they provide much better performance, both bandwidth and CPU-wise, being therefore very suitable for ephemeral protocols.

The IND-CPA secure parameter sets are used in Round5's CPA KEM, r5_cpa_kem. The IND-CCA secure parameter sets are used in Round5's CCA KEM and CCA PKE, r5_cca_kem and r5_cca_pke. A public-key encryption

scheme called r5_cpa_pke is used as a building block for r5_cpa_kem. The key encapsulation mechanism r5_cca_kem is used as a building block for r5_cca_pke.

These schemes use choices and scheme-specific mappings that are described in the following sections with each scheme. In Section 2.4.1, the error-correcting codes applied in some parameter sets of Round5 are described. These codes are built using the same strategy as codes used by TRUNC8 [96] (2-bit correction) and HILA5 [95] (5-bit correction). In each protocol instantiation, Round5 uses a fresh public parameter $\boldsymbol{A}$. In Section 2.4.2, three methods for generating $\boldsymbol{A}$ are described. The IND-CPA secure KEM, r5_cpa_kem, is described in Section 2.4.4, preceded by the description of Round5's main building block r5_cpa_pke in Section 2.4.3. The IND-CCA secure PKE, r5_cca_pke, is described in Section 2.4.6, preceded by its building block, the IND-CCA secure KEM, r5_cca_kem, in Section 2.4.5. Figure 1 provides an overview of our proposal. It also shows the different instantiations of the proposed schemes based on the underlying GLWR problem.

Figure 1: Submission overview

2.4.1 Internal building block: error correction code

In [53], it is analyzed how error-correcting codes can be used to enhance the error resilience of protocols like [8] [29],[31], and it is shown that the usage of error correcting codes can significantly increase the estimated bit-security and decrease the communication overhead. For some of its parameter sets, Round5 uses an f-bit error correcting block code XEf to decrease the failure probability. The code is built using the same strategy as codes used by TRUNC8 [96] (2-bit correction) and HILA5 [95] (5-bit correction).

XEf. The XEf code is described by $2f$ "registers" r_i of size $|r_i| = l_i$ with $i = 0, \ldots, 2f - 1$. We view the κ-bits payload block m as a binary polynomial

$m_{\kappa-1}x^{\kappa-1}+\cdots+m_1x+m_0$ of length κ. Registers are defined via cyclic reduction

$$r_i = m \bmod x^{l_i} - 1, \tag{3}$$

or equivalently by

$$r_i[j] = \sum_{k \equiv j \bmod l_i} m_k \tag{4}$$

where $r_i[j]$ is bit j of register r_i. A transmitted message consists of the payload m concatenated with register set r (a total of $\mu = \kappa + xe$ bits, where $xe = \sum l_i$).

Upon receiving a message $(m' \mid r')$, one computes the register set r'' corresponding to m' and compares it to the received register set r' – that may also have errors. Errors are in coefficients m'_k where there are parity disagreements $r'_i[k \mod l_i] \neq r''_i[k \mod l_i]$ for multitude of registers r_i. We use a majority rule and flip bit m'_k if

$$\sum_{i=0}^{2f-1} ((r'_i[\langle k \rangle_{l_i}] - r''_i[\langle k \rangle_{l_i}]) \bmod 2) \geq f + 1 \tag{5}$$

where the sum is taken as the number of disagreeing register parity bits at k.

XEf codes can include a special register – that is marked with symbol $(*)$ such that $\ell^{(*)}$ divides κ, and the parity bits in register $r^{(*)}$ are computed as the sum of $\kappa/\ell^{(*)}$ consecutive bits. That is, for $0 \leq j \leq l^{(*)} - 1$, bit $r^{(*)}[j]$ is defined as

$$r^{(*)}[j] = \sum_{i=0}^{\frac{\kappa}{\ell^{(*)}}-1} m_{j \cdot \frac{\kappa}{\ell^{(*)}}+i}.$$

In HILA5[95]'s XE5 code, r_0 is such a special register. When using this special register, decoding is done as explained above, but with the term corresponding to the special register $r^{(*)}$ replaced by $\left(r'^{(*)}[\lfloor \frac{k\ell^{(*)}}{\kappa} \rfloor] - r''^{(*)}[\lfloor \frac{k\ell^{(*)}}{\kappa} \rfloor]\right) \mod 2$.

As shown in HILA5[95], if all length pairs satisfy $\mathrm{lcm}(l_i, l_j) \geq \kappa$ when $i \neq j$, then this code always corrects at least f errors. If the XEf code includes a special register $r^{(*)}$, say $r^{(*)} = r_0$, then it is required that $\frac{\kappa}{\ell_0} \leq l_i$ for all $j \geq 1$ and $\mathrm{lcm}(l_i, l_j) \geq \kappa$ for $i, j \geq 1$ and $i \neq j$.

The main advantage of XEf codes is that they avoid table look-ups and conditions altogether and are therefore resistant to timing attacks.

Requirements for using XEf in Round5. A basic requirement for using XEf error correction code is that the errors it aims to correct are independent. As explained in Section 2.4.3, Round5 can use two reduction polynomials $\xi(x) = \Phi_{n+1}(x) = \frac{x^{n+1}-1}{x-1}$ or $\xi(x) = N_{n+1}(x) = x^{n+1} - 1$ in the computation of the ciphertext and in the decryption/decapsulation. As explained in more detail in Section 2.8, using $\xi(x) = \Phi_{n+1}(x)$ leads to correlated errors. The basic reason is that the difference polynomial $d(x)$ governing the error behavior is obtained as $d(x) = \langle \sum_{i=0}^{n} f_i x^i \rangle_{\Phi_{n+1}(x)} = \sum_{i=0}^{n} f_i x^i - f_n \Phi_{n+1}(x) = \sum_{i=0}^{n-1} (f_i - f_n) x^i$. As a result, if f_n is large, then many coefficients of $d(x)$ are likely to be large,

leading to errors in multiple bit positions. As a consequence of this correlation between errors, the XEf code cannot be directly employed with the reduction polynomial $\xi(x) = \Phi_{n+1}(x)$.

As detailed in Section 2.8, Round5 aims to obtain independent errors by imposing two requirements:

- Ciphertext computation and decryption use the reduction polynomial $\xi(x) = N_{n+1}(x)$.
- The secret ternary polynomials $s(x)$ and $r(x)$ are balanced, that is, both have as many coefficients equal to 1 as to -1.

The latter requirement implies that $(x-1)$ is a factor of both $s(x)$ and $r(x)$. As a consequence, for any polynomial $a(x)$, it holds that $\langle s(x)a(x)\rangle_{\Phi_{n+1}(x)} r(x) \equiv s(x)\rangle a(x)r(x)\rangle_{\Phi_{n+1}(x)} \pmod{N_{n+1}(x)}$. This equivalence relation is essential for operational correctness, cf. Section 2.8.

These two requirements are aligned with features of the original Round2 submission [15] since (i) Round2 already internally performed all operations in $\xi(x) = N_{n+1}(x)$ and (ii) Round2's implementation used balanced secrets.

2.4.2 Internal building block: $f_{d,n}^{(\tau)}$ for generating a public matrix

In each protocol instantiation, Round5 uses a fresh public parameter $\boldsymbol{A}$ (cf. Section 2.4.3), which is a $d/n \times d/n$ matrix with entries from $\mathbb{Z}_q[x]/\Phi_{n+1}(x)$. The refreshing of $\boldsymbol{A}$ prevents backdoor and pre-computation attacks, cf. Section 2.7.9. The public matrix $\boldsymbol{A}$ is computed from a seed σ using function $f_{d,n}^{(\tau)}$. Round5 has three options for $f_{d,n}^{(\tau)}$ (more details can be found Section 2.11.6):

- $f_{d,n}^{(0)}$ obtains $\boldsymbol{A}$ by generating pseudorandom data from a random seed and sampling from it its elements. Round5 uses TupleHash to obtain this pseudorandom data, and optionally AES in counter mode. See Section 2.11.4 for specific implementation details. The number of polynomial coefficients to be generated equals $(d/n)^2 \times n = d^2/n$. This can lead to performance penalties in non-ring settings.
- $f_{d,n}^{(1)}$, which only applies for $n = 1$, generates $\boldsymbol{A}$ by permuting a public and system-wide matrix $\boldsymbol{A_{master}}$ according to permutation $\boldsymbol{p}_1 \in \mathbb{Z}_d^d$. The fresh $\boldsymbol{A}$ is defined as

  $$\boldsymbol{A}[i,j] = \boldsymbol{A_{master}}[i, \langle \boldsymbol{p}_1[i] + j\rangle_d].$$

  In order to obtain $\boldsymbol{A}$, it is thus sufficient to generate d elements of $\mathbb{Z}_d$ instead of d^2 elements of $\mathbb{Z}_q$ as with $f_{d,n}^{(0)}$.
- $f_{d,n}^{(2)}$, which only applies for $n = 1$, generates $\boldsymbol{A}$ by first generating a vector $\boldsymbol{a_{master}} \in \mathbb{Z}_q^{len_tau_2}$ from a seed σ and then permuting it according to

permutation vector $\boldsymbol{p}_2$. Rejection sampling is used to ensure that the entries of $\boldsymbol{p}_2$ are distinct. The matrix $\boldsymbol{A}$ is defined as

$$\boldsymbol{A}[i,j] = \boldsymbol{a}_{master}[\langle \boldsymbol{p}_2[i] + j \rangle_{len_tau_2}].$$

With this approach, it is possible to efficiently obtain a fresh $\boldsymbol{A}$ without having to compute a significant amount of pseudorandom data and without having to store a potentially large matrix $\boldsymbol{A}_{\boldsymbol{master}}$. The default value for len_tau_2 is set to 2^{11}, the smallest power of two greater than d for any of the Round5 configurations.

$f_{d,n}^{(0)}$ is the standard approach followed by many other protocols [29],[31],[8], and for which security proofs are available (Section 2.6 and Appendix A). A distinguishability proof cannot be provided for $f_{d,n}^{(1)}$ and $f_{d,n}^{(2)}$; despite this, Round5 considers these two options since they can successfully deal with backdoor and pre-computation attacks (as argued in Section 2.7.9) and they provide clear performance advantages (Table 13). For instance, $f_{d,n}^{(1)}$ can increase the efficiency of a server that has to handle many connections; $f_{d,n}^{(2)}$ reduces memory needs for both initiator and responder, which can be especially useful on small devices. The implementation of $f_{d,n}^{(\tau)}$ is detailed in Section 2.11.6.

2.4.3 Internal building block: r5_cpa_pke

This section describes r5_cpa_pke, the CPA-secure public key encryption that is a building block in both r5_cpa_kem and r5_cca_pke. It consists of algorithms 1 (key-generation), 2 (encryption) and 3 (decryption), and various cryptosystem parameters, *viz* positive integers n, d, h, p, q, t, b, $\overline{n}$, $\overline{m}$, μ, f, τ, and a security parameter κ. The system parameters are listed in Table 1. In the proposed parameter sets, $n \in \{1, d\}$, and b, q, p, t are powers of 2, such that $b|t|p|q$. It is required that

$$\mu \leq \overline{n} \cdot \overline{m} \cdot n \text{ and } \mu * b_bits \geq \kappa \text{ where } b = 2^{b_bits}.$$

In this section, options like the implementation of $f_{d,n}^{(tau)}$ are hidden.

The function $\text{Sample}_\mu : \boldsymbol{C} \in \mathcal{R}_{n,p}^{\overline{n} \times \overline{m}} \rightarrow \mathbb{Z}_p^\mu$ outputs μ polynomial coefficients of the $\overline{n} \cdot \overline{m} \cdot n$ polynomial coefficients present in $\boldsymbol{C}$. These μ coefficients are used in the actual encryption algorithm. This function is fully specified in Appendix 2.11.4.

The integer f denotes the error-correction capability of a code $XE_{\kappa,f} \subset \mathbb{Z}_b^\mu$. We have an encoding function $xef_compute_{\kappa,f} : \{0,1\}^\kappa \rightarrow XE_{\kappa,f}$ and a decoding function $xef_decode_{\kappa,f} : \mathbb{Z}_b^\mu \rightarrow \{0,1\}^\kappa$ such that for each $m \in \{0,1\}^\kappa$ and each error $e = (e_0, \ldots, e_{\mu-1})$ with at most f symbols e_i different from zero,

$$xef_decode_{\kappa,f}(xef_compute_{\kappa,f}(m) + e) = m. \tag{6}$$

The functions $xef_compute()$ and $xef_decode()$, based on Xef codes, are detailed from an implementation perspective in Section 2.11.4.

Table 1: List of symbols and their meaning

n	Degree of reduction polynomial;
	also indicates if a ring ($n > 1$) or a non-ring ($n = 1$) instantiation is used
d	Number of polynomial coefficients per row of public matrix
h	Number of non-zero polynomial coefficient per column of secret matrices
b, p, q, t	Rounding moduli, all powers of two, satisfying $b < t < p < q$
b_bits	Number of extracted bits per symbol in ciphertext component; $b = 2^{b_bits}$.
$\overline{n}$	Number of columns of the secret matrix of the initiator
$\overline{m}$	Number of columns of the secret matrix of the responder
κ	Security parameter; number of information bits in error-correcting code
xe	Number of parity bits of error correcting code
μ	Number of symbols in ciphertext component: $\mu = \lceil \frac{\kappa + xe}{b_{bits}} \rceil$.
Sample_μ	Function for picking up μ polynomial coefficients from a matrix
f	Number of bit errors correctable by error-correcting code
τ	Index for method of determining public matrix from a seed in $\{0,1\}^\kappa$
$f_{d,n}^{(\tau)}$	Method for determining public matrix from a seed in $\{0,1\}^\kappa$
f_S	Function for determining secret matrix for initiator from a seed in $\{0,1\}^\kappa$
f_R	Function for determining secret matrix for responder from a seed in $\{0,1\}^\kappa$
z	$z = \max(p, \frac{tq}{p})$. Relevant in reduction proofs and definition of rounding constants
h_1	$h_1 = \frac{q}{2p}$ is a rounding constant
h_2	$h_2 = \frac{q}{2z}$ is a rounding constant
h_3	$h_3 = \frac{p}{2t} + \frac{p}{2b} - \frac{q}{2z}$ is a constant for reducing bias in decryption
h_4	$h_4 = \frac{q}{2p} - \frac{q}{2z}$ is a constant for reducing bias in decryption
$\Phi_{n+1}(x)$	$\Phi_{n+1}(x) = \frac{x^{n+1}-1}{x-1}$. Reduction polynomial for computation of public keys; $n+1$ a prime.
$\xi(x)$	Reduction polynomial for computation of ciphertext. $\xi(x) \in \{\Phi_{n+1}(x), x^{n+1} - 1\}$

Algorithm r5_cpa_pke_encrypt employs a deterministic function f_R for generating a secret matrix $\boldsymbol{R} \in \left(\mathcal{H}_{n,d/n}(h)\right)^{1\times\overline{m}}$ from an input ρ. Defining ρ as an explicit input to r5_cpa_pke_encrypt allows us to reuse this *same* algorithm as a building block for both IND-CPA and IND-CCA secure cryptographic constructions.
Furthermore, r5_cpa_pke uses four rounding constants, namely

$$h_1 = \frac{q}{2p},\ h_2 = \frac{q}{2z}, h_3 = \frac{p}{2t} + \frac{p}{2b} - \frac{q}{2z} \text{ and } h_4 = \frac{q}{2p} - \frac{q}{2z},\ \text{with } z = \max(p, \frac{tq}{p}) \tag{7}$$

The constant h_1 leads to rounding to the closest integer. The choice of h_2 ensures that Round5's ciphertext $(\boldsymbol{U}, \boldsymbol{v})$ is provably pseudorandom under the GLWR assumption. Details are provided in the proof of IND-CPA security for r5_cpa_pke and r5_cpa_kem (Section A.3). The choices of h_3 and h_4 are made to avoid bias in decryption, see Section 2.8.

Note that the rounding constants are added explicitly here for completeness, but with the specific parameter choices in the different Round5 configurations 2.4.7 some of them can be simplified: $h_1 = h_2 = q/2p$ leading to standard rounding as in Round2 [15, 16] implemented by means of flooring. Furthermore, $h_4 = 0$. Thus, the only difference with respect to Round2 is h_3, which is present to avoid bias in decryption.

Algorithm 1: r5_cpa_pke_keygen()

parameters: Integers $p, q, n, h, d, \overline{n}, \kappa, \tau$
input : -
output : $pk \in \{0,1\}^\kappa \times \mathcal{R}_{n,p}^{d/n \times \overline{n}}, sk \in \{0,1\}^\kappa$

$\sigma \xleftarrow{\$} \{0,1\}^\kappa$
$\boldsymbol{A} = \boldsymbol{f}_{d,n}^{(\tau)}(\sigma)$
$sk \xleftarrow{\$} \{0,1\}^\kappa$
$\boldsymbol{S} = f_S(sk)$
$\boldsymbol{B} = \mathrm{R}_{q \to p, h_1}(\langle \boldsymbol{AS} \rangle_{\Phi_{n+1}})$
$pk = (\sigma, \boldsymbol{B})$
return (pk, sk)

Algorithm 2: r5_cpa_pke_encrypt(pk, m, ρ)

parameters: Integers $p, t, q, n, d, \overline{m}, \overline{n}, \mu, b, \kappa, f, \tau$; $\xi \in \{\Phi_{n+1}(x), x^{n+1} - 1\}$
input : $pk = (\sigma, \boldsymbol{B}) \in \{0,1\}^\kappa \times \mathcal{R}_{n,p}^{d/n \times \overline{n}}, m, \rho \in \{0,1\}^\kappa$
output : $ct = (\tilde{\boldsymbol{U}}, \boldsymbol{v}) \in \mathcal{R}_{n,p}^{\overline{m} \times d/n} \times \mathbb{Z}_t^\mu$

$\boldsymbol{A} = \boldsymbol{f}_{d,n}^{(\tau)}(\sigma)$
$\boldsymbol{R} = f_R(\rho)$
$\boldsymbol{U} = \mathrm{R}_{q \to p, h_2}(\langle \boldsymbol{A}^T \boldsymbol{R} \rangle_{\Phi_{n+1}})$
$\tilde{\boldsymbol{U}} = \boldsymbol{U}^T$
$\boldsymbol{v} = \langle \mathrm{R}_{p \to t, h_2}(\mathrm{Sample}_\mu(\langle \boldsymbol{B}^T \boldsymbol{R} \rangle_\xi)) + \frac{t}{b} xef_compute_{\kappa,f}(m) \rangle_t$
$ct = (\tilde{\boldsymbol{U}}, \boldsymbol{v})$
return ct

Algorithm 3: r5_cpa_pke_decrypt(sk, ct)

parameters: Integers $p, t, q, n, d, \overline{m}, \overline{n}, \mu, b, \kappa, f$; $\xi \in \{\Phi_{n+1}(x), x^{n+1} - 1\}$
input : $sk \in \{0,1\}^\kappa, ct = (\tilde{\boldsymbol{U}}, \boldsymbol{v}) \in \mathcal{R}_{n,p}^{\overline{m} \times d/n} \times \mathbb{Z}_t^\mu$
output : $\hat{m} \in \{0,1\}^\kappa$

$\boldsymbol{v}_p = \frac{p}{t} \boldsymbol{v}$
$\boldsymbol{S} = f_s(sk)$
$\boldsymbol{U} = \tilde{\boldsymbol{U}}^T$
$\boldsymbol{y} = \mathrm{R}_{p \to b, h_3}(\boldsymbol{v}_p - \mathrm{Sample}_\mu((\boldsymbol{S}^T(\boldsymbol{U} + h_4 \boldsymbol{J}))_\xi))$
$\hat{m} = xef_decode_{\kappa,f}(\boldsymbol{y})$
return $\hat{m}$

2.4.4 Submission proposal: r5_cpa_kem

This section describes r5_cpa_kem, an IND-CPA-secure key encapsulation method. It builds on r5_cpa_pke (Section 2.4.3). In addition to the parameters and functions from r5_cpa_pke, it uses a hash function HCPAKEM : $\{0,1\}^\kappa \times \{0,1\}^* \to \{0,1\}^\kappa$. In order to improve readability, in Algorithms 5 and 6 the conversion of the ciphertext ct into a binary string before it is fed to $HCPAKEM$ is not made explicit.

Algorithm 4: r5_cpa_kem_keygen()

parameters: Integers $p, q, n, h, d, \overline{n}, \kappa, \tau$
input : -
output : $pk \in \{0,1\}^\kappa \times \mathcal{R}_{n,p}^{d/n \times \overline{n}}, sk \in \{0,1\}^\kappa$

1 $(pk, sk) =$ r5_cpa_pke_keygen()
2 **return** (pk, sk)

Algorithm 5: r5_cpa_kem_encapsulate(pk)

parameters: Integers $p, t, q, n, d, \overline{m}, \overline{n}, \mu, b, \kappa, f, \tau$; $\xi \in \{\Phi_{n+1}(x), x^{n+1} - 1\}$
input : $pk \in \{0,1\}^\kappa \times \mathcal{R}_{n,p}^{d/n \times \overline{n}}$
output : $(ct, k) \in (\mathcal{R}_{n,p}^{\overline{m} \times d/n} \times \mathbb{Z}_t^\mu) \times \{0,1\}^\kappa$

1 $m \xleftarrow{\$} \{0,1\}^\kappa$
2 $\rho \xleftarrow{\$} \{0,1\}^\kappa$
3 $ct =$ r5_cpa_pke_encrypt(pk, m, ρ)
4 $k = HCPAKEM(m, ct)$
5 **return** (ct, k)

Algorithm 6: r5_cpa_kem_decapsulate(ct, sk)

parameters: Integers $p, t, q, n, d, \overline{m}, \overline{n}, \mu, b, \kappa, f$; $\xi \in \{\Phi_{n+1}(x), x^{n+1} - 1\}$
input : $ct \in \mathcal{R}_{n,p}^{\overline{m} \times d/n} \times \mathbb{Z}_t^\mu, sk \in \{0,1\}^\kappa$
output : $k \in \{0,1\}^\kappa$

1 $m =$ r5_cpa_pke.decrypt(sk, ct)
2 $k = HCPAKEM(m, ct)$
3 **return** k

2.4.5 Submission proposal: r5_cca_kem

This section describes an IND-CCA key encapsulation mechanism, r5_cca_kem. This KEM is also a building block for r5_cca_pke. It consists of the algorithms 7, 8, 9, and several system parameters and functions in addition to those from r5_cpa_pke and r5_cpa_kem. It uses a hash function $HCCAKEM : \{0,1\}^\kappa \times \{0,1\}^* \to \{0,1\}^\kappa$ and hash function $GCCAKEM : \{0,1\}^\kappa \times \{0,1\}^* \to \{0,1\}^\kappa \times \{0,1\}^\kappa \times \{0,1\}^\kappa$. To improve readability, conversion of data types to bit strings before being fed to $HCCAKEM$ and $GCCAKEM$ is not made explicit.

r5_cca_kem is actively secure as it is obtained by application of the Fujisaki-Okamoto transform [63] to r5_cpa_pke, similarly as in [31, Sec. 4]. On decapsulation failure, i.e. if the condition in line 4 of Algorithm 9 is not satisfied, a pseudorandom key is returned, causing later protocol steps to fail implicitly. Explicit failure notification would complicate analysis, especially in the quantum random oracle model (QROM).

Algorithm 7: r5_cca_kem_keygen()

parameters: Integers $p, q, n, h, d, \overline{n}, \kappa, \tau$
input : -
output : $pk \in \{0,1\}^\kappa \times \mathcal{R}_{n,p}^{d/n \times \overline{n}}$, $sk \in \{0,1\}^\kappa \times \{0,1\}^\kappa \times (\{0,1\}^\kappa \times \mathcal{R}_{n,p}^{d/n \times \overline{n}})$

$(pk, sk_{CPA-PKE}) =$ r5_cpa_pke_keygen()
$y \xleftarrow{\$} \{0,1\}^\kappa$
$sk = (sk_{CPA-PKE}, y, pk)$
return (pk, sk)

Algorithm 8: r5_cca_kem_encapsulate(pk)

parameters: Integers $p, t, q, n, d, \overline{m}, \overline{n}, \mu, b, \kappa, f, \tau$; $\xi \in \{\Phi_{n+1}(x), x^{n+1} - 1\}$
input : $pk \in \{0,1\}^\kappa \times \mathcal{R}_{n,p}^{d/n \times \overline{n}}$
output : $ct = (\tilde{\boldsymbol{U}}, \boldsymbol{v}, g) \in \mathcal{R}_{n,p}^{\overline{m} \times d/n} \times \mathbb{Z}_t^\mu \times \{0,1\}^\kappa, k \in \{0,1\}^\kappa$

$m \xleftarrow{\$} \{0,1\}^\kappa$
$(L, g, \rho) = GCCAKEM(m, pk)$
$(\tilde{\boldsymbol{U}}, \boldsymbol{v}) =$ r5_cpa_pke_encrypt(pk, m, ρ)
$ct = (\tilde{\boldsymbol{U}}, \boldsymbol{v}, g)$
$k = HCCAKEM(L, ct)$
return (ct, k)

Algorithm 9: r5_cca_kem_decapsulate(ct, sk)

parameters: Integers $p, t, q, n, d, \overline{m}, \overline{n}, \mu, b, \kappa, f, \tau$; $\xi \in \{\Phi_{n+1}(x), x^{n+1} - 1\}$
input : $ct = (\tilde{\boldsymbol{U}}, \boldsymbol{v}, g) \in \mathcal{R}_{n,p}^{\overline{m} \times d/n} \times \mathbb{Z}_t^\mu \times \{0,1\}^\kappa$, $sk =$ $(sk_{CPA-PKE}, y, pk) \in \{0,1\}^\kappa \times \{0,1\}^\kappa \times (\{0,1\}^\kappa \times \mathcal{R}_{n,p}^{d/n \times \overline{n}})$
output : $k \in \{0,1\}^\kappa$

$m' =$ r5_cpa_pke_decrypt($sk_{CPA-PKE}, (\tilde{\boldsymbol{U}}, \boldsymbol{v})$)
$(L', g', \rho') = GCCAKEM(m', pk)$
$(\tilde{\boldsymbol{U}'}, \boldsymbol{v'}) =$ r5_cpa_pke_encrypt(pk, m', ρ')
$ct' = (\tilde{\boldsymbol{U}'}, \boldsymbol{v'}, g')$
if $(ct = ct')$ **then**
  return $k = HCCAKEM(L', ct)$
else
  return $k = HCCAKEM(y, ct)$
end if

2.4.6 Submission proposal: r5_cca_pke

The IND-CCA [90] public key encryption scheme r5_cca_pke consists of algorithms 10, 11 and 12. It combines r5_cca_kem with a data encapsulation mechanism (DEM), in the canonical way proposed by Cramer and Shoup [44]. r5_cca_kem is used to encapsulate a key k that is then used by the DEM to encrypt an arbitrary-length plaintext, optionally adding integrity protection. In decryption, r5_cca_kem is used to decapsulate k, which is then used by the DEM to decrypt and authenticate the plaintext. The expression $\lceil(\overline{m} \times d \times \log_2(p) + \mu \log_2(t) + \kappa)/8\rceil$ in Algorithms 11 and 12 denotes the length (in bytes) of the

binary representation of elements of $(\mathcal{R}_{n,p}^{\overline{m}\times d/n} \times Z_t^{\mu} \times \{0,1\}^{\kappa})$.

Algorithm 10: r5_cca_pke_keygen()

parameters: Integers $p, q, n, h, d, \overline{n}, \kappa, \tau$
input : -
output : $pk \in \{0,1\}^{\kappa} \times \mathcal{R}_{n,p}^{d/n\times\overline{n}}, sk \in \{0,1\}^{\kappa} \times \{0,1\}^{\kappa} \times (\{0,1\}^{\kappa} \times \mathcal{R}_{n,p}^{d/n\times\overline{n}})$

1 $(pk, sk) =$ r5_cca_kem_keygen()
2 **return** (pk, sk)

Algorithm 11: r5_cca_pke_encrypt$(mlen, m, pk)$

parameters: Integers $p, t, q, n, d, \overline{m}, \overline{n}, \mu, b, \kappa, f, \tau$; $\xi \in \{\Phi_{n+1}(x), x^{n+1} - 1\}$
input : $m \in \mathbb{Z}_{256}^{mlen}, mlen \in \mathbb{Z}, pk \in \{0,1\}^{\kappa} \times \mathcal{R}_{n,p}^{d/n\times\overline{n}}$
output : $ct = (c1||c2) \in (\mathcal{R}_{n,p}^{\overline{m}\times d/n} \times Z_t^{\mu} \times \{0,1\}^{\kappa}) \times \mathbb{Z}_{256}^{c2len}, clen = \lceil(\overline{m} \times d \times \log_2(p) + \mu \log_2(t) + \kappa)/8\rceil + c2len \in \mathbb{Z}$

1 $(c1, k) =$ r5_cca_kem_encapsulate(pk)
2 $(c2, c2len) = \mathrm{DEM}(k, m)$
3 $ct = (c1||c2)$
4 $clen = \lceil(\overline{m} \times d \times \log_2(p) + \mu \log_2(t) + \kappa)/8\rceil + c2len$
5 **return** $(ct, clen)$

Algorithm 12: r5_cca_pke_decrypt$(ct, clen, sk)$

parameters: Integers $p, t, q, n, d, \overline{m}, \overline{n}, \mu, b, \kappa, f, \tau$; $\xi \in \{\Phi_{n+1}(x), x^{n+1} - 1\}$
input : $ct = (c1||c2) \in (\mathcal{R}_{n,p}^{\overline{m}\times d/n} \times Z_t^{\mu} \times \{0,1\}^{\kappa}) \times \mathbb{Z}_{256}^{c2len}$, $clen = \lceil(\overline{m} \times d \times \log_2(p) + \mu \log_2(t) + \kappa)/8\rceil + c2len \in \mathbb{Z}, sk \in \{0,1\}^{\kappa} \times \{0,1\}^{\kappa} \times (\{0,1\}^{\kappa} \times \mathcal{R}_{n,p}^{d/n\times\overline{n}})$
output : $m \in \mathbb{Z}_{256}^{mlen}, mlen \in \mathbb{Z}$

1 $k =$ r5_cca_kem_decapsulate$(c1, sk)$
2 $(m, mlen) = \mathrm{DEM}^{-1}(k, c2)$
3 **return** $(m, mlen)$

2.4.7 Proposed parameter sets

Round5 proposes a unified scheme with a large design space – Table 1 – that can be configured to fit the needs of different applications. In particular, Round5 optimizes over the above design space to define IND-CPA and IND-CCA secure parameter sets. The IND-CPA secure parameter sets are to be used in combination with Round5's IND-CPA secure KEM. The IND-CCA secure parameter sets are applied to Round5's IND-CCA secure KEM and PKE.

The parameter sets are classified into three main sets according to the underlying problem: ring without error correction, ring with error correction, and non-ring.

- Six ring parameter sets (IND-CPA and IND-CCA secure for NIST security levels 1,3 and 5) without error correction, see Tables 4 and 8. These parameter choices can be considered to be conservative, as they are only

based on the Round2 design that has received public review since its submission.

- Six ring parameter sets (IND-CPA and IND-CCA secure for NIST security levels 1,3 and 5) with XEf error correction code, see Tables 5 and 9. These parameter choices are based on the merge of HILA5 with Round2 and lead to the smallest public key and ciphertext sizes.

- Six non-ring parameter sets (IND-CPA and IND-CCA secure for NIST security levels 1,3 and 5) without error correction, see Tables 6 and 10. These parameter choices rely on same design choices as the original Round2 submission. In particular, it uses $\overline{n} \approx \overline{m}$ to minimize total size of public-key plus ciphertext.

Round5 further details three additional specific use-case parameter sets with the only purpose of demonstrating its flexibility:

- A ring-based IND-CPA secure parameter set with error correction, addressing IoT use cases. This parameter set has low bandwidth and computational requirements, yet still provides 87 bits of (quantum) security. See Table 7.

- A ring-based NIST level 1 IND-CPA secure parameter set with error correction, for which the encapsulated key is 192-bit long instead of just 128-bit so that the difficulty of attacking the encapsulated key (by Grover) equals the difficulty of quantum lattice attack to Round5. See Table 7.

- A non-ring-based IND-CCA secure parameter set with NIST level 3 with a ciphertext size of only 988 Bytes, with fast encryption, by taking $\overline{m} = 1$, at the cost of a larger public key. This parameter set targets applications in which the public-key can remain static for a long period, e.g., a fixed VPN between two end points. In such applications, the bandwidth footprint depends on the size of the ciphertext. Hence, this parameter set, despite enjoying the more conservative security assumptions for unstructured lattices, has a bandwidth requirement comparable to ring variants. See Table 11.

In contrast to the original Round2 and HILA5 submissions, Round5 does not include parameter sets suitable for NTT. The reason is that non-NTT parameters allow achieving better CPU-performance, as the advantages of using modular arithmetic with powers of two outweigh the advantages of using an NTT.

Figure 2: Summary of reductions involved in the security proofs for Round5 algorithms. "SPT" refers to a variant of the problem in question where the secret is sparse-ternary, instead of uniform in $\mathbb{Z}_q^d$.

2.5 Known Answer Test Values

The Known Answer Test Values for all algorithm variants and NIST levels can be found on the digital media at the location described in Section 3.4.

Note that for generating intermediate output, the code needs to be compiled with `-DNIST_KAT_GENERATION` (this option is enabled by default when making use of the provided `Makefiles`).

2.6 Expected Security Strength

This section summarizes results on the expected security of Round5 algorithms, its building blocks and underlying hard problem. An overview of these results is also given in Figure 2. For proofs, we refer to Appendix A.

1. Under the assumptions that $\boldsymbol{f}_{d,n}^{(\tau)}$ can be modeled as a random oracle, f_S and f_R can be modeled as pseudo-random functions, and that the decision General Learning with Rounding (GLWR) problem with sparse - ternary secrets is hard for the polynomial ring $\mathbb{Z}[x]/\Phi_{n+1}(x)$, **r5_cpa_pke** is an IND-CPA secure public-key encryption scheme. Theorem A.3.2 gives a

tight, classical reduction against classical adversaries in the random oracle model. The full proof in Appendix A.3, follows a similar approach as [46] to equalize the noise ratios q/p and p/t in the two ciphertext components $\boldsymbol{U}$ and $\boldsymbol{v}$ that allows their combination into a single GLWR sample with noise ratio q/z. Section 2.7.10 discusses why attacks on Round5 exploiting our above assumptions on $\boldsymbol{f}_{d,n}^{(\tau)}$, f_S and f_R based on their concrete instantiations are unlikely.

2. Appendix A.4 presents a proof of IND-CPA security for a Ring LWE based variant of r5_cpa_pke with reduction polynomial $\xi(x) = N_{n+1}(x)$, if the decision Ring LWE problem for $\mathbb{Z}[x]/\Phi_{n+1}(x)$ is hard; this results gives confidence for the RLWR case. Theorem A.4.1 gives a tight, classical reduction against classical and quantum adversaries in the standard model, a simplified version of which is as follows:

   Theorem 2.6.1. *For every adversary $\mathcal{A}$, there exist distinguishers $\mathcal{C}$ and $\mathcal{E}$ such that*

   $$Adv^{IND\text{-}CPA}_{CPA\text{-}PKE,N_{n+1}(x)}(\mathcal{A}) \leq Adv^{\texttt{RLWE}(\mathbb{Z}[x]/\phi(x))}_{m=1}(\mathcal{C}) + Adv^{\texttt{RLWE}(\mathbb{Z}[x]/\phi(x))}_{m=2}(\mathcal{E}). \tag{8}$$

   where m denotes the number of available RLWE samples available.

   This section also gives indications on sufficient conditions for the proof to work. One of them is replacing coordinate-wise rounding as done in Round5 by a more complicated form of rounding which ensures that the sum of the errors induced by rounding sum to zero. We chose not to use this form of rounding as it adds complexity and seems not to improve practical security. Moreover, the Sample_μ function in Round5 stops a well- known distinguishing attack against schemes based on rings with reduction polynomial $x^{n+1} - 1$.

3. Under the assumptions that r5_cpa_pke is an IND-CPA secure public-key encryption scheme, H is a secure pseudo-random function, and that $\boldsymbol{f}_{d,n}^{(\tau)}$ can be modeled as a random oracle, **r5_cpa_kem** is an IND-CPA secure KEM. Theorem A.5.2 gives a tight, classical reduction against classical or quantum adversaries in the standard model; the construction and proof technique are standard.

4. **r5_cca_kem** is constructed using a KEM variant of the Fujisaki-Okamoto transform [63] from r5_cpa_pke. Therefore, assuming that r5_cpa_pke is an IND-CPA secure public-key encryption scheme, and G and H are modeled as random oracles, r5_cca_kem is an IND-CCA secure KEM. Theorem A.6.1 gives a tight, classical reduction against classical adversaries in the random oracle model. Theorem A.6.2 gives a non-tight, classical reduction against quantum adversaries in the quantum random oracle model.

5. **r5_cca_pke** is constructed from r5_cca_kem and a one-time data encapsulation mechanism in the canonical way proposed by Cramer and Shoup [44]. Therefore, if r5_cca_kem is IND-CCA secure, and the data encapsulation mechanism is (one-time) secure against chosen ciphertext attacks and has a keylength fitting the security level of r5_cca_kem, then r5_cca_pke is an IND-CCA secure PKE. Section A.6 contains details.

6. The decision Learning with Rounding (LWR) problem with sparse-ternary secrets is hard if the decision Learning with Errors (LWE) problem with uniform secrets and Gaussian errors is hard. Theorem A.7.1 gives a classical reduction against classical or quantum adversaries in the standard model, under the condition that the noise rate in the LWE problem decreases linearly in the security parameter n of the LWE and LWR problems. A concise version of this theorem is presented below:

   Theorem 2.6.2. *Let p divide q, and $k \geq \frac{q}{p} \cdot m$. Let $\epsilon \in (0, \frac{1}{2})$, and $\alpha, \delta > 0$ such that*

   $$\alpha \geq q^{-1}\sqrt{(2/\pi)\ln(2n(1+\epsilon^{-1}))},\ \binom{n}{h}2^h \geq q^{k+1} \cdot \delta^{-2},\ \textit{and } m = O(\frac{\log n}{\alpha\sqrt{10h}})$$

   Then there is a reduction from $\mathtt{dLWE}_{n,\frac{q}{p},q,D_{\alpha\sqrt{10h}}}(\mathcal{U}(\mathcal{H}_n(h)))$ to $\mathtt{dLWR}_{n,m,q,p}(\mathcal{U}(\mathcal{H}_n(h)))$.

The above summary of the proofs shows that the overall design of Round5 family of algorithms stems from a provable secure design. These proofs do not give any guidance to parameter choices. As is common practice in practical lattice based cryptography, we derive parameters from best known attacks.

2.7 Analysis with respect to known attacks

In this section, we analyze the concrete security of Round5. As the lattice-based attacks all rely on estimating the costs of solving certain lattice problems, we start with preliminaries on this topic in Sections 2.7.1 and 2.7.2. We then consider attacks using lattice basis reduction in Sections 2.7.3, 2.7.4 and 2.7.5, followed by specialized attacks that exploit sparse-ternary secrets used in Round5 in Sections 2.7.6 and 2.7.7. Finally, in Section 2.7.9 we consider precomputation and back-door attacks against the Round5 GLWR public parameter $\boldsymbol{A}$.

2.7.1 Preliminaries: SVP Complexities

On arbitrary lattices, we define the Shortest Vector Problem (SVP) as the problem of finding a vector in a lattice whose Euclidean norm is minimal among all non-zero vectors in the lattice. This problem is known to be NP-hard for randomized reductions [2, 71], and we do not expect any polynomial time algorithms for solving this problem in the worst-case to be found any time soon.

Various algorithms have been studied for solving SVP both in the worst-case and for average-case instances. The algorithm with the current best worst-case (asymptotic) complexity for solving SVP is the discrete Gaussian sampling approach [1], with an asymptotic cost in dimension n of $2^{n+o(n)}$ time and space. For large dimensions, this beats other exponential time and space algorithms based on computing the Voronoi cell [102, 81] or running a lattice sieve [3, 89], and enumeration algorithms requiring superexponential time in the lattice dimension [88, 69, 101, 54, 12]. These worst-case analyses however seem to suffer heavily from the (potential) existence of exotic, highly dense lattices such as the Leech lattice [41], and for average-case instances one can often solve SVP much faster, as also shown by various experiments on random lattices [47].

By making heuristic assumptions on the expected average-case behavior of SVP algorithms on random lattices, various works have demonstrated that some algorithms can solve SVP much faster than the above worst-case bounds suggest. For a long time, lattice enumeration [54, 12] was considered the fastest method in practice for solving SVP in high dimensions, and the crossover point with sieving-based approaches appeared to be far out of reach, i.e. well beyond cryptographically relevant parameters [82]. Recently, improvements to lattice sieving have significantly weakened this view, and the current fastest implementation based on sieving [7] has surpassed the best previous enumeration implementation both in terms of speed and in terms of the highest dimension reachable in practice. Although sieving is hindered by its exponential memory footprint, sieving also scales better in high dimensions compared to enumeration in terms of the time complexity ($2^{\Theta(n)}$ for sieving versus $2^{\Theta(n \log n)}$ for enumeration).

Conservative estimates. To estimate the actual computational complexity of solving SVP, we will use the best asymptotics for sieving [21], which state that solving SVP in dimension n takes time $2^{0.292n+o(n)}$. Clearly the hidden order term in the exponent has a major impact on the actual costs of these methods, and one might therefore be tempted to choose this term according to the actual, experimental value. However, recent improvements have shown that although the leading term $0.292n$ in the exponent is unlikely to be improved upon any time soon [11, 59], the hidden order term may well still be improved with heuristic tweaks such as those discussed in [48, 74, 7]. A conservative and practical cost estimate is therefore to estimate the costs of solving SVP in dimension n as $2^{0.292n}$, ignoring the (positive) hidden order term which may still be reduced over the next decades. Observe that this estimate is also well below the lowest estimates for enumeration or any other SVP method in high dimensions.

Note that some work has also suggested that SVP is slightly easier to solve on structured, ideal lattices when using lattice sieving [67, 33, 22, 108]. However, these are all improvements reducing the time and/or space complexities by a small polynomial factor in the lattice dimension. Moreover, in our cost estimates we will actually be using an SVP algorithm as a subroutine within a blockwise

lattice reduction algorithm, and even if the original lattice on which we run this lattice basis reduction algorithm has additional structure, these low-dimensional sublattices do not. Therefore, even for ideal lattices we do not expect these polynomial speedups to play a role.

Quantum speedups. For making Round5 post-quantum secure, we also take into account any potential quantum speedups to attacks an adversary might run against our scheme. Concretely, for the hardness of SVP on arbitrary lattices this may reduce the cost of lattice sieving to only $2^{0.265n+o(n)}$, assuming the attacker can efficiently run a Grover search [56] on a dynamically changing, exponential-sized database of lattice vectors stored in quantum RAM [75, 73]. Although it may not be possible to ever carry out such an attack efficiently, a conservative estimate for the quantum hardness of SVP in dimension n is therefore to assume this takes the attacker at least $2^{0.265n}$ time [73].

Note that recent work has also indicated that enumeration may benefit from a quantum speedup when applying a Grover-like technique to improve the backtracking search of lattice enumeration [13]. Disregarding significant polynomial overhead as well as simply the overhead of having to do operations quantumly, a highly optimistic estimate for the time costs of quantum enumeration in dimension n is $2^{\frac{1}{2}(0.187n \log n - 1.019n + 16.1)}$ [66]. Even with this model, the attack costs for all our parameter sets are higher than $2^{0.265n}$.

2.7.2 Lattice basis reduction: the core model

The above discussion focused on algorithms for solving exact SVP in high dimensions. The concrete security of lattice-based cryptographic schemes like Round5 however relies on the hardness of unique/approximate SVP, where a break constitutes finding a vector not much longer than the actual shortest non-zero vector in the lattice. This problem has also been studied extensively, and the fastest method known to date for approximate SVP is the BKZ algorithm [99, 100, 37, 83, 7]. Given an arbitrary basis of a lattice, this algorithm (a generalization of the LLL algorithm [77]) performs HKZ reduction [72] on (projected) parts of the basis of a certain block size b. To perform HKZ reduction, the algorithm makes calls to an exact SVP oracle on b-dimensional lattices, and uses the result to improve the basis. Both the quality and time complexity can be tuned by b: running BKZ with larger b gives better bases, but also takes longer to finish.

Although the exact overall time complexity of BKZ remains somewhat mysterious [37, 58, 83, 7], it is clear that the dominant cost of BKZ for large block sizes is running the SVP oracle on b-dimensional lattices. The BKZ algorithm further makes tours through the entire basis on overlapping blocks of basis vectors, but the number of tours only contributes a small multiplicative term, and SVP calls on overlapping blocks do not necessarily add up to independent SVP calls - for multiple overlapping blocks, it may well be possible to solve SVP in almost the same time as solving only one instance of SVP when using a sieving-based SVP solver [7].

This all gives rise to the core SVP model, where the complexity of BKZ with block size b is modeled by just *one* call to an SVP oracle in a b-dimensional lattice. This is clearly a lower bound for the actual cost of BKZ, and as further advances may be made to sieving-based BKZ algorithms reusing information between blocks, this is also the largest lower bound we can use without risking that predicted future advances in cryptanalysis will reduce the security level of our scheme in the near future.

Cost models used in our security analysis. We assume that BKZ is instantiated with a sieving-based SVP solver. Concretely, we estimate the cost of BKZ with block size b as $(b \cdot 2^{cb})$ for Round5 instantiations with $n = 1$. For Round5's ring-based instantiations (i.e., when the parameters $n = d$), we follow a conservative approach similar to [9] and estimate the cost of BKZ with block size b as 2^{cb}. That is, we omit the b factor in the cost of running one instance of BKZ. This accounts for the possibility that techniques in [98, 33] can be adapted to more advanced sieving algorithms.

The value of the sieving exponent c depends on whether we assume a quantum or classical adversary. We use $c = 0.265$ when considering quantum sieving algorithms sped up with Grover's quantum search algorithm [73, 75], and $c = 0.292$ when considering classical sieving.

In order to run certain cryptanalytic algorithms, we require to find many short vectors (rather than just one). We assume that each run of BKZ with block size b provides $2^{0.2075b}$ short vectors [9].

We also provide security estimates based on enumeration for comparison purposes. We would like to remark that this is not the main metric considered in Round5, and if Round5 used it to obtains security parameters, then performance would improve. Our classical security estimates based on enumeration are computed as $2^{c_1 \cdot b \cdot log(b) + c_2 \cdot b + c_3}$ [69, 82]. The exponent halves when quantum speedups due to Grover are applied. The specific constants used are $c_1 = 0.187$, $c_2 = -1.019$, $c_3 = 16.1$ [4, 6].

2.7.3 Lattice-based attacks

We consider lattice-reduction based attacks, namely, the *primal* or decoding attack [18] and the *dual* or distinguishing attack [5], and how they can be adapted to exploit the shortness of secrets in our schemes. We begin by detailing how an attack on Round5 can be formulated as a lattice-reduction based attack on the LWR problem. We then analyze the concrete security of Round5 against the primal attack in order to estimate secure parameters, in Section 2.7.4. We do the same for the dual attack in Section 2.7.5.

The attacker can use the public keys $\boldsymbol{B} = \langle \lfloor \frac{p}{q} \langle \boldsymbol{AS} \rangle_q \rceil \rangle_p$ of the public-key encryption scheme or the key-encapsulation scheme to obtain information on the secret key $\boldsymbol{S}$. We work out how this is done. Let $1 \leq i \leq d$ and $1 \leq j \leq \overline{n}$. If we denote the i-th row of $\boldsymbol{A}$ by $\boldsymbol{a}_i^T$ and the j-th column of $\boldsymbol{S}$ by $\boldsymbol{s}_j$, then

$$\boldsymbol{B}_{i,j} = \langle \lfloor \frac{p}{q} \langle \langle \boldsymbol{a}_i^T \boldsymbol{s}_j \rangle_q \rangle_q \rceil \rangle_p = \langle \lfloor \frac{p}{q} \langle \boldsymbol{a}_i^T \boldsymbol{s}_j \rangle_q \rceil \rangle_p.$$

By the definition of the rounding function $\lfloor \cdot \rceil$, we have that

$$\boldsymbol{B}_{i,j} \equiv \frac{p}{q}\langle \boldsymbol{a}_i^T \boldsymbol{s}_j \rangle_q + e_{i,j} \pmod{p} \text{ with } e_{i,j} \in (-1/2, 1/2].$$

As $\langle \boldsymbol{a}_i^T \boldsymbol{s}_j \rangle_q = \boldsymbol{a}_i^T \boldsymbol{s}_j + \lambda q$ for some integer λ, we infer that

$$\frac{q}{p}\boldsymbol{B}_{i,j} \equiv \boldsymbol{a}_i^T \boldsymbol{s}_j + \frac{q}{p} e_{i,j} \pmod{q}. \tag{9}$$

So we have d equations involving $\boldsymbol{s}_j$. Unlike conventional LWE, the errors $\frac{q}{p}e_{i,j}$ reside in a bounded interval, namely $(-\frac{q}{2p}, \frac{q}{2p}]$. In what follows, we will only consider the case that p divides q.

As $\boldsymbol{s}$ is balanced, it holds that $\sum_{i=0}^{d-1} s_i = 0$. This additional equation can be used in a lattice attack as well. As the securiy loss is (very) minor [**?**], this attack is not further taken into account.

2.7.4 Primal Attack

In (9), we write $\boldsymbol{s}$ for $\boldsymbol{s}_j$, denote by $\boldsymbol{b}$ the vector of length m with j-th component $\frac{q}{p}\boldsymbol{B}_{i,j}$, and with $\boldsymbol{A}_m$ the matrix consisting of the m top rows of $\boldsymbol{A}$. We then have, for $\boldsymbol{e} \in (-\frac{q}{2p}, \frac{q}{2p}]^m$

$$\boldsymbol{b} \equiv \boldsymbol{A}_m \boldsymbol{s} + \boldsymbol{e} \pmod{q} \tag{10}$$

so that $\boldsymbol{v} = (\boldsymbol{s}^T, \boldsymbol{e}^T, 1)^T$ is in the lattice Λ defined as

$$\Lambda = \{\boldsymbol{x} \in \mathbb{Z}^{d+m+1} : (\boldsymbol{A}_m | \boldsymbol{I}_m | -\boldsymbol{b})\boldsymbol{x} = \boldsymbol{0} \pmod{q}\} \tag{11}$$

of dimension $d' = d + m + 1$ and volume q^m [29, 9].

Lattice Rescaling: The attacker wishes to recover the lattice vector $\boldsymbol{v} = (\boldsymbol{s}, \boldsymbol{e}, 1)$, which is unbalanced in that $\|\boldsymbol{s}\| \ll \|\boldsymbol{e}\|$. For exploiting this fact, a rescaling technique originally due to [18], and analyzed further in [40] and [5], is applied. Multiplying the first d columns of Λ's basis (see Eq. 11) with an appropriate scaling factor ω yields the following weighted or rescaled lattice,

$$\Lambda_\omega = \{\boldsymbol{x} \in \mathbb{Z}^{d+m+1} : \big((\omega \cdot \boldsymbol{A}_m^T) | \boldsymbol{I}_m | -\boldsymbol{b}\big)\boldsymbol{x} = \boldsymbol{0} \text{ (mod q)}\} \tag{12}$$

in which the attacker then searches for a short vector, that he hopes to be equal to $\boldsymbol{v}_\omega = (\omega \cdot \boldsymbol{s}^T, \boldsymbol{e}^T, 1)^T$. This search is typically done by using a lattice reduction algorithm to obtain a reduced basis of the lattice, the first vector of which will be the shortest of that basis. We explain later in this section how to choose an appropriate value for ω in order to maximize the chances of the attack's success.

If the quality of the lattice reduction is good enough, the reduced basis will contain $\boldsymbol{v}_\omega$. The attack success condition is as in [9] assuming that BKZ [37, 100] with block-size b is used as the lattice reduction algorithm. The vector $\boldsymbol{v}_\omega$ will

be detected if its projection $\widetilde{\boldsymbol{v}}_b$ onto the vector space of the last b Gram-Schmidt vectors of Λ is shorter than the expected norm of the $(d'-b)^{th}$ Gram-Schmidt vector $\widetilde{\boldsymbol{b}}_{d'-b}$, where d' is the dimension of Λ [9, Sec. 6.3],[29]. The condition to be satisfied for the primal attack to succeed is therefore $\|\widetilde{\boldsymbol{v}}_b\| < \|\widetilde{\boldsymbol{b}}_{d'-b}\|$, i.e.

$$\|\widetilde{\boldsymbol{v}}_b\| < \delta^{2b-d'-1} \cdot (\mathrm{Vol}(\Lambda))^{\frac{1}{d'}}, \text{ where } \delta = ((\pi b)^{\frac{1}{b}} \cdot \frac{b}{2\pi \mathbf{e}})^{\frac{1}{2(b-1)}}. \tag{13}$$

The attack success condition (13) yields the following *security* condition that must be satisfied by the parameters of our public-key encryption and key-encapsulation schemes to remain secure against the primal attack:

$$\sqrt{(\omega^2 \cdot h + \sigma'^2 m) \cdot \frac{b}{d+m}} \geq \delta^{2b-d'-1} \cdot (q^m \omega^d)^{\frac{1}{d'}}, \tag{14}$$

where $\delta = ((\pi b)^{\frac{1}{b}} \cdot \frac{b}{2\pi \mathbf{e}})^{\frac{1}{2(b-1)}}, \sigma'^2 = ((q/p)^2 - 1)/12,$ and $d' = d + m + 1$.

For finding an appropriate value for ω, we rewrite (14) as

$$\delta^{2b-d'-1} b^{-1/2} \leq \sqrt{\omega^2 h + m\sigma'^2 \cdot \frac{1}{m+d}} \omega^{-d/d'} q^{-(d-d'-1)/d}. \tag{15}$$

Given d, m, h and σ', the attacker obtains the least stringent condition on the block size b by maximizing the right hand side of (15) over ω, or equivalently, by maximizing

$$\frac{1}{2} \log(\omega^2 h + m\sigma'^2) - \frac{d}{d'} \log \omega.$$

By differentiating with respect to ω, we find that the optimizing value for ω satisfies

$$\omega^2 = \frac{dm\sigma'^2}{h(d'-d)} = \frac{dm\sigma'^2}{h(m+1)} \approx \frac{d}{h}\sigma'^2.$$

2.7.5 Dual Attack

The dual attack against LWE/LWR [9],[5] employs a short vector $(\boldsymbol{v}, \boldsymbol{w}) \in \mathbb{Z}^m \times \mathbb{Z}^d$ in the dual lattice

$$\Lambda^* = \{(\boldsymbol{x}, \boldsymbol{y}) \in \mathbb{Z}^m \times \mathbb{Z}^d : \boldsymbol{A}_m^T \boldsymbol{x} = \boldsymbol{y} \pmod q\} \tag{16}$$

The attacker constructs the distinguisher using $z = |\boldsymbol{v}^T \boldsymbol{b}|_q$. If $\boldsymbol{b}$ is an LWR samples, then $z = |\boldsymbol{v}^T(\boldsymbol{A}_m \boldsymbol{s} + \boldsymbol{e})|_q = |\boldsymbol{w}^T \boldsymbol{s} + \boldsymbol{v}^T \boldsymbol{e}|_q$. Note that $\|\boldsymbol{s}\| \ll \|\boldsymbol{e}\|$ in our case, the attacker can enforce that $\|\boldsymbol{w}\| \gg \|\boldsymbol{v}\|$ to ensure that $|\boldsymbol{w}^T \boldsymbol{s}| \approx |\boldsymbol{v}^T \boldsymbol{e}|$ similar to [5]. He does so by choosing $\omega = \sigma' \sqrt{m/h}$ (for the LWR rounding error with variance $\sigma'^2 = ((q/p)^2 - 1)/12$), and considering the lattice:

$$\Lambda_\omega^* = \{(\boldsymbol{x}, \boldsymbol{y}/\omega) \in \mathbb{Z}^m \times (\frac{1}{\omega} \cdot \mathbb{Z}^d) : \boldsymbol{A}_m^T \boldsymbol{x} = \boldsymbol{y} \pmod q\} \tag{17}$$

A short vector $(\boldsymbol{v}, \boldsymbol{w}) \in \Lambda^*_\omega$ gives a short vector $(\boldsymbol{v}, \omega\boldsymbol{w}) \in \Lambda^*$ that is used to construct the distinguisher z. If $\boldsymbol{b}$ is uniform modulo q, so is z. If $\boldsymbol{b}$ is an LWR sample, then $z = |\boldsymbol{v}^T\boldsymbol{b}|_q = |(\omega\boldsymbol{w})^T\boldsymbol{s} + \boldsymbol{v}^T\boldsymbol{e}|_q = \boldsymbol{w}^T(\omega\boldsymbol{s}) + \boldsymbol{v}^T\boldsymbol{e}$ has a distribution approaching a Gaussian of zero mean and variance $\|(\boldsymbol{v}, \boldsymbol{w})\|^2 \cdot {\sigma'}^2$ as the lengths of the vectors increase, due to the Central limit theorem. Note that ω has been chosen such that $\|\omega\boldsymbol{s}\| \approx \|\boldsymbol{e}\|$. The maximal statistical distance between this and the uniform distribution modulo q is bounded by $\epsilon \approx 2^{-1/2}\exp(-2\pi^2(\|(\boldsymbol{v}, \boldsymbol{w})\|^2 \cdot \sigma'/q)^2)$ [24, Appendix B]. Lattice reduction with root-Hermite factor δ yields a shortest vector of length $\delta^{d'-1} \cdot \mathrm{Vol}(\Lambda^*_\omega)^{1/d'}$, where $d' = m + d$ and $\mathrm{Vol}(\Lambda^*_\omega) = (q/\omega)^d$ are Λ^*_ω's dimension and volume, respectively.

However, finding only one such short vector is not enough, as the resulting distinguishing advantage ϵ is too small to distinguish a final key which is hashed. The attack needs to be repeated approximately ϵ^{-2} times to achieve constant advantage. We assume that each run of BKZ with block size b provides $2^{0.2075b}$ vectors [9]. Under the conservative assumption that each of these vectors is short enough to guarantee a distinguishing advantage ϵ, the lattice reduction algorithm must therefore be run at least $\max(1, 1/2^{0.2075b} \cdot \epsilon^2)$ times [9], when considering BKZ with block size b. The cost of the weighted dual attack on LWR (with dimension d, large modulus q, rounding modulus p) using m samples thus is the cost of running one instance of BKZ lattice reduction with block size b times the number of repetitions required, i.e.,

$$(b \cdot 2^{cb}) \cdot \max(1, 1/(\epsilon^2 \cdot 2^{0.2075 \cdot b})), \text{where} \tag{18}$$

$$\epsilon = 2^{-1/2} \cdot \mathbf{e}^{-2\pi^2\left(\left(\|(\boldsymbol{v},\boldsymbol{w})\|^2 \cdot \sigma'\right)/q\right)^2}, \ \|(\boldsymbol{v}, \boldsymbol{w})\|^2 = \delta^{m+d-1} \cdot (q/\omega)^{d/(m+d)},$$

$$\delta = ((\pi b)^{\frac{1}{b}} \cdot \frac{b}{2\pi\mathbf{e}})^{\frac{1}{2(b-1)}}, \ \omega = \sigma' \cdot \sqrt{m/h}, \text{ and } {\sigma'}^2 = ((q/p)^2 - 1)/12.$$

2.7.6 Hybrid Attack

In this section, we consider a hybrid lattice reduction and meet-in-the-middle attack (henceforth called *hybrid attack*) originally due to [65] that targeted the NTRU [61] cryptosystem. The hybrid attack is applied to the lattice

$$\Lambda' = \{\boldsymbol{x} \in \mathbb{Z}^{m+d+1} \mid (\boldsymbol{I}_m|\boldsymbol{A}_m| - \boldsymbol{b})\boldsymbol{x} \equiv 0 \bmod q\}$$

for some $m \in \{1, \ldots, d\}$. We first find a basis $\boldsymbol{B'}$ for Λ' of the form

$$\boldsymbol{B}' = \begin{pmatrix} \boldsymbol{B} & \boldsymbol{C} \\ \boldsymbol{0} & \boldsymbol{I}_r \end{pmatrix} \tag{19}$$

where $0 < r < d$ is the meet-in-the-middle dimension and $\boldsymbol{I}_r$ is the r-dimensional identity matrix. We aim to find the short vector $\boldsymbol{v} = (\boldsymbol{e}^T, \boldsymbol{s}^T, 1)^T$ in Λ'. We write $\boldsymbol{v} = (\boldsymbol{v}_l^T, \boldsymbol{v}_g^T)^T$ where $\boldsymbol{v}_g$ has length r. We recover the vector $\boldsymbol{v}_g$ of length

$r < d$ consisting of the $(r-1)$ bottom entries of $\boldsymbol{s}$ followed by a '1' by guessing. As the columns of $\boldsymbol{B'}$ generate Λ', there exists a $\boldsymbol{x} \in \mathbb{Z}^{d+m+1-r}$ such that

$$\boldsymbol{v} = \begin{pmatrix} \boldsymbol{v}_l \\ \boldsymbol{v}_g \end{pmatrix} = \boldsymbol{B'} \begin{pmatrix} \boldsymbol{x} \\ \boldsymbol{v}_g \end{pmatrix} = \begin{pmatrix} \boldsymbol{B} & \boldsymbol{C} \\ \boldsymbol{0} & \boldsymbol{I}_r \end{pmatrix} \begin{pmatrix} \boldsymbol{x} \\ \boldsymbol{v}_g \end{pmatrix} = \begin{pmatrix} \boldsymbol{Bx} + \boldsymbol{Cv}_g \\ \boldsymbol{v}_g \end{pmatrix} \tag{20}$$

As $\boldsymbol{v}_l$ is short, $\boldsymbol{Cv}_g$ is close to $-\boldsymbol{Bx}$, a vector from the lattice $\Lambda(\boldsymbol{B})$. As explained in [106], the idea is that if we correctly guess $\boldsymbol{v}_g$, we can hope to find $\boldsymbol{v}_l$ by using Babai's Nearest Plane (NP) algorithm [17]. This algorithm, given a basis $\tilde{\boldsymbol{B}}$, finds for every target vector $\boldsymbol{t} \in \mathbb{R}^{d+m+1-r}$ a vector $\boldsymbol{e} = \mathrm{NP}_{\tilde{\boldsymbol{B}}}(\boldsymbol{t})$ such that $\boldsymbol{t} - \boldsymbol{e} \in \Lambda(\tilde{\boldsymbol{B}})$. For the cost of one NP call in dimension D, one may assume it takes $T_{NP} = \frac{D^2}{2^{1.06}}$ operations, or more conservatively $T_{NP} = \frac{D}{2^{1.06}}$ based on experiments in [60]. We choose the more conservative one $T_{NP} = \frac{D}{2^{1.06}}$.

As a result, the cost for the hybrid attack is the sum of two terms: the lattice reduction cost $\mathrm{Cost}_{\text{Lattice Reduction}}$ of finding a good basis $\tilde{\boldsymbol{B}}$ and the guessing cost $\mathrm{Cost}_{\text{Guess}}$ of guessing $\boldsymbol{v}_g$ of length r which is typically represented by $T_{NP} \cdot L$ where L is the number of repetitions. If we exhaustively guess $\boldsymbol{v}_g$, then L would be the number of candidates of $\boldsymbol{v}_g$. L can be lowered by the classical meet-in-the-middle approach or a quantum algorithm, and our security estimates are indeed obtained from those methods. For each method, we also have a corresponding success probability p_{succ}, and we repeat this attack p_{succ}^{-1} times to boost the overall success probability. Hence, the total cost is given by

$$\frac{\mathrm{Cost}_{\text{Lattice Reduction}} + \mathrm{Cost}_{\text{Guess}}}{p_{succ}}. \tag{21}$$

Below we give some details for the classical meet-in-the-middle approach and the quantum algorithm.

Remark. In some previous works regarding the hybrid attack [106, 107], it was assumed that the expensive lattice reduction can be amortized on each repetition, which yields a highly conservative cost model $\mathrm{Cost}_{\text{Lattice Reduction}} + \frac{\mathrm{Cost}_{\text{Guess}}}{p_{succ}}$. An amortization over lattice reduction of different lattices is definitely improbable. One remaining possibility is an amortization over the same lattice. For this, we observe that a similar assumption used in the guessing+dual attack has very limited success, details in the following section. Therefore, we decide not to consider this cost model in the hybrid attack.

Remark. As $r < d$, $\boldsymbol{v}_g$ is a ternary vector. The attacker can benefit from the fact that $\boldsymbol{s}$ has h non-zero entries in the generation of candidates for $\boldsymbol{v}_g$: candidates with high Hamming weight are not very likely. Also, the $(d-r)$ bottom entries of $\boldsymbol{v}_l$, being the $(d-r)$ top elements of $\boldsymbol{s}$, are ternary and sparse. In order to benefit from this fact, the $d-r$ rightmost columns of the matrix $\boldsymbol{B}$ are multiplied with an appropriate scaling factor ω. The scaling factor ω is calculated similarly to Section 2.7.4 by equalizing the *per-component* expected norms of the secret $\boldsymbol{s}$ and LWR rounding error $\boldsymbol{e}$: $\omega = \sqrt{\frac{(q/p)^2-1}{12} \cdot \frac{d}{h}}$. This

scales up the volume of the lattice generated by $\boldsymbol{B}$ by a factor ω^{d-r}. For the ease of analysis, hereafter each component of $\boldsymbol{v}_l$ is assumed to be sampled from a Gaussian distribution of variance σ'^2 denoted by $\mathcal{D}_{\sigma'}$.

Classical cost of hybrid attack with meet-in-the-middle. The meet-in-the-middle (mitm) speed up reduces the guessing cost at the expense of using considerable storage requirements. Indeed, in his classical paper for exploiting the mitm technique to NTRU [65], Howgrave-Graham considers the memory requirements the largest obstacle for the attack on one of the parameter sets. In [105], a reduced-memory technique is analyzed. Our security analysis ignores all memory cost and focuses only on the timing cost. In the following, we provide a high-level description of the most up-to-date classical analysis of the hybrid attack due to Wunderer [106, 107] and Son and Cheon [103].

Due to the structure of the Round5 secret, the guessed part $\boldsymbol{v}_g$ is a ternary vector, and for the mitm strategy to work, we restrict our searching scope for $\boldsymbol{v}_g$ to the set of vectors having Hamming weight $2k$ for $k \leq h_M$ for some $h_M \leq h/2$. Then we can recover $\boldsymbol{v}_g$ by repeatedly guessing $\boldsymbol{v}'_g$ in the set W of all ternary vectors having Hamming weight h_M, and storing $\boldsymbol{v}'_g$ in hash boxes whose addresses depend on $\boldsymbol{v}'_l = \mathrm{NP}_{\boldsymbol{B}}(\boldsymbol{C}\boldsymbol{v}'_g)$ and an attack parameter y. The addresses of the hash box follows [107, Definition 5.1], and are designed to ensure that any two vectors $\boldsymbol{v}'_l$ and $\boldsymbol{v}'_l + \boldsymbol{v}^*_l$ such that $\|\boldsymbol{v}^*_l\| \leq y$ share at least one address. In particular, the attack parameter y is taken so that $\|\boldsymbol{v}_l\|_\infty \leq y$ with high probability.

To see how this strategy succeeds, suppose that two vectors $\boldsymbol{v}'_g$ and $\boldsymbol{v}''_g$ in W are found such that $\boldsymbol{v}'_g + \boldsymbol{v}''_g = \boldsymbol{v}_g$ and $\boldsymbol{v}'_l + \boldsymbol{v}''_l = \boldsymbol{v}_l$ where $\boldsymbol{v}'_l = \mathrm{NP}_{\boldsymbol{B}}(\boldsymbol{C}\boldsymbol{v}'_g)$ and $\boldsymbol{v}''_l = \mathrm{NP}_{\boldsymbol{B}}(\boldsymbol{C}\boldsymbol{v}''_g)$. Then by the definition of address, there is at least one hash box containing both $\boldsymbol{v}_g$ and $\boldsymbol{v}''_g$. From that hash box one can recover $\boldsymbol{v}_g$ by examining whether each component of the sum $\boldsymbol{v}'_g + \boldsymbol{v}''_g$ is ternary. Here if our choice of y is too large, there would be too many vectors in each hash box and this attack would take too much time. In this regard, we follow [107, Assumption 5.3] that y is chosen properly so that it suffices to consider the NP call cost for each guess of $\boldsymbol{v}'_g$. Note that this assumption is rather conservative, because it leads to a definitely smaller cost estimation.

To analyze the expected number of repetitions L, we consider the subset $V \subseteq W$ defined as

$$V = \{\boldsymbol{w} \in W \,|\, (\boldsymbol{v}_g - \boldsymbol{w} \in W) \wedge (\mathrm{NP}_{\boldsymbol{B}}(\boldsymbol{C}\boldsymbol{w}) + \mathrm{NP}_{\boldsymbol{B}}(C\boldsymbol{v}_g - C\boldsymbol{w}) = \boldsymbol{v}_l)\},$$

and probabilities

$$p_s = \Pr_{\substack{\boldsymbol{w} \in W \\ \boldsymbol{v}_l \leftarrow \mathcal{D}^{d+m+1-r}_{\sigma'}}} [\mathrm{NP}_{\boldsymbol{B}}(C\boldsymbol{w}) - \mathrm{NP}_{\boldsymbol{B}}(\boldsymbol{v}_l) \in \mathcal{P}(\boldsymbol{B}^*)]$$

and

$$p_c = \Pr_{\substack{\boldsymbol{w} \in W \\ \boldsymbol{s} \leftarrow \mathcal{H}_n(h)}} [\boldsymbol{v}_g - \boldsymbol{w} \in W].$$

We first observe that $\mathrm{NP}_{\boldsymbol{B}}(C\boldsymbol{v}_g) = \mathrm{NP}_{\boldsymbol{B}}(\boldsymbol{v}_l)$ from our construction. Then p_s is equal to the probability

$$\Pr_{\substack{\boldsymbol{w}\leftarrow W \\ \boldsymbol{v}_l\leftarrow\mathcal{D}_{\sigma'}^{d+m+1-r}}}\left[\mathrm{NP}_{\boldsymbol{B}}(C\boldsymbol{w}) + \mathrm{NP}_{\boldsymbol{B}}(C\boldsymbol{v}_g - C\boldsymbol{w}) = \mathrm{NP}_{\boldsymbol{B}}(\boldsymbol{v}_l)\right].$$

To calculate it, we assume that $\boldsymbol{Cw}$ is randomly distributed modulo the parallelepiped $\mathcal{P}(\boldsymbol{B}^*)$ defined by the Gram-Schmidt vectors $\boldsymbol{B}^*$ and $\mathrm{NP}_{\boldsymbol{B}}(C\boldsymbol{v}_g) = \boldsymbol{v}_l$, which enables us to approximate p_s by

$$\Pr_{\substack{\boldsymbol{x}\leftarrow\mathcal{P}(\boldsymbol{B}^*) \\ \boldsymbol{y}\leftarrow\mathcal{D}_{\sigma'}^{d+m+1-r}}}\left[\boldsymbol{x}+\boldsymbol{y}\in\mathcal{P}(\boldsymbol{B}^*)\right].$$

which can be numerically calculated.

Regarding p_c, we further assume that $HW(\boldsymbol{v}_g) = 2k$ for some $k \le h_M$ according to our searching scope and then p_c is calculated by

$$p_c = \sum_{k=0}^{h_M} \frac{1}{2^k} \frac{\binom{2k}{k}\binom{r-2k}{h_M-k}}{\binom{r}{h_M}} \cdot \frac{\binom{h}{2k}\binom{d-h}{r-2k}}{\sum_{i=0}^{h_M}\binom{h}{2i}\binom{d-h}{r-2i}}$$

following [103, Lemma 4.1].

By assuming the independence of p_s and p_c, the size of V is expected to be $p_s p_c \cdot |W|$, and then the loop is expected to sample one vector in V per $\frac{1}{p_s p_c}$ repetitions. As our attack ends when the loop visits two vectors $\boldsymbol{v}_g'$ and $\boldsymbol{v}_g''$ in V, we have from the birthday paradox

$$L \approx \frac{1}{p_s p_c} \cdot \sqrt{|V|} \approx \frac{1}{p_s p_c} \cdot \sqrt{p_s p_c \cdot |W|} = \sqrt{\frac{|W|}{p_s p_c}}. \tag{22}$$

Since $|W| = 2^{h_M} \cdot \binom{r}{h_M}$, we conclude

$$\mathrm{Cost}_{\mathrm{Guess}}(\beta, r) = T_{NP} \cdot \sqrt{\frac{2^{h_M}\binom{r}{h_M}}{p_s p_c}}. \tag{23}$$

Finally, we describe how to determine the success probability p_{succ}. Note that we have two assumptions $\mathrm{NP}_{\boldsymbol{B}}(C\boldsymbol{v}_g) = \boldsymbol{v}_l$ and $HW(\boldsymbol{v}_g) = 2k$ for some $k \le h_M$ in our analysis. Assuming independence of these two events, the success probability can be estimated as

$$p_{\mathrm{succ}} = p_{h_M} \cdot p_{\mathrm{NP}}\,. \tag{24}$$

The probability p_{h_M} can be calculated combinatorially by

$$p_{h_M} = \sum_{k=0}^{h_M} \frac{\binom{h}{2k}\cdot\binom{d-h}{r-2k}}{\binom{d}{r}}.$$

The probability p_{NP} can be calculated via [107, Equation 5.6], which depends on the Gram-Schmidt vectors $\boldsymbol{b}_i^*$ and generalizes a result of Lindner and Peikert [78].

Quantum cost of hybrid attack. A quantum hybrid attack was proposed by Göpfert *et al.* [55, 107]. At a high level, this quantum hybrid attack follows the classical hybrid attack as described above with the meet-in-the-middle phase being replaced by a variant of Grover's algorithm [36]. The quantum guessing cost in this case is

$$\mathrm{Cost}_{\mathrm{Guess}} = T_{NP} \cdot \left(\sum_{\boldsymbol{x} \in S} d_{\boldsymbol{x}}^{\frac{2}{3}} \right)^{\frac{3}{2}} .$$

where S is our searching scope for $\boldsymbol{v}_g$, and $d_{\boldsymbol{x}}$ is the probability of $\boldsymbol{v}_g = \boldsymbol{x}$ on condition $\boldsymbol{v}_g \in S$.

For Round5 case, our searching scope S is partitioned into sets S_i of ternary vectors of Hamming weight i for some index set I, and we denote p_S be the probability of $\boldsymbol{v}_g \in S$. Furthermore, for any $\boldsymbol{x} \in S_i$, the probability of $\boldsymbol{v}_g = \boldsymbol{x}$ is $2^{-i}\binom{d-r}{h-i}/\binom{d}{h}$, and then

$$d_{\boldsymbol{x}} = \frac{2^{-i}\binom{d-r}{h-i}}{\binom{d}{h}} \cdot \frac{1}{p_S}.$$

Since $|S_i| = \binom{r}{i}2^i$, finally we have

$$\mathrm{Cost}_{\mathrm{Guess}} = T_{NP} \cdot \left(\sum_{i \in I} \binom{r}{i} 2^i \cdot \left(\frac{2^{-i}\binom{d-r}{h-i}}{\binom{d}{h}} \right)^{\frac{2}{3}} \right)^{\frac{3}{2}} \cdot \frac{1}{p_S} . \tag{25}$$

Similar to the classical attack, the success probability is estimated by $p_{succ} = p_S \cdot p_{NP}$ from which the total cost can be estimated by (21).

Wunderer provides a script to estimate the cost of the quantum hybrid attack[1], which we adapted to obtain estimates for the cost of this attack against Round5 parameter sets. In particular, different to the original code that assumes $T_{NP} = \frac{D^2}{2^{1.06}}$, we use $T_{NP} = \frac{D}{2^{1.06}}$ which leads to a more conservative estimation.

2.7.7 Guessing + Dual attack

This section considers attacks due to Albrecht [5] against *sparse and small* secrets with the goal of choosing an appropriate Hamming weight providing both optimal performance and security. Albrecht describes two attacks, a basic one and a more powerful that gives the name to this section. These attacks complement the Hybrid attack described in Section 2.7.6.

Basic attack: Since many rows of the public matrix $\boldsymbol{A}$ are irrelevant in the calculation of the product $\boldsymbol{As}$ for sparse secrets, Albrecht's attack ignores a random set of $k \leq d$ components of $\boldsymbol{s}$ and brings down the lattice dimension (and hence attack cost) during lattice reduction. In this basic attack, Albrecht proposes to guess k *zero* components and then perform a lattice reduction in dimension $d - k$ for the primal attack. From this point of view, this attack shares some similarities with the hybrid attack.

[1] Available at `https://github.com/lducas/LatRedHybrid`

As $\boldsymbol{s}$ has $d-h$ zeroes, there are $\binom{d-h}{k}$ choices (out of $\binom{d}{k}$) for the k ignored components such that these ignored components only contain zeroes. We therefore repeat the attack $\binom{d}{k}/\binom{d-h}{k}$ times. We estimate the cost (in bits) for a given Hamming weight $h \leq d$, as the number of repetitions each low cost attack is performed times the cost of the low-cost attack on a lattice of dimension $d-k$:

$$\frac{\binom{d}{k}}{\binom{d-h}{k}} \times \mathrm{Cost}_{\text{Lattice Reduction}}(d,k,h)$$

Here $\mathrm{Cost}_{\text{Lattice Reduction}}$ is defined as

$$\min\{b \cdot 2^{cb} \mid b \in \mathbb{N}, \text{ there exists } m \in \mathbb{N} \text{ such that } m \leq d \text{ and (26) is satisfied}\}.$$

$$\sqrt{(\omega^2 \cdot h + \sigma'^2 m) \cdot \frac{b}{d+m}} < \delta^{2b-d'-1} \cdot (q^{d'-(d-k)-1}\omega^{d-k})^{\frac{1}{d'}} \tag{26}$$

$$\text{where } \delta = ((\pi b)^{\frac{1}{b}} \cdot \frac{b}{2\pi \mathbf{e}})^{\frac{1}{2(b-1)}}, \omega = \sigma' \cdot \sqrt{(d-k)/h},$$

$$\sigma'^2 = ((q/p)^2 - 1)/12, \text{ and } d' = m + d - k + 1.$$

The attack runs on a LWR problem of dimension $d-k$ with $m \leq d$ samples. Condition 26, which is essentially Condition 13, ensures that such an attack has chances of succeeding.

Guessing + Dual: A similar attack is possible in combination with the dual attack. In this case, $\mathrm{Cost}_{\text{Lattice Reduction}}$ is calculated as in Equation 18, with the parameter d replaced by $d-k$. However, in contrast to the primal attack case, Albrecht shows that it is possible to compensate up to ℓ guessing failures by exhaustively guessing every vector of length k having Hamming weight less than ℓ. By this modification, one low-cost attack requires additional guessing cost, but the number of repetitions would be reduced. In fact, for any ternary vector x of length d and Hamming weight h, there are $\sum_{i=0}^{\ell} \binom{d-h}{k-i} \cdot \binom{h}{i}$ choices for the k components (out of $\binom{d}{k}$) such that x has at most ℓ non-zeros in them. As a result, the attack is repeated $\binom{d}{k}/\sum_{i=0}^{\ell} \binom{d-h}{k-i}\binom{h}{i}$ times.

For the guessing cost estimation, we look into the detailed process where the guessing strategy is combined with the dual attack. We may assume that one ignores the first k columns of $\boldsymbol{A}$, and denote $\boldsymbol{A} = [\boldsymbol{A}_1|\boldsymbol{A}_2]$. Then the dual attack applied on $(\boldsymbol{A}_2, \boldsymbol{b})$ finds short vectors $(\boldsymbol{v}_i, \boldsymbol{w}_i)$ in $\Lambda^*_\omega(\boldsymbol{A}_2)$. Then we have

$$z = |\boldsymbol{v}_i^T \boldsymbol{b}|_q = \boldsymbol{v}_i^T \boldsymbol{A}_1 \boldsymbol{s}_1 + \boldsymbol{w}_i^T(\omega \boldsymbol{s}_2) + \boldsymbol{v}_i^T \boldsymbol{e}.$$

Now one can guess $\boldsymbol{s}_1$ and observe whether $z - \boldsymbol{v}_i A_1 \boldsymbol{s}_1$ follows a Gaussian distribution. Here, as mentioned in Section 2.7.5, we require about ϵ^{-2} different short vectors $\boldsymbol{v}_i$ to amplify the success probability. Thus one guess for $\boldsymbol{s}_1$ requires at least ϵ^{-2} times of computations of $\boldsymbol{v}_i A_1$. We conservatively set one computation cost by 1, and have $\mathrm{Cost}_{\text{Guess}} = \frac{1}{\epsilon^2} \sum_{i=0}^{\ell} \binom{k}{i} 2^i$.

[1] Note that $\boldsymbol{s}_1$ corresponds to the guess part, and the basic attack expects that $\boldsymbol{s}_1$ would be the zero vector.

Finally the total attack cost is estimated as

$$\frac{\binom{d}{k}}{\sum_{i=0}^{\ell}\binom{d-h}{k-i}\binom{h}{i}} \times (\mathrm{Cost}_{\text{Lattice Reduction}} + \mathrm{Cost}_{\text{Guess}}).$$

where

$$\mathrm{Cost}_{\text{Lattice Reduction}} = b \cdot 2^{cb} \max(1, \frac{1}{\epsilon^2 \cdot 2^{0.2075b}}),\ \mathrm{Cost}_{\text{Guess}} = \frac{1}{\epsilon^2}\sum_{i=0}^{\ell}\binom{k}{i}2^i.$$

with

$$\epsilon = 2^{-1/2}e^{-2\pi^2((\|(\boldsymbol{v},\boldsymbol{w})\|_2\sigma'/q)^2},\ \|\ (\boldsymbol{v},\boldsymbol{w})\ \|_2 = \delta^{m+d-k-1}(q/\omega)^{(d-k)/(m+d-k)},$$

$$\delta = \left((\pi b)^{1/b}\cdot\frac{b}{2\pi e}\right)^{\frac{1}{2(b-1)}},\ \omega = \sigma'\cdot\sqrt{m/(h-\ell)},\ \sigma'^2 = ((q/p)^2-1)/12.$$

Our choice of ω implicitly assumes the case where the Hamming weight of $\boldsymbol{s}_1 = \ell$, which is the most frequent weight among the guessed vectors. Note that there is no way to choose ω depending on the weight of $\boldsymbol{s}_1$, since the attacker cannot know the exact weight of $\boldsymbol{s}_1$ during lattice reduction phase.

For all configurations of Round5, we performed a (limited) search over the quadruples (k, ℓ, m, b) that gives minimal cost. Again, we assume that each run of BKZ with block size b provides $2^{0.2075b}$ vectors [9].

Remark. The total attack cost is computed as the number of repetitions $\binom{d}{k}/\sum_{i=0}^{\ell}\binom{d-h}{k-i}\binom{h}{i}$ times the cost of the lattice reduction. An attacker with many resources might run those lattice reductions in parallel instead of sequentially. This does not decrease the total cost, e.g., measured as the total energy cost, however, it can provide the attacker with the right answer, slightly faster. For Round5 parameters, the number of repetitions when minimizing the total cost does not exceed 2^{10}.

Remark. Albrecht's original paper [5] describes an approach for amortizating the cost of lattice reduction that assumes that ϵ^{-2} short vectors can be obtained by applying cheap LLL lattice reductions while re-randomizing the first BKZ-basis. Then $\mathrm{Cost}_{\text{Lattice Reduction}}$ equals the cost of a a single BKZ call, ignoring the cost of the ϵ^{-2} LLL calls. In order the obtain tight security estimates, we have examined this heuristic by carrying out the following experiment suggested in [5]. Given a lattice basis, we first perform BKZ with large block size to have a reduced basis $\boldsymbol{B}$ and let the first short vector be the first column vector of $\boldsymbol{B}$. To have another short vector, we sample a *sparse* unimodular matrix $\boldsymbol{U}$ having ternary entries, and run LLL on $\boldsymbol{B'} = \boldsymbol{B}\cdot\boldsymbol{U}$,. Then we take the first column vector of it as the new short vector. Note that $\boldsymbol{B'}$ is another basis of the lattice, and every first column vector is a desired lattice vector. Albrecht expects that this amortization technique will give a new short vector for almost every randomizing matrix $\boldsymbol{U}$.

However, our own experiments cannot verify this heuristic as Table 2 indicates. In that table, the parameters are selected to be Round5 relevant, e.g., the Hamming weight is 25% and we include q values between 2^10 and 2^{25}. The main two observations are that the amount of short vectors that are obtained decreases when q decreases making this approach costly. Furthermore, the table shows that only a few different ones are found, and even most importantly, the amount of new found vectors decreases when we make more LLL calls.

For these two reasons, we do not consider amortization techniques in Round5's concrete security analysis. Note that this is also the reason why cost estimates for the guessing+dual attack are only provided for sieving, and not for enumeration.

Table 2: Experiments on Albrecht's heuristic [5] to find short vectors for fixed $n = 100$, $h = 25$, $b = 60$, $\sigma = 3.2$ and variable q. The table indicates the total number of short vectors found after 256/512/768/1024 LLL calls.

q	Number of LLL calls			
	256	512	768	1024
2^{25}	14	17	19	22
2^{20}	10	13	17	19
2^{15}	8	10	12	13
2^{10}	2	5	5	5

Hybrid dual attack. The guessing and dual attack was recently improved by Cheon *et al.* [39], who propose a meet-in-the-middle speed up in the guessing part, giving rise to a *hybrid dual* attack that is competitive in the homomorphic encryption parameter regime. However, it is noted in [39] that this meet-in-the-middle step is ineffective in the public-key encryption regime, and hence we do not consider this approach further.

2.7.8 Exhaustive search

To ensure that an exhaustive, brute-force search of each secret-key vector in the secret-key using Grover's quantum search algorithm [56] has a cost of at least λ (in bits), the chosen Hamming weight should satisfy:

$$\sqrt{\binom{d}{h} \cdot 2^h} > 2^\lambda \tag{27}$$

Note that for a typical security level of $\lambda = 128$, a dimension of at least $d = 512$ would be secure against Grover's quantum search, for any Hamming weight h that is at least $0.1d$.

2.7.9 Use of $f_{d,n}^{(\tau)}$ to stop Pre-computation and Back-door Attacks

Works prior to New Hope [9], like [30] and [85], defined key exchange protocols or key encapsulation protocols with a fixed public parameter $\boldsymbol{A}$ in the case of unstructured lattices, $\boldsymbol{a}$ in the case of structured lattices. NewHope [9] proposed generating $\boldsymbol{a}$ on the fly from a seed that needs to be exchanged. The rationale for having a fresh $\boldsymbol{A}$ or $\boldsymbol{a}$ includes preventing pre-computation and backdoor attacks. In a pre-computation attack on a system with fixed public parameter $\boldsymbol{A}$, the attacker performs lattice reduction on $\boldsymbol{A}$ over a long period of time. A back-door attack can be mounted if the fixed $\boldsymbol{A}$ has deliberately been chosen so as to result in a lattice with weak security.

Round5 addresses these attacks and performance issues by generating a fresh $\boldsymbol{A}$ based on function $f_{d,n}^{(\tau)}$ (see Section 2.4.3) with $\tau \in \{0, 1, 2\}$. For its ring instantiations, Round5 only defines $f_{d,n}^{(0)}$, as this solution is sufficiently fast and memory efficient. For the non-ring instatiations, all three options $f_{d,n}^{(\tau)}$ with $\tau \in \{0, 1, 2\}$ can be applied.

$f_{d,n}^{(0)}$, Non-ring and ring instantiations. With this function, a fresh $\boldsymbol{A}$ is generated in each protocol instantiation, similar to [29] and [9]. This prevents both pre-computation attacks and backdoors since all entries of the matrix are sampled from pseudorandom data generated from a fresh and random seed. This option performs well in the ring case, but for the non-ring case it requires the generation of a high amount of pseudorandom data, between 0.75 MByte and 2.5 MByte for typical parameters. This motivates the usage of $f_{d,n}^{(1)}$ and $f_{d,n}^{(2)}$.

$f_{d,n}^{(1)}$, Non-ring instantiation. With $f_{d,n}^{(1)}$, the matrix $\boldsymbol{A}$ is derived from a fixed long-term system-wide matrix $\boldsymbol{A}_{\text{master}} \in \mathbb{Z}_q^{d \times d}$. This is done by applying to $\boldsymbol{A}_{\text{master}}$ a fresh permutation chosen by the initiator of the protocol at the start of each protocol exchange. The permutation consists in random, cyclic shifts of the rows of $\boldsymbol{A}_{\text{master}}$. Computing this permutation is cheap, and thus, this approach is efficient in terms of CPU overhead. Memory-wise, only $\boldsymbol{A}_{\text{master}}$ needs to be kept in memory and simple permutations of it can be used for connecting to multiple clients. This prevents any pre-computation attacks since the possible number of permuted versions of $\boldsymbol{A}_{\text{master}}$ obtained in this way equals d^d. Back-doors are avoided since $\boldsymbol{A}_{\text{master}}$ is derived by means of a pseudo-random function from a randomly generated seed, in other words, by using $f_{d,n}^{(\tau)}$ for $\tau = 0$. Proving formal security in terms of indistinguishability is not feasible if $(\boldsymbol{A}, \boldsymbol{B})$ is jointly considered as the public key.

$f_{d,n}^{(2)}$, Non-ring instantiation. With $f_{d,n}^{(2)}$, $\boldsymbol{A}$ is obtained from a vector $\boldsymbol{a}_{\text{master}} \in \mathbb{Z}_q^{len_tau_2}$ that is generated from a seed determined by the initiator in each protocol interaction. Each row in $\boldsymbol{A}$ is obtained from $\boldsymbol{a}_{\text{master}}$ by

means of a permutation derived from σ as well. Each row of $\boldsymbol{A}$ consists of d consecutive entries of $\boldsymbol{a}_{\text{master}}$. It is ensured that the leftmost entries of different rows of $\boldsymbol{A}$ correspond to different entries of $\boldsymbol{a}_{\text{master}}$. Since only a few – len_tau_2 – elements need to be generated and kept in memory, $f^{(2)}_{d,n}$ is efficient both in terms of memory and CPU consumption.

Since elements in $\boldsymbol{A}$ might correspond to the same entry of $\boldsymbol{a}_{\text{master}}$, the security of Round5 when employing $f^{(2)}_{d,n}$ cannot be based on the results from Section A.7. However, we argue that pre-computation and backdoor attacks are avoided since the seed that determines $\boldsymbol{A}$ is new in each protocol interaction, and this approach allows computing many $\boldsymbol{A}$'s: $\boldsymbol{A}$ is obtained by permuting – there are a total of $\binom{len_tau_2}{d}$ permutations – a fresh vector $\boldsymbol{a}_{\text{master}}$ for which there are $q^{len_tau_2}$ choices.

We now analyze $f^{(2)}_{d,n}$ from a different perspective. If $len_tau_2 = d$, then $\boldsymbol{A}$ contains all cyclic shifts of $\boldsymbol{a}_{\text{master}}$, resulting in a RWLR-based scheme with reduction polynomial $x^d - 1$.

Next, assume that $len_tau_2 > d$. We say that two rows of $\boldsymbol{A}$ overlap if they have have at least one entry originating from the same entry of $\boldsymbol{a}_{\text{master}}$. We now consider two rows of $\boldsymbol{A}$ for which the leftmost entries correspond to entries i and j of $\boldsymbol{a}_{\text{master}}$. The rows overlap if and only if $j \in \{\langle i-k\rangle_d \mid |k| \leq d-1\}$. As $\boldsymbol{p}$ has distinct entries, $2(d-1)$ of the $len_tau_2 - 1$ choices for j result in an overlap. Hence, the probability of the two rows overlapping equals $2(d-1)/(len_tau_2-1)$. By the union bound, the probability that some pair of rows of $\boldsymbol{A}$ overlap is at most $\binom{d}{2} \times 2(d-1)/(len_tau_2-1)$. Hence, if len_tau_2 is much larger than d^3, then with high probability all entries of $\boldsymbol{A}$ originate from distinct entries from $\boldsymbol{a}_{\text{master}}$, and using $f^{(2)}_{d,n}$ resembles to having an LWR-based scheme.

If the two rows do not overlap, then we argue that for those two rows, $f^{(2)}_{d,n}$ is equivalent to $f^{(0)}_{d,n}$ since the entries of those rows are sampled from different pseudorandom data.

Now we consider two overlapping rows of $\boldsymbol{A}$ that share $d-1-k$ elements, namely $a = \langle a_0, a_1, a_2, \ldots, a_{d-1}\rangle$ and $b = \langle b_0, b_1, \ldots, b_{k-1}, a_0, a_1, a_2, \ldots, a_{d-k-1}\rangle$. If we define $a(x) := a_0 + a_1x + a_2x^2 + \cdots + a_{d-1}x^{d-1}$ and $b(x) := b_0 + b_1x + \cdots + b_{k-1}x^{k-1} + a_0x^k + a_1x^{k+1} + \cdots + a_{d-k-1}x^{d-1}$, then we have $b(x) = a(x)x^k + (a_{d-k} + b_0) + (a_{n-k+1} + b_1)x + \cdots + (a_{d-1} + b_{k-1})x^{k-1} \bmod x^d + 1$. Effectively, that is, each row can be seen as using the $x^d + 1$ ring with a random shifting (due to k) and additional random noises, those $(a_{d-k} + b_0) + (a_{d-k+1} + b_1)x + \cdots + (a_{d-1} + b_{k-1})x^{k-1}$. The random shift is due to the the random permutation and the random noises are due to the random generation of $\boldsymbol{a}_{\text{master}}$. We argue that this fact makes it harder to exploit any ring structure in the resulting $\boldsymbol{A}$ (as can be found in circulant or anti-circulant matrices for ideal lattices, for example). We also argue that this approach of generating $\boldsymbol{A}$ with $f^{(2)}_{d,n}$ is at least as secure as using the ring instantiation of Round5.

2.7.10 Attacks against symmetric primitives

The formal security proof of Round5 (Appendix A.3) assumes that the function $\boldsymbol{f}_{d,n}^{(\tau=0)}$ can be modeled as a random oracle, and that the functions f_S and f_R can be modeled as pseudo-random functions. In Round5, these functions are instantiated using TupleHash. *Optionally*, $\boldsymbol{f}_{d,n}^{(\tau=0)}$ is instantiated by means of AES in counter mode. We argue here why it is unlikely that there exist attack avenues against this instantiation. If such attack avenues were discovered, the instantiations of the above functions must be replaced by others.

First, the random oracle assumption on $\boldsymbol{f}_{d,n}^{(\tau=0)}$ implies assuming that no inter-dependencies exist in the outputs of TupleHash. The pseudo random function assumptions on f_S and f_R imply assuming that TupleHashXOF produces pseudorandom output. Breaking any of these assumptions would constitute a major breakthrough in the cryptanalysis of the SHA3 family.

Next, the generated pseudorandom data is not used directly in above functions, but is first converted to the appropriate value ranges. Round5 ensures uniform sampling so that both the random oracle and the pseudo-random function assumptions on $\boldsymbol{f}_{d,n}^{(\tau=0)}$, f_S and f_R, respectively, hold. The generation of $\boldsymbol{A}$ from a public seed using $\boldsymbol{f}_{d,n}^{(\tau=0)}$ (see sections 2.11.4 and 2.11.6) consists in taking TupleHash output that is uniform in $[0, 2^{16})$ and keeping its $log_2\ q$ least significant bits to obtain a uniformly distributed integer in $[0, q)$, and repeating this independently to generate all entries of the matrix $\boldsymbol{A}$. This method is sound since q is a power of two. The generation of Round5's secret-keys using the functions f_S and f_R is defined in the sample() function in Section 2.11.5. It consists in taking TupleHashXOF output x that is uniform in $[0, 2^{16})$, rejecting those values that are greater than $rrange \cdot d$, the largest multiple of d smaller than 2^{16} and dividing suitable candidates x by $rrange$. This method ensures that the output is uniform in $[0, d)$ and gives a low rejection ratio.

2.8 Correctness of Round5

The following subsections we first derive the condition for correct decryption in Round5. Subsequently, we work out this condition for non-ring parameters, ring parameters with reduction polynomial $\xi(x) = \Phi_{n+1}(x)$, and ring parameters with $\xi(x) = x^{n+1} - 1$. The analysis for ring parameters with $\xi(x) = \Phi_{n+1}(x)$ show that decryption errors (before error correction) are correlated. For this reason, error correction in combination with reduction polynomials $\xi(x) = x^{n+1} - 1$ is not effective. Finally, results from the decryption failure analysis are compared with simulations for scaled-down versions of Round5. Here and in the remainder of the specification, the terms "failure probability" and "failure rate" are used interchangeably.

2.8.1 Decryption failure analysis

In this section, the decryption failure behavior of r5_cpa_pke is analyzed. In decryption, the vector $\boldsymbol{x'} = \langle \lfloor \frac{b}{p}\boldsymbol{\zeta} \rfloor \rangle_b$ is computed, where

$$\boldsymbol{\zeta} = \left\langle \frac{p}{t}\boldsymbol{v} + h_3\boldsymbol{j} - \mathrm{Sample}_\mu\left(\left\langle \boldsymbol{S}^T(\boldsymbol{U} + h_4\boldsymbol{J})\right\rangle_\xi\right)\right\rangle_p .$$

First, a sufficient condition is derived so that $\boldsymbol{x'}$ and $\boldsymbol{x} = xef_compute_{\kappa,f}(m)$ agree in a given position, where $\boldsymbol{x}$ is considered as a vector of μ symbols, each consisting of *b_bits* bits. We have that

$$\boldsymbol{v} \equiv \langle \frac{t}{p}\mathrm{Sample}_\mu(\langle \boldsymbol{B}^T\boldsymbol{R}\rangle_\xi + h_2\boldsymbol{j}) - \frac{t}{p}\boldsymbol{I}_v\rangle_p + \frac{t}{b}\boldsymbol{x} \pmod t,$$

where $\frac{t}{p}\boldsymbol{I}_v$ is the error introduced by the rounding downwards, with each component of $\boldsymbol{I}_v$ in $\mathbb{Z}_{p/t}$. As a result,

$$\boldsymbol{\zeta} \equiv \frac{p}{b}\boldsymbol{x} + \boldsymbol{\Delta} \pmod p \text{ with } \boldsymbol{\Delta} = (h_2 + h_3)\boldsymbol{j} - \boldsymbol{I}_v + \mathrm{Sample}_\mu(\langle \boldsymbol{B}^T\boldsymbol{R} - \boldsymbol{S}^T(\boldsymbol{U} + h_4\boldsymbol{J}\rangle_\xi). \tag{28}$$

As $\boldsymbol{x'} = \lfloor \frac{b}{p}\boldsymbol{\zeta} \rfloor = \lfloor \frac{b}{p}\boldsymbol{\zeta} - \frac{1}{2} \rceil$, we have that

$$\boldsymbol{x'} \equiv \boldsymbol{x} + \lfloor \frac{b}{p}\boldsymbol{\Delta} - \frac{1}{2}\boldsymbol{J} \rceil \equiv \boldsymbol{x} + \lfloor \frac{b}{p}\{\boldsymbol{\Delta} - \frac{p}{2b}\boldsymbol{J}\}_p \rceil \pmod b.$$

Here $\{y\}_p$ denotes the integer in $(-p/2, p/2]$ that is equivalent to y modulo p. As a consequence, $x_i = x'_i$ whenever $|\{\boldsymbol{\Delta}_i - \frac{p}{2b}\}_p| < \frac{p}{2b}$. We multiply both sides of the above inequality with $\frac{q}{p}$, and infer that $x_i = x'_i$ whenever

$$|\ \{\frac{q}{p}\boldsymbol{\Delta}_i - \frac{q}{2b}\}_q\ | < \frac{q}{2b}. \tag{29}$$

Equivalently, as $\frac{q}{p}\boldsymbol{\Delta}_i$ has integer components, if $x_i \neq x'_i$, then

$$\langle \frac{q}{p}\boldsymbol{\Delta}_i\rangle_q \in \left[\frac{q}{2b}, q - \frac{q}{2b}\right] \tag{30}$$

The probability that $\boldsymbol{x}$ and $\boldsymbol{x'}$ differ in position i thus is at most the probability that (30) is satisfied. In order to analyze this probability, we work out $\frac{q}{p}\boldsymbol{\Delta} - \frac{q}{2b}\boldsymbol{J}$, using (28).

We write $\boldsymbol{J}_v = \frac{q}{p}(h_2\boldsymbol{j} + h_3\boldsymbol{j} - \boldsymbol{I}_v - \frac{p}{2^b}\boldsymbol{J})$. The definitions of h_2 and h_3 imply that $\boldsymbol{J}_v = \frac{q}{p}(\frac{p}{2t} - \boldsymbol{I}_v)$. Each component of $\boldsymbol{I}_v$ is in $\mathbb{Z}_{p/t}$. The value of h_3 thus ensures that the absolute value of each coefficient of $\frac{p}{2t} - \boldsymbol{I}_v$ is at most $\frac{p}{2t}$.
We now analyse $\frac{q}{p}\langle \boldsymbol{B}^T\boldsymbol{R} - \boldsymbol{S}^T(\boldsymbol{U} + h_4\boldsymbol{J})\rangle_\xi$. Similarly to the expression for $\boldsymbol{v}$, we write

$$\boldsymbol{B} = \left\langle \frac{p}{q}\left(\langle \boldsymbol{A}\boldsymbol{S}\rangle_{\Phi_{n+1}} + h_1\boldsymbol{J}\right) - \frac{p}{q}\boldsymbol{I}_B\right\rangle_p \text{ and } \boldsymbol{U} = \left\langle \frac{p}{q}(\langle \boldsymbol{A}^T\boldsymbol{R}\rangle_{\Phi_{n+1}} + h_2\boldsymbol{J}) - \frac{p}{q}\boldsymbol{I}_U\right\rangle_p ,$$

with all components of $\boldsymbol{I}_B$ and $\boldsymbol{I}_U$ in $\mathbb{Z}_{q/p}$. We thus can write

$$\frac{q}{p}(\boldsymbol{B}^T\boldsymbol{R}-\boldsymbol{S}^T(\boldsymbol{U}+h_4\boldsymbol{J}) \equiv \langle \boldsymbol{S}^T\boldsymbol{A}^T\rangle_{\Phi_{n+1}}\boldsymbol{R}-\boldsymbol{S}^T\langle \boldsymbol{A}^T\boldsymbol{R}\rangle_{\Phi_{n+1}}+\boldsymbol{J}_B^T\boldsymbol{R}-\boldsymbol{S}^T\boldsymbol{J}_U \pmod q \tag{31}$$

where

$$\boldsymbol{J_B} = h_1\boldsymbol{J} - \boldsymbol{I}_B, \text{ and } \boldsymbol{J_U} = (h_2+h_4)\boldsymbol{J} - \boldsymbol{I}_U. \tag{32}$$

As $h_1 = h_2 + h_4 = \frac{q}{2p}$, all entries of $\boldsymbol{J}_B$ and of $\boldsymbol{J}_U$ are from the set $I := (-\frac{q}{2p}, \frac{q}{2p}] \cap \mathbb{Z}$. The value of h_4 thus ensures that the absolute value of the entries of $\boldsymbol{J}_B$ and $\boldsymbol{J}_U$ are at most $\frac{q}{2p}$.

Clearly, if $\xi = \Phi_{n+1}$, then $\langle \boldsymbol{S}^T\boldsymbol{A}^T\rangle_{\Phi_{n+1}}\boldsymbol{R} \equiv \boldsymbol{S}^T\langle \boldsymbol{A}^T\boldsymbol{R}\rangle_{\Phi_{n+1}}$, so that

$$\frac{q}{p}\boldsymbol{\Delta} \equiv \boldsymbol{J}_v + \text{Sample}_\mu\left(\langle \boldsymbol{J}_B^T\boldsymbol{R} - \boldsymbol{S}^T\boldsymbol{J}_U\rangle_{\Phi_{n+1}}\right) \pmod q \tag{33}$$

In Section 2.8.4, the special case $\xi(x) = x^{n+1} - 1$ will be analyzed.

The probability that (30) is satisfied will be analyzed under the following assumptions: the entries $\boldsymbol{J}_v$ are drawn independently, and each such entry is distributed as $\frac{q}{p}y$ with y uniform on $(-\frac{p}{2t}, \frac{p}{2t}] \cap \mathbb{Z}$. The entries of $\boldsymbol{J}_B$ and $\boldsymbol{J}_U$ are drawn independently and uniformly from $I = (-\frac{q}{2p}.\frac{q}{2p}] \cap \mathbb{Z}$. In our analysis, we also assume that all columns of the secret matrices $\boldsymbol{S}$ and $\boldsymbol{R}$ have $h/2$ coefficients equal to 1 and $h/2$ coefficients equal to -1. This is true for the implementations of f_S and f_R.

2.8.2 Failure probability computation: non-ring parameters

In the non-ring case, each entry of $\boldsymbol{J}_B^T\boldsymbol{R}$ and of $\boldsymbol{S}^T\boldsymbol{J}_U$ is the inner product of a row of $\boldsymbol{J}_B^T$ (resp. a column of $\boldsymbol{J}_U$) and a ternary vector with $h/2$ entries equal to one and $h/2$ entries equal to minus one. Hence each entry of $\boldsymbol{J}_B^T\boldsymbol{R}-\boldsymbol{S}^T\boldsymbol{J}_U$ is distributed as the sum of h uniform variables on I minus the sum of h uniform variables on I. Assuming independence, the latter distribution (modulo q) can easily be computed explicitly (using repeated convolutions). Indeed, if c and d are two independent variables on $\{0, 1, \ldots, q-1\}$ with probability distributions p_c and p_d, then the probability distribution p_e of $\langle c + d\rangle_q$ is given by

$$p_e(k) = \sum_{i=0}^{q-1} p_c(i)p_d(\langle k - i\rangle_q) \text{ for } 0 \le k \le q-1.$$

Assuming independence between the i-th components of $\boldsymbol{J}_v$ and of $\text{Sample}_\mu(\boldsymbol{J}_B^T\boldsymbol{R}-\boldsymbol{S}^T\boldsymbol{J}_U)$, the probability that (30) is satisfied can be computed by using another convolution. By the union bound, the probability that at least one of the symbols of $\boldsymbol{x}$ is not retrieved correctly is at most μ times the probability that (30) is satisfied.

2.8.3 Failure probability computation: ring parameters with $\xi(x) = \Phi_{n+1}(x)$

Round5 parameters without error correction use $\xi(x) = \Phi_{n+1}(x)$. As $N(x)$ is a multiple of $\Phi_{n+1}(x)$, we have that $\langle f\rangle_{\Phi_{n+1}} = \langle\langle f\rangle_N\rangle_{\Phi_{n+1}}$. Moreover, if $g(x) = \sum_{i=0}^{n} g_i x^i$, then $\langle g\rangle_{\Phi_{n+1}} = g - g_n\Phi_{n+1}$. In particular, for all polynomials s, e,

$$\text{if } \langle se\rangle_N = \sum_{k=0}^{n} c_k(s,e)x^k, \text{ then } \langle se\rangle_{\Phi_{n+1}} = \sum_{k=0}^{n-1}(c_k(s,e) - c_n(s,e))x^k, \quad (34)$$

with $c_k(s,e)$ as defined in (37). If the k-th symbol is not retrieved correctly, then

$$\langle (j_v(x))_k + c_k(j_B,r) - c_n(j_B,r) + c_k(s,j_u) + c_n(s,j_u)\rangle_q \in \left[\frac{q}{2b}, q - \frac{q}{2b}\right] \quad (35)$$

Assuming independence, and taking into account that r and s contain $h/2$ ones and $h/2$ minus ones, $c_k(j_B,r) - c_n(j_B,r) - c_n(j_B,r) + c_k(s,j_u)$ is distributed as the difference of $2h$ independent random variables on I, minus the sum of $2h$ independent random variables on I. The probability that (35) is satisfied thus can be computed explicitly. By the union bound, the probability that at least one of the μ symbols is not retrieved correctly is at most μ times the probability that (35) is satisfied.

Remark The condition in (35) for decryption error in position k shows the term $-c_n(j_B,r) + c_n(s,j_u)$ that is common to all positions k. This is the reason that using error correction in conjunction with $\xi(x) = \Phi_{n+1}(x)$ is not effective. The union bound can be used as it also applies to dependent random variables.

2.8.4 Failure probability computation: ring parameters with $\xi(x) = x^{n+1} - 1$

Round5 parameters using error correction are restricted to the ring case. So in (31) we have

$$\langle \boldsymbol{S}^T\boldsymbol{A}^T\rangle_{\Phi_{n+1}}\boldsymbol{R} - \boldsymbol{S}^T\langle \boldsymbol{A}^T\boldsymbol{R}\rangle_{\Phi_{n+1}} = \lambda_s(x)\Phi_{n+1}(x)r(x) - s(x)\lambda_r(x)\Phi_{n+1}(x)$$

for some $\lambda_s, \lambda_r \in \mathbb{Z}[x]$.

For the Round5 parameters with error correction, it is required that $\xi(x) = (x-1)\Phi_{n+1}(x) = x^{n+1} - 1$, and that $s(x)$ and $r(x)$ both are balanced, that is, have $h/2$ coefficients equal to 1, $h/2$ coefficients equal to -1, and the other coefficients equal to zero. Then $x - 1$ divides both $r(x)$ and $s(x)$, and so $\xi(x)$ divides both $\Phi_{n+1}(x)r(x)$ and $s(x)\Phi_{n+1}(x)$. As a result, (33) reads as

$$\frac{q}{p}\Delta(x) \equiv j_v(x) + \text{Sample}_\mu\left(\langle \boldsymbol{j}_B(x)r(x) - s(x)j_U(x)\rangle_{x^{n+1}-1}\right) \pmod q. \quad (36)$$

For any two polynomials $e(x) = \sum_{i=0}^{n} e_i x^i$ and $s(x) = \sum_{i=0}^{n} s_i x^i$,

$$\langle s(x)e(x)\rangle_{x^{n+1}-1} = \sum_{k=0}^{n} c_k(s,e)x^k \text{ where } c_k(s,e) = \sum_{i=0}^{n} e_i s_{\langle k-i\rangle_{n+1}}. \tag{37}$$

If the k-th symbol is not retrieved correctly, then

$$\langle (j_v(x))_k + c_k(j_B, r) - c_k(s, j_u)\rangle_q \in \left[\frac{q}{2b}, q - \frac{q}{2b}\right]. \tag{38}$$

Assuming independence, using that r and s both contain $h/2$ and $h/2$ minus ones, $c_k(j_B, r) - c_k(s, j_u)$ is distributed as the sum of h independent uniform variables on I, minus the sum of h uniform variables on I. The probability p_n that (37) is satisfied thus can be computed explicitly.

Now let the error-correcting code be capable of correcting f symbol errors. Assuming that $c_k(s,e)$ and $c_\ell(s,e)$ are independent whenever $k \neq \ell$, the probability of not decoding correctly is at most $\sum_{e \geq f+1} \binom{\mu}{e} p_n^e (1-p_n)^{\mu-e}$.

2.8.5 Experimental results

Figure 3 compares the estimated probabilities of at least one error occurring and that of at least two errors occurring, when $\xi = N_{n+1}$ (as in r5_cpa_pke) and when $\xi = \Phi_{n+1}$, respectively. These estimates are computed by explicitly convolving probability distributions. Parameters are simulated without error correction, and are $n = 800$, $q = 2^{11}$, $p = 2^7$, $t = 2^4$, $\mu = \kappa = 128$, while the Hamming weight h varies between 100 and 750 in order to show its effect on both the bit failure rate and error correlation.

For $\xi = \Phi_{n+1}$, the probabilities are computed as follows. For any a, (35) can be used to compute $p(k \mid a)$, the probability that bit k is not retrieved correctly, given that $-c_n(j_b, r) + c_n(s, j_u) \equiv a \pmod q$. We assume that having a bit error in position k, given that $c_n(s, j_u) - c_n(j_b, r) \equiv a$, is independent of having a bit error in another position j, given that $c_n(s, j_u) - c_n(j_{b,r}) \equiv a$. The probability of having exactly e bit errors, given that $c_n(s, j_u) - c_n(j_b, r) \equiv a$, then equals $\binom{\mu}{k}(p(0 \mid a)^e(1 - p(0 \mid a))^{\mu-e}$. By summing these probabilities over a, weighted with the probability that $c_n(s, j_u) - c_n(j_b, r) \equiv a$, the probability of having exactly e bit errors is obtained.

Clearly, the probability of at least two errors is much higher when multiplications are done modulo Φ_{n+1} instead of N_{n+1}, and in the latter case, this probability is significantly lower than the probability of at least one error. Figure 3 also shows corresponding probabilities of at least one and at least two errors, obtained from simulations of scaled-down r5_cpa_pke parameters, showing that the actual behavior closely matches that predicted by the failure analysis.

As further evidence, Table 3 reports experimental results for actual, proposed parameters for the ring instantiation of Round5's IND-CPA secure key-encapsulation mechanism that use error correction, i.e., R5ND_1CPA_5d, R5ND_3CPA_5d and R5ND_5CPA_5d (presented in Section 2.9). These results are

Figure 3: Probabilities of at least one (continuous lines) and at least two errors (dotted lines) in Round5 ring parameters, plotted against the Hamming weight of secrets (X-axis). Red and green curves respectively represent predicted values for the above in parameters using $\Phi_{n+1}(x)$ and $N_{n+1}(x)$ as reduction polynomial, respectively. Diamonds represent corresponding probabilities computed from actual Round5 simulations for the same parameters, with 10^6 runs per datapoint. Scripts for analyzing and reproducing these results can be found at `www.round5.org`.

compared with those predicted by the failure probability analysis from Section 2.8.4. For each of the parameter sets, n_i, the number of simulated message exchanges for which the XEf decoder flipped exactly i bits was measured. The total number of flipped bits in the simulations thus equals $\sum_i in_i$. As the XEf decoder can only flip the κ message bits, and does not change the parity bits, only errors in κ message bits are taken into account, and the experimental bit failure rate $\hat{p}_{b,\text{expt}}$ equals

$$\hat{p}_{b,\text{expt}} = \frac{\sum_i in_i}{\kappa S}, \tag{39}$$

where S equals the number of simulated message exchanges. Table 3 shows that $\hat{p}_{b,\text{expt}}$ closely fits the value of $\hat{p}_{b,\text{pred}}$ for the corresponding parameter set predicted by the failure analysis from Section 2.8.4.

In case of independent bit failures with probability $\hat{p}_b$, the probability of

Table 3: Experimental and predicted bit failure probabilities $\hat{p}_{b,\text{expt}}$, $\hat{p}_{b,\text{pred}}$, for proposed parameters of Round5's error correction using, ring-based instantiation (Section 2.9). Also shown are overall failure rates $p_{>f,\text{expt}}$, $p_{>f,\text{pred}}$ that are computed using $p_{b,\text{expt}}$ and predicted by the failure analysis, respectively.

Parameters	S	n_1	n_2	n_3	$\hat{p}_{b,\text{expt}}$	$\hat{p}_{b,\text{pred}}$	$\frac{n_2}{S}_{\text{expt}}$	$\frac{n_2}{S}_{\text{pred}}$	$p_{>f,\text{expt}}$	$p_{>f,\text{pred}}$
R5ND_1CPA_5d	8.5×10^9	226639	6	0	$2^{-22.19}$	$2^{-21.35}$	$2^{-30.4}$	$2^{-31.4}$	$2^{-92.85}$	$2^{-87.79}$
R5ND_3CPA_5d	2.2×10^9	4120	0	0	$2^{-26.61}$	$2^{-26.61}$	N/A	$2^{-39.06}$	$2^{-117.14}$	$2^{-117.13}$
R5ND_5CPA_5d	2.8×10^9	2685625	1314	1	$2^{-18.02}$	$2^{-17.99}$	$2^{-21.02}$	$2^{-21.06}$	$2^{-64.07}$	$2^{-63.85}$

having exactly two bit failures in κ information bits equals

$$\binom{\kappa}{2}\hat{p}_b^2(1-\hat{p}_b)^{\kappa-2} \tag{40}$$

The fraction of simulated exchanges with exactly two bit errors equals n_2/S. Table 3 tabulates the values $(n_2/S)_{\text{expt}}$ from simulations, and shows that they fit the expected $(n_2/S)_{\text{pred}} = \binom{\kappa}{2}\hat{p}_{b,\text{expt}}^2(1-\hat{p}_{b,\text{expt}})^{\kappa-2}$ for R5ND_5CPA_5d, for which n_2 is sufficiently large to draw conclusions. This supports the assumption of independent bit failures. Finally, the probability of having more than f errors (overwhelming the f-bit error correction code) is computed using $\hat{p}_{b,\text{expt}}$ and compared with the failure rate predicted by the correctness analysis for each parameter set.

To conclude, the effect of dependence between polynomial coefficients due to polynomial multiplication modulo Φ_{n+1}, is made negligible by the combined use of polynomial multiplication modulo N_{n+1} and balanced secrets, allowing the use of forward error correction, resulting in better security and performance.

2.9 Round5: Parameter Sets and Performance

Round5 offers a large design space allowing for a unified and efficient implementation of Round5, independently of the fact that it instantiates LWR or RLWR.

The r5_cpa_kem, r5_cca_kem and r5_cca_pke algorithms can be configured to instantiate the LWR and RLWR underlying problems depending on the input parameter n. The IND-CPA secure KEM r5_cpa_kem uses Round5's IND-CPA secure parameter sets. The IND-CCA secure KEM and PKE, namely r5_cca_kem and r5_cca_pke, require Round5's IND-CCA secure parameter sets.

As described in detail later, the security level depends on the input value d and also the choice of q and p. All moduli, q, p, and t are chosen to be powers-of-two. Usage of error correction to better deal with decryption failures can also be configured by setting up parameter f. If $f > 0$, then secrets must be balanced and the reduction polynomial $\xi(x)$ for the ciphertext component v must be $x^{n+1} - 1$. A final restriction is that $\Phi_{n+1}(x)$ is irreducible modulo two.

The Round5 parameter sets are described in Sections 2.9.1 and Section 2.9.2. Section 2.9.3 describes the implementations in the submission package. Section 2.9.6 details the IND-CPA secure parameter sets for r5_cpa_kem. Section 2.9.7 details the IND-CCA secure parameter sets of r5_cca_kem and r5_cca_pke. Section 2.9.8 reports performance of Round5 KEMs on the main development environment. Sections 2.9.9 and 2.9.10 reports performance on other platforms, namely Cortex M4 and a Hardware-Software Codesign.

2.9.1 Main parameter sets

The Round5 cryptosystem has 18 main parameters sets: six ring parameter sets without error correction, six ring parameter sets with error correction, and six non-ring parameter sets. Each set of six parameter sets is for IND-CPA and IND-CCA security targets and NIST levels 1,3, and 5. A parameter set is denoted as R5N{1,D}_{1,3,5}{CPA,CCA}_{0,5}{version} where:

- 1,D refers whether it is a non-ring (1) or ring (D) parameter set.
- 1,3,5 refers to the NIST security level that is strictly fulfilled.
- CPA,CCA refers to the security property that the scheme fulfils.
- 0,1,2,3,4,5 identifies the amount of corrected bits, 0 means no-errors are corrected and this description is equivalent to the original Round2; 5 means that up to 5 errors can be corrected as in the original HILA5 submission.
- version is a letter to indicate the version of published parameters to account for potential differences in published parameters.

R5ND_{1,3,5}CPA_5d: Merged parameters for the ring variant ($n = d$) of Round5 IND-CPA KEM, for NIST security levels 1, 3 and 5, resulting from the merge of the NIST PQC first round candidate cryptosystems Round2 and HILA5. XE5 forward error correction is used to decrease decryption failure rates (hence the 5 at the end of the parameter designator), and improve bandwidth and security.

R5ND_{1,3,5}CCA_5d: Merged parameters for the ring variant ($n = d$) of Round5 IND-CCA KEM and PKE, for NIST security levels 1, 3 and 5, resulting from the merge of the NIST PQC first round candidate cryptosystems Round2 and HILA5. XE5 forward error correction is used to decrease decryption failure rates (hence the 5 at the end of the parameter designator), and improve bandwidth and security.

R5ND_{1,3,5}CPA_0d: Parameters for the ring variant ($n = d$) of Round5 IND-CPA KEM, for NIST security levels 1, 3 and 5. No forward error correction is used, hence the 0 at the end of the parameter designator. All polynomial multiplications are done modulo the prime-order cyclotomic polynomial. This choice is considered more conservative since it uses the same design principles as Round2.

R5ND_{1,3,5}CCA_0d: Parameters for the ring variant ($n = d$) of Round5 IND-CCA KEM and PKE, for NIST security levels 1, 3 and 5. No forward error correction is used, hence the 0 at the end of the parameter designator. All polynomial multiplications are done modulo the prime-order cyclotomic polynomial. This choice is considered more conservative since it uses the same design principles as Round2.

R5N1_{1,3,5}CPA_0d: Parameters for the non-ring/unstructured variant ($n = 1$) of Round5 IND-CPA KEM, for NIST security levels 1, 3 and 5. No forward error correction is used, hence the 0 at the end of the parameter designator. Since the generation of the public-parameter $\boldsymbol{A}$ is expensive, we include performance results for three alternative ways of generating it denoted as $T0, T1, T2$ and discuss performance trade-offs between the usage of SHAKE256 and AES128.

R5N1_{1,3,5}CCA_0d: Parameters for the non-ring/unstructured variant ($n = 1$) of Round5 IND-CCA KEM and PKE, for NIST security levels 1, 3 and 5. No forward error correction is used, hence the 0 at the end of the parameter designator.

2.9.2 Parameter sets for specific use-cases

Round5 has three additional "specific use-case" parameter sets with the only purpose of demonstrating the flexibility of Round5 and its applicability to a number of diverse, specialized usage scenarios.

R5ND_0CPA_2iot: This parameter set is thought to be used in Round5's IND-CPA KEM and targets Internet of Things use-cases, with lower bandwidth and computational footprints. We set as security targets the encapsulation of a 128-bit key and a security strength of at least 80/96-bits of quantum/classical security (core sieving) with a failure probability at least as low as 2^{-40}. We believe that these settings are suitable for low security IoT applications and the lower bandwidth needs can facilitate adoption. It turns out that these targets fit a classical security level of 128-bit XE2 forward error correction is used to improve failure rate, bandwidth and security.

R5ND_1CPA_4longkey: An alternative to NIST level 1 IND-CPA secure parameter set, this ring-variant key-encapsulation parameter set encapsulates a 192-bit key despite targeting the NIST security level 1. This ensures that the (quantum) cost of attacking the encapsulated key (e.g., by using Grover's quantum search algorithm) is as much as the (quantum) cost of attacking the underlying cryptosystem, i.e., Round5.

R5N1_3CCA_0smallCT: An alternative to the NIST level 3, this non-ring variant parameter set is suitable for Round5's IND-CCA KEM and PKE. It has exceptionally small ciphertexts and targets use cases in which the public-key is static and hence is exchanged rarely, implying that bandwidth footprint depends on the size of the ciphertext. Hence this parameter set, despite enjoying the more conservative security assumption based on unstructured lattices, has a bandwidth requirement comparable to ring variants.

2.9.3 Implementations

We include the following implementations of Round5. The latest version of code can be found at `https://github.com/round5/code`.

- Reference: This is a reference implementation of Round5 capable of running all parameter sets after compilation. Matrix and polynomial operations are explicit so that it is simple to verify the correctness of the implementation. This implementation is detailed in Section 2.11.
- Optimized: This is an optimized implementation of Round5 capable of running a single parameter set, fixed at compile time. This implementation can also fix – at compile time – the way to generate $\boldsymbol{A}$, i.e., $f^{(0)}_{d,n}$, $f^{(1)}_{d,n}$, or $f^{(2)}_{d,n}$ and whether to use (c)SHAKE or AES to generate pseudorandom data required to compute $\boldsymbol{A}$. Trade-offs are discussed in the following sections. This implementation can also select multiple ways of computing the secrets and computing ring and matrix multiplications.
- Additional implementations: We include and/or report on results of additional implementations.
  - Configurable: This is an optimized implementation of Round5 that can be configured and can execute all parameter sets at run time. This implementation shows the feasibility of an implementation running very different parameter sets with a common code base that can give flexibility, e.g., if the user needs to choose parameter sets with different security levels or an structured/unstructured problem, *post compilation*. The reason why this is feasible is the specific choices in Round5 that allow performing the core operations in very similar code. The most important feature is that for both ring and non-ring configurations, the core operations can be represented as a matrix multiplication of dimension $d \times d$ times a vector of length d.
  - AVX2: This implementation optimizes the core ring and matrix multiplication operations in the optimized implementation for the Round5.

2.9.4 Flexibility in the implementation of side-channel countermeasures

Round5 is designed to support simple and flexible countermeasures against various types of side-channel attacks. These have a varying impact on performance. System designers should study the circumstances of the implementation environment to choose the most appropriate ones; is key generation performed online or offline, what type of processor is being used, etc.

Protection against malformed public parameters $\boldsymbol{B}$ and $\boldsymbol{U}$

The exchange of malformed public parameters $\boldsymbol{B}$ and $\boldsymbol{U}$ in the core Round5 algorithms 2 and 3 can lead to simple, but powerful, attacks that can easily leak out either the encrypted key or the secret $\boldsymbol{S}$ or $\boldsymbol{R}$ if that is re-used. This malformed public parameters might be due to, e.g., (i) implementation errors, (ii) fault injection attacks, or (iii) key mismatch attacks. In (i) and (ii), if $\boldsymbol{B}$ is small, then the encrypted key leaks out. In (iii), if an attacker sends many specially crafted $\boldsymbol{B}$ or $\boldsymbol{U}$, he can infer $\boldsymbol{R}$ or $\boldsymbol{S}$ in case these keys are re-used, [**?**],[**?**].

Thus, careful input validation is important in cryptographic implementations. All public parameters should be checked to be within valid numerical ranges. Furthermore, it should be checked whether $\boldsymbol{B}$ and $\boldsymbol{U}$ follow their expected uniform distributions. If they do not, they should be rejected by the receiving party. This protection capability can be activated in Round5's optimized implementation by using compiler option "CM_MALFORMED".

Specific tests to verify that the distribution of the exchanged public-parameters is as expected include a binomial test or a Chi-squared test. In case of the non-ring parameter sets, these tests should be performed for each of the $\bar{n}$ and $\bar{m}$ components in $\boldsymbol{B}$ and $\boldsymbol{U}$ public-parameters.

The Chi-squared test verifies that $\boldsymbol{B}$ and $\boldsymbol{U}$ are uniformly distributed as follows: (i) compute a histogram of the public parameter, (ii) compute its Chi-squared statistic, and (iii) compare that to a fixed pre-computed critical value. The critical value is determined by the degree of freedom (number of bins - 1) and P-value, which should be smaller than the target failure probability of the Round5 parameter set. The Chi-squared test requires that the expected number of elements per bin to be at least 10. Furthermore, the test tends to be more accurate for a larger number of bins. Thus, we set the number of bins to $2^{\lfloor log_2(d/10) \rfloor}$. Since the test is performed on a histogram version of the public parameters, the test should be performed twice, once on the histogram version of $\boldsymbol{B}$ and once on $\boldsymbol{B}$'s histogram obtained after shifting the public-key components over half the bin size.

A binomial test checks whether a certain value, e.g., the zero value, appears more frequently than the target failure probability of a Round5 parameter set. Given the expected probability of a value, or set of values, we can obtain the threshold value so that the tail of the binomial distribution is smaller than the target failure probability of a Round5 parameter set. This check is to be performed throughout the whole range of possible values of the components of $\boldsymbol{B}$ and $\boldsymbol{U}$ due to Round5's balanced secrets. This test can be performed directly on $\boldsymbol{B}$ or $\boldsymbol{U}$. If the test is performed on their histogram version, e.g., to reduce memory needs, it should be performed on both the non-shifted and shifted histogram.

For instance, parameter set R5ND_1CPA_0d has the following two thresholds for the Chi-squared and binomial tests: 297 and 43. The first value considers a histogram version of the exchanged parameter sets using a bin size of 32. The second threshold value considers that the check is done for each of the p potential values of each component of $\boldsymbol{B}$ or $\boldsymbol{U}$.

Protection against timing attacks

Round5 uses balanced fixed-weight secrets. This gives flexibility since it allows for the usage of both a standard secret representation and an index-based representation. In a standard representation, the secret contains d elements in $\{-1, 0, 1\}$. In an index-based representation, the secret contains h elements in $\{0, \ldots, d-1\}$. When choosing one of them, either during generation or usage, we need to consider that timing attacks can leak out the secret easily, e.g., if the execution time depends on the secret value.

In the case of having a cache-less device, the index-based representation brings clear advantages without risk. In particular, polynomial or matrix/vector multiplication is modified to make use of an index-based representation of the secret. This approach, that we denote as $CACHELESS$ is faster since it is only required to loop over a fixed number of non-zero elements. Furthermore, only additions and subtractions are involved. The usage of an index-based secret key representation involves a fixed number of cpu operations.

The next level of protection, denoted by CM_CACHE, provides countermeasures against cache attacks. For instance, the time required for the check in line 6 of Algorithm 20 might leak out the value of the sampled value x. Similarly, the time required for a polynomial multiplication might depend on the coefficient index.

The countermeasures are two-fold. First, lines 6-10 in the secret key generation Algorithm 20 are modified to loop through all d elements every time a new candidate value x is sampled. When looping through all d elements, it sets $\boldsymbol{s}[x]$ only if not occupied. This algorithm stops as soon as h different positions have been assigned. Second, the ring multiplication is implemented by looping over all d coefficients for each non-zero index. The matrix multiplication is implemented by looping through all d elements.

The next level of protection, denoted by CM_CT, relies on the standard secret representation and constant-time implementation. This option addresses the problem that the secret key generation time can depend on the amount of pseudorandom data is that is required to generate (number of calls to a pseudorandom function) to sample h different values in $\{0, \ldots, d-1\}$. An attacker might use the time difference in the re-encryption step with the FO transform in the decapsulation in r5_cca_kem resulting from this in order to find out whether a given message was decoded correctly or not.

In the secret key generation, Algorithm 20 is extended to not only loop over all positions when checking whether a candidate value x is sampled, but also to have a fixed number HMAX of calls to the function used to generate pseudorandom data that is big enough to ensure with probability higher than $1 - 2^{\kappa}$ that at least h distinct coefficients are generated. In case that more than h distinct coefficients are sampled, then only h positions that were generated earliest are set to 1 or -1. Appendix B details how to compute HMAX, assuming that each call to the pseudorandom function produces a fresh sample from the uniform distribution on $\{0, 1, \ldots, 2^{16} - 1\}$. This is a valid assumption since as described in Section 2.11.4 Round5 uses as a pseudorandom function TupleHashXof.

Ring multiplications are made fully constant time by going through all elements when performing the multiplication. Note that the ring and matrix multiplications can still be easily implemented in terms of additions and subtractions even if the full secret representation is used, e.g., by using masks.

$$out[j] = out[j] + b[i]\&mask_add - b[i]\&mask_sub$$

where $mask_add$ and $mask_sub$, respectively, are set to $0xFF$ when if $s[d-i]$ equals 1 and -1, respectively, and otherwise to $0x00$. This gives more implementation options since different operations (+, -, *) might leak more or less information in different platforms.

Last but not least, XEf is a relatively simple error correction code that can be easily implemented in a constant-time and with a constant memory access pattern. This implementation is used in all cases. Thus, XEf does not introduce any additional risks.

All options discussed in this section are simple to implement and offer a great performance. Tailored multiplication algorithms can be designed and applied to Round5 as well, however, they impact the flexibility of Round5 and make the code more complex to understand.

2.9.5 Development Environment

The performance numbers for the optimized implementation of Round5 have been gathered on a MacBookPro15.1 with an Intel Core i7 2.6GHz, running macOS 10.13.6. The code has been compiled with `gcc -march=native -mtune=native -O3 -fomit-frame-pointer -fwrapv`, using Apple LLVM version 10.0.0 (clang-1000.10.44.4). Cache attack countermeasures (`-DCM_CACHE`) were enabled.

All tests were run 1000 times, the measurements shown are the median values of all test runs and are for the optimized implementation of the algorithm.

For the memory requirements, we have provided an indication based on a possible implementation. Note that the actual memory usage depends, of course, on the specifics of a particular implementation (e.g., an implementation might require matrices to exist (also) in transposed form, need room for storing intermediate results, etc.).

2.9.6 IND-CPA secure parameter sets

This section contains specific IND-CPA secure parameter sets used in Round5's r5_cpa_kem.

Tables 4, 5, and 6 show the parameter sets for NIST security levels 1, 3, and 5. Table 7 present the parameter sets for specific use cases. In all of the above tables, the values under *Security Levels* represent the cost of known attacks (discussed in Section 2.7) against the underlying LWR or RLWR problem.

The main conclusions from these tables are as follows:

- All parameter sets strictly fulfil NIST security levels and the hybrid attack is the one that has the highest impact on Round5.

- Parameter sets using XE5 (R5ND_1,3,5CPA_5d) have around 25% lower bandwidth requirements compared with those without error correction (R5ND_1,3,5CPA_0d). Since these Round5 parameter sets are used in a KEM that offers CPA security, no active attacks are applicable.
- The application-specific IoT parameter set (R5ND_0CPA_2iot) only requires 736 bytes and it still offers relatively high classical/quantum security levels.
- Many security protocols that require a handshake to exchange a session key do not require active security and a relatively high failure probability is good enough. This allows finding parameters that offer smaller keys and ciphertext at the price of a slightly higher failure rate. For instance, for IoT deployment the failure rate of a wireless communication link will be likely worse than the failure rate of R5ND_0CPA_2iot, and thus, a failure probability of 2^{-41} is sufficient. Alternatively, it is possible to further increase this failure probability so that the sizes of public-key and ciphertext further drop.

Table 4: R5ND_{1,3,5}CPA_0d parameters. Bandwidth numbers for KEM.

	Security Level		
	NIST1	**NIST3**	**NIST5**
Parameters			
$d/n/h$	618/618/104	786/786/384	1018/1018/428
$q/p/t/b$	$2^{11}/2^8/2^4/2^1$	$2^{13}/2^9/2^4/2^1$	$2^{14}/2^9/2^4/2^1$
$\overline{n}/\overline{m}$	1/1	1/1	1/1
$f/xe/\kappa/\mu$	0/0/128/128	0/0/192/192	0/0/256/256
Performance			
Total bandwidth (bytes)	1316	1890	2452
Public key (bytes)	634	909	1178
Ciphertext (bytes)	682	981	1274
Failure rate	2^{-69}	2^{-72}	2^{-64}
Classical/Quantum security (bits) – Core Sieving			
Primal attack	144/131	192/175	256/233
Dual attack	147/134	193/175	258/235
Hybrid attack	132/116	232/199	299/263
Guessing + Dual	129/121	188/170	246/227
Classical/Quantum security (bits) – Enumeration			
Primal attack	340/170	500/250	729/365
Dual attack	350/175	503/252	737/368
Hybrid attack	161/146	335/302	431/400
Guessing + Dual	-/-	-/-	-/-

Table 5: R5ND_{1,3,5}CPA_5d parameters. Bandwidth numbers for KEM.

	Security Level		
	NIST1	**NIST3**	**NIST5**
Parameters			
$d/n/h$	490/490/162	756/756/242	940/940/414
$q/p/t/b$	$2^{10}/2^7/2^3/2^1$	$2^{12}/2^8/2^2/2^1$	$2^{12}/2^8/2^2/2^1$
$\overline{n}/\overline{m}$	1/1	1/1	1/1
$f/xe/\kappa/\mu$	5/190/128/318	5/218/192/410	5/234/256/490
Performance			
Total bandwidth (bytes)	994	1639	2035
Public key (bytes)	445	780	972
Ciphertext (bytes)	549	859	1063
Failure rate	2^{-93}	2^{-119}	2^{-65}
Classical/Quantum security (bits) – Core Sieving			
Primal attack	130/118	194/176	256/233
Dual attack	132/120	197/179	259/235
Hybrid attack	148/129	226/187	305/265
Guessing + Dual	125/115	184/171	246/226
Classical/Quantum security (bits) – Enumeration			
Primal attack	297/148	507/254	729/365
Dual attack	301/151	515/258	739/369
Hybrid attack	189/167	286/262	428/393
Guessing + Dual	-/-	-/-	-/-

Table 6: R5N1_{1,3,5}CPA_0d parameters. Bandwidth numbers for KEM.

	Security Level		
	NIST1	**NIST3**	**NIST5**
Parameters			
$d/n/h$	594/1/230	881/1/238	1186/1/712
$q/p/t/b$	$2^{13}/2^{10}/2^{7}/2^{3}$	$2^{13}/2^{10}/2^{7}/2^{3}$	$2^{15}/2^{12}/2^{7}/2^{4}$
$\overline{n}/\overline{m}$	7/7	8/8	8/8
$f/xe/\kappa/\mu$	0/0/128/43	0/0/192/64	0/0/256/64
Performance			
Total bandwidth (bytes)	10450	17700	28552
Public key (bytes)	5214	8834	14264
Ciphertext (bytes)	5236	8866	14288
Failure rate	2^{-69}	2^{-69}	2^{-81}
Classical/Quantum security (bits) – Core Sieving			
Primal attack	132/121	201/184	257/234
Dual attack	131/120	202/184	256/233
Hybrid attack	166/146	209/189	322/263
Guessing + Dual	132/121	189/176	254/236
Classical/Quantum security (bits) – Enumeration			
Primal attack	275/138	499/250	696/348
Dual attack	272/136	500/250	692/346
Hybrid attack	219/192	276/258	488/448
Guessing + Dual	-/-	-/-	-/-

Table 7: Specific use case Round5 CPA parameters. Bandwidth numbers for KEM.

	Parameter Set	
	R5ND_0CPA_2iot	**R5ND_1CPA_4longkey**
Parameters		
$d/n/h$	372/372/178	490/490/162
$q/p/t/b$	$2^{11}/2^{7}/2^{3}/2^{1}$	$2^{10}/2^{7}/2^{3}/2^{1}$
$\overline{n}/\overline{m}$	1/1	1/1
$f/xe/\kappa/\mu$	2/53/128/181	4/163/192/355
Performance		
Total bandwidth (bytes)	736	1016
Public key (bytes)	342	453
Ciphertext (bytes)	394	563
Failure rate	2^{-41}	2^{-67}
Classical/Quantum security (bits) – Core Sieving		
Primal attack	98/89	135/123
Dual attack	98/89	137/125
Hybrid attack	121/122	148/129
Guessing + Dual	93/87	128/119
Classical/Quantum security (bits) – Enumeration		
Primal attack	201/100	312/156
Dual attack	202/101	318/159
Hybrid attack	158/136	189/167
Guessing + Dual	-/-	-/-

2.9.7 IND-CCA secure parameter sets

This section contains specific IND-CCA secure parameter sets required in r5_cca_kem and r5_cca_pke.

Tables 8, 9, and 10 show the parameter sets for NIST security levels 1, 3, and 5. Table 11 present the parameter sets for specific use cases.

In all of the above tables, the values under *Security Levels* represent the cost of known attacks (discussed in Section 2.7) against the underlying LWR or RLWR problem.

The main conclusions from these tables are as follows:

- The IND-CCA security parameter sets fulfil NIST security levels. The Guessing + Dual attack is the one that has the highest impact on Round5.
- Parameter sets relying on XE5 (R5ND_{1,3,5}CCA_5d) have around 25% lower bandwidth requirements compared with those parameters without error correction (R5ND_{1,3,5}CCA_0d). For instance, R5ND_5CCA_5d requires around 500 Bytes less than R5ND_5CCA_0d.
- IND-CCA secure parameter sets require a lower failure probability compared with IND-CPA secure parameter sets. This leads to parameters that require slightly longer public-keys and ciphertexts.
- The application-specific R5N1_3CCA_0smallCT parameter sets, i.e., a non-ring parameter set with short ciphertext, is a desirable alternative in use cases in which the public-key remains static for a long period of time, since the ciphertext is small and comparable in size with ring parameter sets, minimizing the overall bandwidth requirement.

Table 8: R5ND_{1,3,5}CCA_0d parameters. Bandwidth numbers for KEM.

	Security Level		
	NIST1	**NIST3**	**NIST5**
Parameters			
$d/n/h$	586/586/182	852/852/212	1170/1170/222
$q/p/t/b$	$2^{13}/2^9/2^4/2^1$	$2^{12}/2^9/2^5/2^1$	$2^{13}/2^9/2^5/2^1$
$\overline{n}/\overline{m}$	1/1	1/1	1/1
$f/xe/\kappa/\mu$	0/0/128/128	0/0/192/192	0/0/256/256
Performance			
Total bandwidth (bytes)	1416	2086	2858
Public key (bytes)	676	983	1349
Encryption overhead (bytes)	740	1103	1509
Failure rate	2^{-157}	2^{-154}	2^{-145}
Classical/Quantum security (bits) – Core Sieving			
Primal attack	131/119	199/181	281/255
Dual attack	132/120	202/183	286/260
Hybrid attack	146/126	207/192	263/232
Guessing + Dual	125/115	186/174	253/238
Classical/Quantum security (bits) – Enumeration			
Primal attack	298/149	524/262	822/411
Dual attack	301/151	534/267	842/421
Hybrid attack	193/174	271/250	337/317
Guessing + Dual	-/-	-/-	-/-

Table 9: R5ND_{1,3,5}CCA_5d parameters. Bandwidth numbers for KEM.

	Security Level		
	NIST1	**NIST3**	**NIST5**
Parameters			
$d/n/h$	508/508/136	756/756/242	946/946/388
$q/p/t/b$	$2^{10}/2^{7}/2^{4}/2^{1}$	$2^{12}/2^{8}/2^{3}/2^{1}$	$2^{11}/2^{8}/2^{5}/2^{1}$
$\overline{n}/\overline{m}$	1/1	1/1	1/1
$f/xe/\kappa/\mu$	5/190/128/318	5/218/192/410	5/234/256/490
Performance			
Total bandwidth (bytes)	1081	1714	2263
Public key (bytes)	461	780	978
Encryption overhead (bytes)	620	934	1285
Failure rate	2^{-150}	2^{-259}	2^{-239}
Classical/Quantum security (bits) – Core Sieving			
Primal attack	133/121	194/176	256/233
Dual attack	135/122	197/179	259/235
Hybrid attack	142/126	226/187	300/263
Guessing + Dual	125/117	184/171	246/226
Classical/Quantum security (bits) – Enumeration			
Primal attack	305/152	507/254	729/365
Dual attack	311/156	515/258	740/370
Hybrid attack	177/160	286/262	418/386
Guessing + Dual	-/-	-/-	-/-

Table 10: R5N1_{1,3,5}CCA_0d parameters. Bandwidth numbers for KEM.

	Security Level		
	NIST1	**NIST3**	**NIST5**
Parameters			
$d/n/h$	636/1/114	876/1/446	1217/1/462
$q/p/t/b$	$2^{12}/2^{9}/2^{6}/2^{2}$	$2^{15}/2^{11}/2^{7}/2^{3}$	$2^{15}/2^{12}/2^{9}/2^{4}$
$\overline{n}/\overline{m}$	8/8	8/8	8/8
$f/xe/\kappa/\mu$	0/0/128/64	0/0/192/64	0/0/256/64
Performance			
Total bandwidth (bytes)	11528	19376	29344
Public key (bytes)	5740	9660	14636
Encryption overhead (bytes)	5788	9716	14708
Failure rate	2^{-155}	2^{-146}	2^{-151}
Classical/Quantum security (bits) – Core Sieving			
Primal attack	146/133	194/177	257/234
Dual attack	146/134	193/176	257/234
Hybrid attack	134/114	226/196	285/252
Guessing + Dual	130/123	185/179	251/233
Classical/Quantum security (bits) – Enumeration			
Primal attack	317/159	473/237	697/348
Dual attack	319/160	469/235	696/348
Hybrid attack	162/146	337/316	426/420
Guessing + Dual	-/-	-/-	-/-

Table 11: Specific use case Round5 CCA parameters. Bandwidth numbers for KEM.

	Parameter Set **R5N1_3CCA_0smallCT**
Parameters	
$d/n/h$	757/1/378
$q/p/t/b$	$2^{14}/2^{9}/2^{4}/2^{1}$
$\overline{n}/\overline{m}$	192/1
$f/xe/\kappa/\mu$	0/0/192/192
Performance	
Total bandwidth (bytes)	164508
Public key (bytes)	163536
Encryption overhead (bytes)	972
Failure rate	2^{-150}
Classical/Quantum security (bits) – Core Sieving	
Primal attack	194/177
Dual attack	193/176
Hybrid attack	228/191
Guessing + Dual	184/172
Classical/Quantum security (bits) – Enumeration	
Primal attack	473/237
Dual attack	469/235
Hybrid attack	323/290
Guessing + Dual	-/-

2.9.8 Performance of Round5 KEMs

Table 12 provides timing performance of Round5's *optimized* implementation when executed in the development platform described in 2.9.5. It compares the timing performance of r5_cpa_kem and r5_cca_kem for all Round5 parameter sets when the three types of countermeasures against timing attacks (Section 2.9.4) are applied. In all cases, ring parameter sets offer very fast performance without using any type of hardware instructions. CPU performance for non-ring parameter sets can be sufficient for many applications, except those that require very high throughput. Due to the asymmetry of $\bar{n}$ and $\bar{m}$, the key generation time of R5N1_3CCA_0smallCT is relatively high; however, this is only a one-time cost since the public-key remains static for a long period of time. On the other hand, the benefit of the asymmetry is that the encryption time decreases. Ring versions of Round5 perform around 70 times faster than its non-ring versions. Finally, we observe that the $CACHELESS$, CM_CACHE, and CM_CT countermeasures incur in general an increasing performance penalty, except in parameter sets in which the value of h is relatively high. The first technique is specially suitable for small devices without a cache.

Table 13 shows the performance of the AVX2 optimized implementation for the ring and non-ring parameter sets. AVX2 optimizations in the ring case provide a speed up of up to 2x with the CM_CT countermeasure. AVX2 optimizations provide a speed up of between 3x and 5x in the non-ring case ($\tau = 0$, CM_CT).

Finally, this table compares the performance of parameter set R5N1_1CPA_0d for different choices of $f_{d,n}^{(\tau)}$ using TupleHashXOF128. These measurements are taken using the AVX2 optimized implementation. We observe that the CPU performance of $f_{d,n}^{(0)}$ is worse than $f_{d,n}^{(2)}$ and $f_{d,n}^{(1)}$. The reasons for this are as follows: $f_{d,n}^{(1)}$ requires the generation of the smallest amount of pseudorandom data, $f_{d,n}^{(2)}$ requires the generation of slightly more pseudorandom data, but the total amount of data to keep in memory is much lower; finally, $f_{d,n}^{(0)}$ requires the generation of the highest amount of pseudorandom data, and it makes it slower. In particular, in this configuration $f_{d,n}^{(2)}$ is a factor 6 faster than $f_{d,n}^{(0)}$ and it has low memory requirements. Thus, it is a good choice for small devices. $f_{d,n}^{(1)}$ is suitable for systems in which a central device, e.g., a server, has to handle many connections.

Table 12: Performance comparison of Round5 KEMs, r5_cpa_kem and r5_cca_kem, using different parameter sets and different types of countermeasures against timing attacks without AVX2 instructions, fn with TAU=0 and STANDALONE TupleHash library. The first block of rows includes performance numbers for ring parameter sets. The second block of rows shows performance numbers for non-ring parameter sets. Numbers are given in thousands of CPU cycles in a machine running at 2.6 GHz.

Parameter set	Flags	KeyGen			Enc			Dec			Total		
		cacheless	cm_cache	cm_ct	cacheless	cm_cache	cm_ct	cacheless	cm_cache	cm_ct	cacheless	cm_cache	cm_ct
R5ND_1CPA_5d	TAU=0	49	75	87	67	117	158	29	61	90	146	254	335
R5ND_3CPA_5d	TAU=0	71	111	166	90	174	268	34	92	131	196	378	566
R5ND_5CPA_5d	TAU=0	101	175	223	148	282	374	77	161	218	327	619	816
R5ND_1CPA_0d	TAU=0	41	59	96	50	88	122	17	42	42	109	191	261
R5ND_3CPA_0d	TAU=0	88	160	171	107	233	203	44	123	84	240	517	459
R5ND_5CPA_0d	TAU=0	108	185	267	127	279	292	49	146	110	286	610	670
R5ND_1CCA_5d	TAU=0	50	70	100	64	106	170	79	145	248	194	322	519
R5ND_3CCA_5d	TAU=0	75	114	173	98	180	267	117	258	384	291	553	825
R5ND_5CCA_5d	TAU=0	101	173	228	152	275	387	207	409	589	461	858	1205
R5ND_1CCA_0d	TAU=0	52	84	88	65	120	101	75	163	143	193	368	333
R5ND_3CCA_0d	TAU=0	73	111	168	95	166	190	109	223	229	278	501	588
R5ND_5CCA_0d	TAU=0	87	135	213	115	206	282	133	275	338	335	617	834
R5ND_0CPA_2iot	TAU=0	51	76	77	65	118	117	27	63	57	144	258	252
R5ND_1CPA_4longkey	TAU=0	51	75	90	72	117	152	34	61	83	158	254	326
R5N1_1CPA_0d	TAU=0	5713	6983	7043	5224	5376	5439	165	217	290	11103	12577	12773
R5N1_3CPA_0d	TAU=0	14545	18522	18915	13932	13970	14287	229	326	420	28707	32819	33623
R5N1_5CPA_0d	TAU=0	29238	34835	35613	25599	26166	26846	647	1028	1501	55485	62030	63961
R5N1_1CCA_0d	TAU=0	6164	8244	8230	5918	6207	6214	5997	6341	6380	18080	20794	20825
R5N1_3CCA_0d	TAU=0	15784	18228	18724	14272	14368	14807	14569	14994	15628	44626	47591	49161
R5N1_5CCA_0d	TAU=0	29048	35711	36083	26589	27354	27696	26844	27891	28488	82481	90956	92267
R5N1_3CCA_0smallCT	TAU=0	54471	111925	115940	11804	12114	12173	16928	18945	22975	83204	142985	151090

Table 13: Performance comparison of Round5 KEMs, r5_cpa_kem and r5_cca_kem, using different parameter sets optimized with AVX2 instructions for fn with TAU=0 using the STANDALONE TupleHash library. The first block of rows includes performance numbers for ring parameter sets. The second block of rows shows performance numbers for non-ring parameter sets. The last row block compares performance of R5N1_5CCA_0d parameter set for different TAU choices. Numbers are given in thousands of CPU cycles in a machine running at 2.6 GHz.

Parameter set	Flags	KeyGen			Enc			Dec			Total		
		cacheless	cm_cache	cm_ct	cacheless	cm_cache	cm_ct	cacheless	cm_cache	cm_ct	cacheless	cm_cache	cm_ct
R5ND_1CPA_5d	AVX2, TAU=0	n/a	n/a	44	n/a	n/a	67	n/a	n/a	39	n/a	n/a	151
R5ND_3CPA_5d	AVX2, TAU=0	n/a	n/a	69	n/a	n/a	112	n/a	n/a	67	n/a	n/a	249
R5ND_5CPA_5d	AVX2, TAU=0	n/a	n/a	105	n/a	n/a	160	n/a	n/a	102	n/a	n/a	369
R5ND_1CPA_0d	AVX2, TAU=0	n/a	n/a	44	n/a	n/a	56	n/a	n/a	23	n/a	n/a	124
R5ND_3CPA_0d	AVX2, TAU=0	n/a	n/a	90	n/a	n/a	109	n/a	n/a	59	n/a	n/a	258
R5ND_5CPA_0d	AVX2, TAU=0	n/a	n/a	121	n/a	n/a	151	n/a	n/a	72	n/a	n/a	345
R5ND_1CCA_5d	AVX2, TAU=0	n/a	n/a	46	n/a	n/a	68	n/a	n/a	95	n/a	n/a	210
R5ND_3CCA_5d	AVX2, TAU=0	n/a	n/a	72	n/a	n/a	119	n/a	n/a	171	n/a	n/a	363
R5ND_5CCA_5d	AVX2, TAU=0	n/a	n/a	105	n/a	n/a	166	n/a	n/a	247	n/a	n/a	520
R5ND_1CCA_0d	AVX2, TAU=0	n/a	n/a	54	n/a	n/a	67	n/a	n/a	86	n/a	n/a	208
R5ND_3CCA_0d	AVX2, TAU=0	n/a	n/a	82	n/a	n/a	106	n/a	n/a	133	n/a	n/a	322
R5ND_5CCA_0d	AVX2, TAU=0	n/a	n/a	124	n/a	n/a	164	n/a	n/a	200	n/a	n/a	489
R5ND_0CPA_2iot	AVX2, TAU=0	n/a	n/a	41	n/a	n/a	52	n/a	n/a	28	n/a	n/a	122
R5ND_1CPA_4longkey	AVX2, TAU=0	n/a	n/a	47	n/a	n/a	66	n/a	n/a	37	n/a	n/a	151
R5N1_1CPA_0d	AVX2, TAU=0	n/a	n/a	1622	n/a	n/a	1727	n/a	n/a	149	n/a	n/a	3499
R5N1_3CPA_0d	AVX2, TAU=0	n/a	n/a	4148	n/a	n/a	4365	n/a	n/a	210	n/a	n/a	8724
R5N1_5CPA_0d	AVX2, TAU=0	n/a	n/a	7607	n/a	n/a	7978	n/a	n/a	558	n/a	n/a	16145
R5N1_1CCA_0d	AVX2, TAU=0	n/a	n/a	1787	n/a	n/a	2016	n/a	n/a	2085	n/a	n/a	5889
R5N1_3CCA_0d	AVX2, TAU=0	n/a	n/a	4181	n/a	n/a	4585	n/a	n/a	4816	n/a	n/a	13583
R5N1_5CCA_0d	AVX2, TAU=0	n/a	n/a	7947	n/a	n/a	8416	n/a	n/a	8662	n/a	n/a	25026
R5N1_3CCA_0smallCT	AVX2, TAU=0	n/a	n/a	16536	n/a	n/a	4963	n/a	n/a	8952	n/a	n/a	30452
R5N1_5CCA_0d	AVX2, TAU=0	n/a	n/a	7947	n/a	n/a	8416	n/a	n/a	8662	n/a	n/a	25026
R5N1_5CCA_0d	AVX2, TAU=1	n/a	n/a	1222	n/a	n/a	1648	n/a	n/a	1888	n/a	n/a	4759
R5N1_5CCA_0d	AVX2, TAU=2	n/a	n/a	948	n/a	n/a	1334	n/a	n/a	1586	n/a	n/a	3869

2.9.9 Performance on Cortex M4

The performance of Round5 on a Cortex M4 has been reported in [97]. In the following, we report updated numbers after running Round5 on the popular STM32F407 Discovery board. This board has also been used in the PQM4 project [70].

This particular MCU (and Cortex M4 in general) does not deploy a data cache – a separate flash cache exists on the instruction bus. Code execution paths are therefore designed to be constant, while there is some variation in the data access paths. This implementation may be considered *resistant* against a time-channel attack, while not strictly constant time.

Table 14 gives cycle counts for the Cortex M4 implementation. Round5 maintains roughly equivalent or better performance than any comparable NIST candidate. As the only candidate that supports both ring-based and general lattices, the performance lead over Frodo [32] is especially noteworthy.

Table 15 gives a summary of other resource utilization of the implementation. We see that in addition to having the shortest messages, also the RAM requirement by the implementation itself is usually the smallest. The implementation footprint was one of the optimization criteria.

We note that during the second round of the NIST competition Round5 had overall leading embedded performance according to PQM4 data[2], although the margin is not particularly large. Compared to some other candidates, the implementation is much smaller and more of it is written in a high-level language, as it was written for portability.

2.9.10 Hardware-Software Codesign

Round5 has been implemented in the PQSoC[3] hardware-software codesign. Its lattice and ring arithmetic coprocessor can support Round5 directly. To assess the performance, PQSoC is synthesized with and without the ring arithmetic accelerator on a Xilinx Artix-7 platform (Digilent Arty A7-35T board).

Table 16 indicates its relative size, which is very small. Even with the CPU the implementation is smaller than some proposed hardware modules; as a codesign it is minuscule.

From Table 17 we see that the performance advantage gained from the coprocessor is between 664% and 1382%, depending on the variant. The design achieves timing closure at 100 MHz – that was also the clock frequency used in timing runs. As can be seen, depending on (ring variant) security level key generation requires $1.3 - 3.4$ ms, encapsulation $1.7 - 4.5$ ms, and decapsulation $0.9 - 6.2$ ms. What is noteworthy in comparison to monolithic hardware implementations is that all of these options are available *simultaneously* via the same hardware module with very small additional cost.

[2] PQM4: Cortex M4 post-quantum cryptography library: `https://github.com/mupq/pqm4`.
[3] `https://pqsoc.com`

Table 14: Round5 performance on ARM Cortex M4 (STM32F407 Discovery) clocked at 24 Mhz. All of these numbers are in 1000s of cycles; KG = keypair generation, Enc = encapsulation, Dec = decapsulation, Total = KG+Enc+Dec measured as a whole (both sides of an ephemeral key exchange).

Parameter set	KeyGen	Enc	Dec	Total
`R5ND_1CPA_5d`	425	607	247	1280
`R5ND_3CPA_5d`	839	1136	400	2376
`R5ND_5CPA_5d`	1455	1976	697	4129
`R5ND_1CCA_5d`	384	593	755	1734
`R5ND_3CCA_5d`	840	1253	1567	3661
`R5ND_5CCA_5d`	1386	2011	2563	5961
`R5ND_1CPA_0d`	360	474	155	990
`R5ND_3CPA_0d`	1223	1615	555	3393
`R5ND_5CPA_0d`	1593	2141	719	4455
`R5ND_1CCA_0d`	504	750	926	2181
`R5ND_3CCA_0d`	832	1241	1505	3579
`R5ND_5CCA_0d`	1161	1714	2047	4923
`R5N1_1CPA_0d`, TAU=2	6625	4488	1209	12323
`R5N1_3CPA_0d`, TAU=2	9935	7063	1849	18849
`R5N1_5CPA_0d`, TAU=2	34833	20891	4455	60181
`R5N1_1CCA_0d`, TAU=2	4166	3723	4051	11942
`R5N1_3CCA_0d`, TAU=2	17094	11986	13572	42654
`R5N1_5CCA_0d`, TAU=2	23206	16681	17949	57837
`R5ND_0CPA_2iot`	393	517	195	1106
`R5ND_1CPA_4longkey`	423	628	271	1324

Table 15: Transfer, storage, stack usage, and implementation code size requirements of various variants on an ARMv7 architecture system (such as Cortex M4). KeyGen, Enc, and Dec give the RAM memory requirement (in bytes) for keypair generation, encapsulation, and decapsulation. PK and CT indicate the public key and ciphertext sizes in bytes. Code is the firmware size excluding Keccak and other standard components (ROM or Flash).

	RAM (Stack) Usage in			Bandwidth for		ROM
Parameter set	KeyGen	Enc	Dec	PK	CT	Code
`R5ND_1CPA_5d`	3862	4317	2124	445	549	5894
`R5ND_3CPA_5d`	5598	6173	2708	780	859	7332
`R5ND_5CPA_5d`	7038	7717	3468	972	1063	4828
`R5ND_1CCA_5d`	3958	4405	5028	461	620	6248
`R5ND_3CCA_5d`	5638	6229	7164	780	934	7788
`R5ND_5CCA_5d`	7078	7781	9068	978	1285	5412
`R5ND_1CPA_0d`	4526	4765	1716	634	682	3054
`R5ND_3CPA_0d`	6054	6565	3676	909	981	3114
`R5ND_5CPA_0d`	7542	8205	4628	1178	1274	3160
`R5ND_1CCA_0d`	4518	4877	5620	676	740	3440
`R5ND_3CCA_0d`	6150	6669	7772	983	1103	3554
`R5ND_5CCA_0d`	8078	8757	10268	1349	1509	3586
`R5N1_1CPA_0d`, TAU=2	19286	19501	12996	5214	5236	3796
`R5N1_3CPA_0d`, TAU=2	26950	27221	19556	8834	8866	3804
`R5N1_5CPA_0d`, TAU=2	40934	41213	32324	14264	14288	3910
`R5N1_1CCA_0d`, TAU=2	19878	20109	25900	5740	5788	3892
`R5N1_3CCA_0d`, TAU=2	30206	30485	40204	9660	9716	4228
`R5N1_5CCA_0d`, TAU=2	37638	37933	52644	14636	14708	4164
`R5ND_0CPA_2iot`	3198	3501	1740	342	394	3618
`R5ND_1CPA_4longkey`	3830	4357	2180	453	563	5764

Table 16: Synthesis of PQSoC with and without the Round5 lattice coprocessor on a Xilinx Artix-7 (XC7A35) FPGA platform (Arty 7), indicating its size.

Artix-7 FPGA	Coprocessor?		Area
Component	No	Yes	Delta
SLICEL	1,525	1,533	+8
SLICEM	626	691	+64
LUT as Logic	7,064	7,720	+656
LUT as Memory	48	48	+0
Slice Registers	2,626	3,336	+710
DSP48E1	4	5	+1

Table 17: Performance of Round5 on a lightweight RISC-V SoC with the lattice coprocessor and without. The numbers are in 1000s of cycles at 100 MHz (equivalent to 10 μs). Neither of the implementations uses assembly language. The hardware accelerator can be used with other CPU architectures as well.

	With coprocessor			Plain C Code			Total
Parameter set	KeyGen	Enc	Dec	KeyGen	Enc	Dec	Gain
`R5ND_1CPA_5d`	137	195	89	888	1578	724	7.59
`R5ND_3CPA_5d`	205	273	105	1937	3222	1329	11.12
`R5ND_5CPA_5d`	346	450	164	4001	6595	2663	13.82
`R5ND_1CCA_5d`	130	195	276	789	1387	1997	6.94
`R5ND_3CCA_5d`	207	290	401	1939	3248	4575	10.86
`R5ND_5CCA_5d`	338	458	627	3794	6257	8758	13.22
`R5ND_0CPA_2iot`	127	166	73	761	1193	473	6.64
`R5ND_1CPA_4longkey`	132	196	91	884	1653	801	7.96

2.10 Advantages and limitations

A single scheme with multiple parameter sets Round5 defines a unified scheme that can be configured with multiple parameter sets to fit the needs of multiple applications. Although this implies additional effort to define which parameter set an application requires, a unified scheme such as Round5 has advantages. Standardization effort is limited since a single scheme needs to be specified. This also prevents potential over-provisioning of resources (memory, bandwidth) since a device supporting Round5 can handle a wide range of parameter sets without big burdens. Finally, all Round5 parameter sets can be realized by means of a single library so that review and maintenance work is reduced.

Flexibility in the underlying problem's choice Round5 can be configured to rely on the Learning with Rounding (LWR) or Ring-Learning with Rounding (RLWR) problems, by controlling the input parameters n and d. This allows users to flexibly choose the parameter set (and underlying problem instantiation) that fits best their application and security requirements, even while Round5 is already in deployment. For instance, users dealing with strictly confidential information might only trust a public-key encryption (PKE) algorithm with a construction having no additional (e.g., ring) structure, while users operating a wireless network for a less critical application would prioritize low bandwidth and/or energy requirements and thus might prefer a (more efficient) ring-based construction. The unified approach can provide from day one a contingency and smooth transition path, should vulnerabilities in ring-based constructions be discovered, since the non-ring based construction is already deployed.

Small public-keys and ciphertexts Round5 relies on rounding (specifically, the GLWR problem, see Section 2.3), leading to public-keys and ciphertexts with coefficients that have only $\lceil \log p \rceil$ and $\lceil \log t \rceil$ bits. Furthermore, Round5 relies on prime cyclotomic polynomials that provide a large pool of (q, n) values to choose from, allowing the selection of parameters that satisfy security requirements while minimizing bandwidth requirements. The usage of constant-time XEf error correction allows dealing with multiple errors so that even smaller parameters ($n = d, p$), and thus, messages are feasible. Round5 thus is suited for bandwidth-constrained applications, and Internet protocols that only allow limited packet sizes. Comparing with other submissions, as reported in [57] (with "Performance" as label for the X-axis), Round5 shows a very good trade-off between security and the sizes of public keys and ciphertexts.

Common building blocks for KEM and PKE By design, r5_cpa_kem, r5_cca_kem and r5_cca_pke are constructed using common building blocks. This allows for a common security and correctness analysis of the schemes. Furthermore, it reduces the amount of code in devices, and the effort required for code-review.

Flexibility in achieving security levels The design choices in Round5, especially the choice for prime cyclotomic polynomials, allows the fine-tuning of parameters to each NIST level. Round5 thus enables the user to choose parameters that tightly fit the required security level.

Flexibility for bandwidth Different applications can have different security needs and operational constraints. Round5 enables the flexible choice of parameters so that it is possible to adjust bandwidth requirements and security level according to the application needs. Round5 achieves this by using prime cyclotomic polynomials and rounding. For instance, parameter set R5ND_1KEM_5d for NIST security level 1 requires the exchange of 994 Bytes so that it can be used by an application with communication constraints; parameter set R5N1_5CCA_0d offers a much higher security level and does not rely on any ring structure so that it might be a preferred option for the exchange of highly confidential information. The amount of data to be exchanged for the latter parameter set (29360 Bytes) is larger than for the former, but is smaller than in another existing non-ring proposal for an equivalent security level [29].

Flexibility for CPU Different applications can have different security needs and operational constraints. Round5 allows for flexibility in the choice of parameters so that it is possible to adjust CPU needs and security requirements according to the application needs. Furthermore, the parameters in Round5 are chosen such that a unified implementation performs well for any input value (n, d). If necessary, optimized implementations for specific parameters can be realized, leading to even faster operation than with the unified implementation. For instance, parameter set R5N1_5CPA_0d for NIST security level 5, intended for a high security level and not relying on a ring structure, requires just a few milliseconds for key generation, encapsulation and decapsulation in our testing platform. Another application, requiring faster operation and with less security needs, can use parameter set R5ND_1CPA_5d for NIST security level 1 that performs orders of magnitude faster.

Flexibility for cryptographic primitives Round5 and its building blocks can be used to create cryptographic primitives such as authenticated key-exchange schemes in a modular way, e.g., as in [31].

Flexibility for integration into real-world security protocols The Internet relies on security protocols such as TLS, IKE, SSH, IPsec, DNSSEC etc. Round5 can be easily integrated into them because many of its parameter sets lead to relatively small messages and efficient CPU performance. For instance, the public-key and ciphertext in R5ND_5CPA_5d for NIST security level 5 require a total of 2035 Bytes. This is smaller than other lattice-based proposals such as [31] or [9], and facilitates integration into protocols so that required changes, such as packet fragmentation, are minimized. An example of a protocol for which direct integration of a KEM

is challenging is IKEv2 (RFC 7296). The reason is that the first message exchange in IKEv2, *IKE_SA_INIT* does not support fragmentation. If we assume Ethernet (1500 B layer 2 packets), and we use the minimal header sizes, then there is room for a 1384 B public-key/ciphertext assuming IPv4, with IPv6, this is 1364 B. Still, this misses important information that is exchanged in most real-world deployments and that further reduces the available space. Examples of such information are notification/vendor ids, a cookie that the responder could use to decide whether it might be under a DoS attack (a minimum of 12 Bytes), and an initial contact notify that tells the responder that it is the first time we are talking to it and it should clear out any stale state (8 Bytes). If NAT traversal needs to be supported, then another 56 B are required for the corresponding notify. In general, most implementations might have enough space for perhaps 1250-1300 B; smaller than that makes things easy; larger than that forces implementations to make hard decisions. All ring-based Round5 parameter sets fit in IKEv2's *IKE_SA_INIT*.

Flexiblity in the generation of $\boldsymbol{A}$ Round5 offers different alternatives to refresh $\boldsymbol{A}$ in a way that is efficient but also secure against pre-computation and back-door attacks. In the ring setting, this is achieved by computing a new $\boldsymbol{A}$ in each protocol exchange. In the non-ring setting, three options are provided: ($f^{(0)}_{d,n}$) randomly generating $\boldsymbol{A}$ in each protocol exchange, ($f^{(1)}_{d,n}$) permuting a fixed and system-wide public parameter $\boldsymbol{A_{master}}$ in each protocol exchange, or ($f^{(2)}_{d,n}$) deriving $\boldsymbol{A}$ from a large pool of values – determined in each protocol exchange – by means of a permutation. Permutation-based approaches show a performance advantage compared with generating $\boldsymbol{A}$ randomly— for instance, in settings in which a server has to process many connections. This is because the server can keep a fixed $\boldsymbol{A}$ in memory and just permute it according to the client request. If keeping a fixed $\boldsymbol{A}$ in memory in the client is an issue, then $f^{(2)}_{d,n}$ has a clear advantage compared with $f^{(1)}_{d,n}$ due to its lower memory needs.

Post-deployment flexibility A single implementation can be used for all Round5 parameter sets, without the need to recompile the code. This approach reduces the amount of code in the devices and makes code review easier. Furthermore, it enables a unified Round5 deployment that can be customized to fit non-ring or ring-based use cases, and a smooth transition to non-ring usage, should vulnerabilities in ring-based constructions be discovered.

Efficiency in constrained platforms The implementation of Round5 uses up to 16 bit long integers to represent the Round5 data. This enables good performance even in architectures with constrained processors. Moreover, algorithms are simple, and all modular arithmetic is easy as it is done with powers of two. Finally, the fixed-weight ternary secret distribution also facilitates efficient implementations.

Round5 incorporates the special parameter set R5ND_0KEM_2iot that has a total bandwidth requirement of just 736 Bytes, while ensuring a reasonable quantum-security level (at least 2^{87} workload for an adversary utilizing lattice reduction in the core sieving model [6]). This is feasible due to the usage of prime cyclotomic rings that allows configuring Round5 with a $n = d$ parameter between 256 and 512, the only two options available with power-of-two cyclotomic rings.

Resistance against side-channel attacks The design of Round5 allows for efficient constant-time implementations, since by design all secrets are ternary and have a fixed number of ones and minus ones. This facilitates very efficient constant-time implementations in cacheless platforms. Fully constant-time implementations are relatively simple to implement at a moderate performance cost. The XEf error correction codes avoid conditions and table look-ups altogether and are therefore resistant against timing attacks.

Parallelization Many routines in Round5 can be parallelized by means of AVX2 vector instructions bringing important performance improvements. Some of these routines include the generation of public matrix $\boldsymbol{A}$, the matrix and ring multiplications, and important subroutines required for constant-time secret key generation.

Low failure probability The failure probability for all proposals for r5_cpa_kem (except the one for the IoT use case) is at most 2^{-64}. The failure probability for all proposals for r5_cca_pke is at most 2^{-142}. These failure probabilities can be achieved because of the usage of sparse, ternary secrets and the large pool of parameter sets. The usage of XEf error correction codes in some Round5 parameter sets plays a fundamental role to deal with multiple errors and decrease the overall failure probability.

Known underlying mathematical problems Round5 builds on the well-known Learning with Rounding and Ring Learning with Rounding problems.

Provable security We provide security reductions from the sparse ternary LWR and RLWR problems to r5_cpa_kem and r5_cca_pke in the ROM model and from the standard Learning with Errors (LWE) problem to the sparse ternary LWR problem. Even though the latter reduction is not tight, it gives confidence in the Round5 design. As the parameters using error correction require performing certain operations modulo $x^{n+1} - 1$, the above security reductions do not apply to them. A reduction from an RLWE-based analogue of Round5 with error correction to RLWE is presented. This gives confidence in Round5 parameters with error correction. We discuss why this reduction does not directly translate to the RLWR case, and argue that it does not have any impact on the concrete security estimates.

Easy adoption A device that supports Round5 can handle a wide range of parameter sets, for both the ring and the non-ring versions. This is also feasible even without re-compilation. This flexibility can ease a smooth adoption.

Perfect forward secrecy Round5's key generation algorithm is fast, which makes it suitable for scenarios in which it is necessary to refresh a public/private key pair in order to maintain forward secrecy.

Application-specific parameter sets Round5 has three parameter application-specific parameter sets:

1. A ring-based KEM parameter set, addressing Internet of Things applications, with very small bandwidth requirements while still providing a moderate security level.
2. A ring-based, NIST level 1 KEM parameter set in which the encapsulated key is 192-bits long instead of just 128-bits, so that the difficulty of attacking the encapsulated key (e.g., brute-forcing it using Grover's quantum search algorithm [56]) is approximately equal to the difficulty of a quantum-enabled, lattice-reduction based attack against Round5. This parameter set has a total bandwidth requirement of less than 1 KB.
3. A non-ring based PKE parameter set with very small encryption overhead, under 1 KB, at the cost of a larger public key. This parameter set thus is especially useful in applications with static or long-term public-keys, e.g., in secure email, while still providing the security guarantees of an unstructured lattice-based assumption.

2.11 Technical Specification of Reference Implementation

This section specifies Round5 from an implementation perspective. The description is close to Round5's C reference implementation and aims at explaining it and allowing other developers to create own implementations. Algorithms 26, 27, and 28 correspond to r5_cpa_kem proposed in the key encapsulation mechanism category. Algorithms 32, 33, and 34 correspond to r5_cca_pke proposed in the public-key encryption category. In the description, we avoid special symbols to facilitate its direct implementation. For instance, Greek letters are not included and, e.g., we write *kappa* instead of κ; we write *q_bits* instead of q_{bits} or *n_bar* instead of $\bar{n}$. To increase readability, some functions will use Round5 main (Section 2.11.1) or derived or configurable (Section 2.11.2) parameters.

2.11.1 Round5 main parameters

Each Round5 parameter set (Sections 2.9.1 and 2.9.2) is determined by the following parameters that are located on the top of each parameter table in Sections 2.9.6 and 2.9.7.

d	Number of polynomial coefficients per public matrix row.
n	Reduction polynomial degree: ring: $n > 1$; non-ring: $n = 1$.
h	Number of non-zero values per column in secret matrices.
q, q_bits	Power of two modulo size where $q = 2^{q_bits}$.
p, p_bits	Power of two modulo size where $p = 2^{p_bits}$.
t, t_bits	Power of two modulo size where $t = 2^{t_bits}$.
b, b_bits	b_bits bits are extracted per ciphertext symbol; $b = 2^{b_bits}$.
n_bar	Number of columns of the secret matrix to compute $\boldsymbol{B}$.
m_bar	Number of columns of the secret matrix to compute $\boldsymbol{U}$.
$kappa$	Security parameter; number of information bits in error-correcting code.
f	Number of bit errors correctable by error-correcting code.
xe	Number of parity bits of error correcting code.
mu	Number of ciphertext symbols: $mu \cdot b_bits \geq kappa + xe$.

2.11.2 Round5 derived or configurable parameters

)

The following parameters are derived from the main parameters. Parameter tau indicates a configuration choice in function $f_{d,n}^{(\tau)}$ used to generate $\boldsymbol{A}$.

d/n	Number of polynomial elements in a row of $\boldsymbol{A}$.
$kappa_bytes$	Security parameter in bytes, i.e., $kappa/8$.
z	$z = \max(p, \frac{tq}{p})$. Relevant in reduction proofs and definition of rounding constants.
z_bits	$z_bits = \lceil \log_2(z) \rceil$.
h_1	$h_1 = \frac{q}{2p}$ is a rounding constant.
h_2	$h_2 = \frac{q}{2z}$ is a rounding constant.
h_3	$h_3 = \frac{p}{2t} + \frac{p}{2b} - \frac{q}{2z}$ is a constant to reduce decryption bias.
h_4	$h_4 = \frac{q}{2p} - \frac{q}{2z}$ is a constant to reduce decryption bias.
N	Identifies polynomial $N_{n+1}(x) = x^{n+1} - 1$.

Phi	Identifies polynomial $\Phi_{n+1}(x) = N_{n+1}(x)/(x-1)$.
Xi	Identifies if reduction polynomial is N or Phi.
tau	Index in $f_{d,n}^{(\tau)}$.

For all proposed Round5 parameter sets, $z = p$, $h_1 = h_2 = \frac{q}{2p}$, and $h_4 = 0$.

2.11.3 Basic data types, functions and conversions

Bit	A binary digit: 0 or 1.
Bit string	An ordered sequence of bits, e.g., $[0,1,1,1]$ contains 4 bits, 0 is the left-most bit. Bit strings are denoted by a lower case letter.
Byte	An ordered sequence of 8 bits, e.g., $[0,1,1,1,0,1,1,1]$. Bytes are interpreted in little-endian. The previous example represents $0xEE$ in hexadecimal or 238 in decimal representation.
Byte string	An ordered sequence of bytes e.g., $[0x01, 0x02, 0x03]$ contains 3 bytes, 0x01 is the left-most byte. Byte strings are denoted by a lower case letter.
0^c	A bit string containing c 0s.
$\|\|$	The concatenation operator is represented by $\|\|$ and concatenates two strings, e.g., two bit or two byte stings. For instance, $$[0,1,1,1,0,1] = [0,1,1]\|\|[1,0,1]$$
$\lceil a \rceil$	For a real number a, the ceiling operator is represented by $\lceil a \rceil$ and returns the next integer value of a. For instance, $\lceil 15/8 \rceil = 2$, $\lceil -3.2 \rceil = -3$.
$\lfloor a \rfloor$	For a real number a, the flooring operator is represented by $\lfloor a \rfloor$ and returns the integer part of value a. For instance, $\lfloor 15/8 \rfloor = 1$, $\lfloor -3.2 \rfloor = -4$.
$\oplus$	For two bits x and y, $x \oplus y$ represents the modulo 2 addition of two bits. For instance, $1 \oplus 1 = 0$.
Little endianness	Round5 uses a little endianness representation for bit strings and byte strings as defined above as well as for vectors and polynomials. In a bit string this means that the leftmost bit is the least significant bit and the rightmost bit or the last bit is the most significant bit. The same applies to byte string, vectors, and polynomials.

For instance, the following byte c contains 8 bits, starting with bit 0 (c_0) and ending with bit 7 (c_7).

$$c = [c_0, c_1, c_2, c_3, c_4, c_5, c_6, c_7]$$

In another example, a 64-bit word w contains 8 bytes such as the first byte is byte 0 (c_0) and the last byte is byte 7 (c_7).

$$w = [c_0, c_1, c_2, c_3, c_4, c_5, c_6, c_7]$$

For instance, $c = [0, 1, 0, 1, 1, 1, 0, 1]$ equals 186, or $0xba$ in hexadecimal representation.
$w = [0xef, 0xcd, 0xab, 0x89, 0x67, 0x45, 0x23, 0x01]$ equals $0x0123456789abcdef$.

Moduli

Round5 performs operations modulo r with $r = \{q, p, t\}$ being powers of two. The number of bits is denoted as $r_bits = \{q_bits, p_bits, t_bits\}$ such that $r = 2^{r_bits}$.

Vectors

Round5 vectors $\boldsymbol{v}_r^{(k,1)}$ are defined column-wise, and contain k integers in $\mathbb{Z}_r$. Vector element with index 0 $\boldsymbol{v}[0]$ comes first (little-endian) followed by element with index 1 $\boldsymbol{v}[1]$ till last element with index $k-1$, i.e., $\boldsymbol{v}[k-1]$. A vector element $\boldsymbol{v}[i]$ is represented as a bit string containing $r_bits = \lceil log_2 r \rceil$ bits. Vectors are denoted by a bold low case letter.

Polynomials

Round5 polynomials are in $\mathcal{R}_{n,r} = \mathbb{Z}_r[x]/\left(\xi_{n+1}(x)\right)$ where $r = \{q, p, t\}$ is a power of two, $n+1$ is chosen to be a prime number, and $\xi_{n+1}(x)$ can be either the prime cyclotomic polynomial $\Phi(x) = 1 + x + \ldots + x^n$, or the NTRU polynomial $N_{n+1}(x) = x^{n+1} - 1 = (x-1) \cdot \Phi_{n+1}(x)$ having $n+1$ coefficients. All coefficients are $r_bits = \lceil log_2(r) \rceil$ bits long, i.e., $r_bits = \{q_bits, p_bits, t_bits\}$. When $n = 1$, polynomials have a single coefficient in $\mathbb{Z}_r$.

Polynomials are represented in little endian, i.e., coefficient of degree 0 comes first and the highest degree coefficient comes last.

A polynomial is represented as a vector $\boldsymbol{poly}$ so that $\boldsymbol{poly}[i]$ is the coefficient of degree i. In particular,

$$\boldsymbol{poly} = \boldsymbol{poly}[0] + \boldsymbol{poly}[1] \cdot x + \cdots + \boldsymbol{poly}[s] \cdot x^s$$

where $s = n$ when $Xi = N$ and $s = n-1$ when $Xi = Phi$.

Each polynomial coefficient $\boldsymbol{poly}[i]$ is represented as a bit string of length r_bits.

$$\boldsymbol{poly}[i] = [\boldsymbol{poly}[i]_0, \boldsymbol{poly}[i]_1, \ldots, \boldsymbol{poly}[i]_(r_bits - 1)]$$

Polynomial vectors	Round5 polynomial vectors $\boldsymbol{v}_r^{(k,1)}$ are defined column-wise, and contain $k = d/n$ polynomials in $\mathcal{R}_{n,r} = \mathbb{Z}_r[x]/\left(\xi_{n+1}(x)\right)$. Polynomial vectors are denoted by a bold lower case letter.
Matrices	Round5 matrices $\boldsymbol{A}_r^{(row,col)}$ contain *row* rows and *col* columns and their elements are polynomials in $\mathcal{R}_{n,r} = \mathbb{Z}_r[x]/\left(\xi_{n+1}(x)\right)$. Matrices are denoted by a bold capital letter.

2.11.4 Supporting Cryptographic Algorithms and derived Functions

Several Round5 routines require the generation of a deterministic sequence of pseudorandom data, namely: the generation of public matrix $\boldsymbol{A}$, the generation of permutations in $f_{d,n}^{(\tau)}$ with $\tau = \{1, 2\}$, and the generation of the secret keys $\boldsymbol{R}$ and $\boldsymbol{S}$. The Round5 KEM algorithms *r5_cpa_kem* and *r5_cca_kem* require three hash functions. The Round5 DEM algorithm requires both a key and an initialization vector that are derived also by means of a hash function. Round5 implements the deterministic generation of pseudorandom data and the hash functions by means of TupleHash and TupleHashXOF defined in SP 800-185 [68].

Furthermore, Round5 uses AES specified in FIPS 197 [52] with two purposes. First, Round5 defines a public-key encryption scheme requiring a DEM. Round5's DEM is AES in GCM mode. GCM mode is specified in SP 800-38D [51]. Second, Round5 defines an alternative and optional method to generate the pseudorandom data required to sample public matrix $\boldsymbol{A}$. This is based on AES in counter mode specified in SP 800-38A [50].

The main reason for choosing TupleHash and TupleHashXOF is that they allow combining a sequence of inputs in a generic and misuse-resistant way. A TupleHash computed on the tuple ("abc" ,"d") produces a different hash value than a TupleHash computed on the tuple ("ab","cd") [68]. Thus, TupleHash separates Round5 routines in different domains. The main reason for also using the eXtensible output function (XOF) variant of TupleHash in some cases is because some of above routines require an output of variable length.

Table 18 specifies the input X to TupleHash(X, L, S) and TupleHashXOF(X, L, S) [68, Section 5] for each Round5 routine using it. $S =$ "" since no customization string is used. In the table, *ns* refers to the number of strings or variables of the input tuple X.

The first input string is a domain identifier used to identify each of the routines. The largest length of a domain identifier is 12 bytes. The second input string is a byte string of length *kappa_bytes*≤ 32. The third input parameter, if present, is either a 1 byte long index i in $[0, ..., 255]$ or the bit string encoding the ciphertext (CT) or public-key (PK). The longest encoded is smaller CT and PK is less than 2^{21}. Thus, the left encoding of the length of the second parameter requires up to 4 bytes.

If *kappa* ≤ 128 (NIST Security level 1, or R5ND_0CPA_2iot), then TupleHash128 and AES128 are used. If *kappa* $= 192$ (NIST Security level 3), then

Table 18: Definition of TupleHash input X in Round5 routines.

Routine	XOF?	ns	X[0]	X[1]	X[2]	len(X[0])	len(X[1])	len(X[2])
Generation of $\boldsymbol{A}$	No	3	"AGEN"	sigma	"i"	4	*kappa_bytes*	1
Secret key generation	Yes	3	"SGEN" "RGEN"	seed, ρ	"i"	4	*kappa_bytes*	1
Generation of permutations	Yes	2	"APermutation"	sigma	-	12	*kappa_bytes*	-
H in r5_cpa_kem	No	3	"HCPAKEM"	m	CT	7	*kappa_bytes*	CTSize
G in r5_cca_kem	No	3	"GCCAKEM"	m	PK	7	*kappa_bytes*	PKSize
H in r5_cca_kem	No	3	"HCCAKEM"	L'	CT	7	*kappa_bytes*	CTSize
H in r5_cca_pke (DEM)	No	2	"HR5DEM"	k	-	6	*kappa_bytes*	-

TupleHash256 and AES192 are used. If $kappa = 256$ (NIST Security level 5), then TupleHash256 and AES256 are used. Following the notation in SP 800-185, the following supporting derived functions are defined:

AGeneration() Function that generates a deterministic sequence of pseudorandom data used to sample matrix $\boldsymbol{A}$. The function has as input a *kappa_ bytes* long seed *sigma*, a 1-byte identifier i in $[0, 255]$ and desired output length L in bytes, and is defined as
AGeneration(*sigma,i,L*) =
TupleHash(<"AGEN", *sigma*, i >, 8*L, "").
The encoded value L depends on the Round5 variant.
In the ring case, $L = 2 * \lceil d/8 \rceil$.
In the non-ring case with $f_{n=1,d}^{(\tau=0,1)}$, $L = 2 * d * \lceil d/8 \rceil$.
In the non-ring case with $f_{n=1,d}^{(\tau=2)}$, $L = 2 * \lceil len_tau_2/8 \rceil$.

AGeneration() is divided into two functions, initialization (absorb) and generation (squeeze):
AGenerationInit($sigma$, i, L) initializes the internal state of TupleHash; AGenerationGen(L', *state*) returns the next L' bytes of pseudorandom data and updates the internal state *state* of TupleHash.

[Alternative AES method] *The above method based on TupleHash is the default method to generate the pseudorandom data to sample* $\boldsymbol{A}$. *Optionally,* $\boldsymbol{A}$ *is sampled by using AES in counter mode. This option is motivated by its faster operation thanks to hardware instructions available in certain platforms. In this optional method, AES in Counter Mode is initialized with IV equal to* 0 *and a* kappa_bytes *bytes long key equal to*

*TupleHash(<"AGEN", sigma, i >, 8*kappa_bytes, "").*

SKGeneration() — Function that generates a deterministic sequence of pseudorandom data used to sample secret keys $\boldsymbol{S}$ and $\boldsymbol{R}$. The function has as input a byte string *domain* of length 4 that can be "SGEN" (for $\boldsymbol{S}$) or "RGEN" (for $\boldsymbol{R}$), a *kappa_bytes* long byte string *seed*, a 1-byte identifier i in $[0, 255]$ and a desired output length L in bytes, and is defined as
SKGeneration($domain, seed, i, L$) =
TupleHashXOF($< domain, seed, i >$, 8*L, "").

SKGeneration() is divided into two functions, initialization (absorb) and generation (squeeze):
SKGenerationInit($domain, seed, i$) initializes the internal state of TupleHashXOF; SKenerationGen(L', *state*) returns the next L' bytes of pseudorandom data and updates the internal state *state* of TupleHashXOF.

Note that the generation of random data for the sampling of secret keys $\boldsymbol{S}$ (and $\boldsymbol{R}$) can be based on a true random number generator. However, the current Round5 specification opts for obtaining first a *kappa_bytes* bytes long seed and generating from it a deterministic sequence of pseudorandom data for performance purposes.

APermutation() — Function that generates a deterministic sequence of pseudorandom data to be used to sample permuations for $f_{d,n}^{(\tau)}$. This function has as input a byte string *sigma* of length *kappa_bytes*, and a desired output length L in bytes, and is defined as
APermutations($sigma, L$) =
TupleHashXOF(<"APermutation", *sigma* >, 8*L, "").

APermutation() is divided into two functions, initialization (absorb) and generation (squeeze):
APermutationInit($sigma, i$) initializes the internal state of TupleHashXOF; APermutationGen(L', *state*) returns the next L' bytes of pseudorandom data and updates the internal state *state* of TupleHashXOF.

HCPAKEM() — Hash function used in r5_cpa_kem() that is given as input a byte string m of length *kappa_bytes* and a public key *ct*, and returns a byte string of length *kappa_bytes*:
HCPAKEM(m,*ct*) =
TupleHash(<"HCPAKEM", m, *ct* >, 8* *kappa_bytes*, "").

GCCAKEM() — Hash function used in r5_cca_kem() that is given as input a byte string m of length *kappa_bytes* and a ciphertext

pk, and returns a byte string of length 3**kappa_bytes*:
GCCAKEM(m,pk) =
TupleHash(<"GCCAKEM", m, pk >, 24* *kappa_bytes*, "").

HCCAKEM() Hash function used in r5_cca_kem() that is given as input a byte string m of length *kappa_bytes* and a public key *ct*, and returns a byte string of length *kappa_bytes*:
HCCAKEM(m,ct) =
TupleHash(<"HCCAKEM", m, ct >, 8* *kappa_bytes*, "").

HR5DEM() Hash function used in the DEM in r5_cca_pke() that is given as input a *kappa_bytes* bytes long key k, and returns a byte string of length *kappa_bytes* + 12:
HR5DEM(k) =
TupleHash(<"HR5DEM", k >, 8* (*kappa_bytes* + 12), "").
The first *kappa_bytes* output bytes correspond to the key used in AES in GCM mode. The last 12 output bytes correspond to the IV used in AES in GCM mode.

2.11.5 True random data generation and uniform sampling

The generation of secret keys $\boldsymbol{R}$ and $\boldsymbol{S}$ and the computation of public parameter $\boldsymbol{A}$ require an initial source of true random data *kappa_bytes* bytes long. Furthermore entries must be uniformly sampled to avoid any bias. The following functions are used to this end:

randombytes_init Function to initialize a *true* random number generator randombytes().

randombytes() Function that returns B bytes of true random data denoted as *randomness*.

$$randomness = \text{randombytes}(B)$$

sample() Function for deterministic uniform sampling in $\{0, 1, \ldots, range-1\}$ given pseudorandom data input uniform in $\{0, 1, \ldots, 2^{16}-1\}$ generated by SKGeneration() and APermutation() by means of TupleHashXOF().

The function is defined as follows:

Algorithm 13: sample($state, range$)

```
rrange = ⌊(2^16 − 1) / range⌋
do
    x = SKGenerationGen(2, state)
while x ≥ d · rrange
return ⌊x / rrange⌋
```

2.11.6 Core functions

mult_poly_ntru()

Function that multiplies input polynomials $\boldsymbol{a}$ and $\boldsymbol{b}$ in $\mathcal{R}_{n,r} = \mathbb{Z}_r[x]/\left(N_{n+1}(x)\right)$ obtaining polynomial $\boldsymbol{c}$.

$$\boldsymbol{c} = \text{mult_poly_ntru}(\boldsymbol{a}, \boldsymbol{b}, n, r)$$

lift_poly()

Function that lifts input polynomial $\boldsymbol{a}$ in $\mathbb{Z}_r[x]/\left(\Phi_{n+1}(x)\right)$ obtaining polynomial $\boldsymbol{a^{(L)}}$ in $\mathbb{Z}_r[x]/\left(N_{n+1}(x)\right)$.

$$\boldsymbol{a^{(L)}} = \text{lift_poly}(\boldsymbol{a}, n, r)$$

In mathematical terms, lifting means:

$$\boldsymbol{a}^{(L)}(x) = (x-1)\boldsymbol{a}(x)$$

Coefficient-wise, this means that:

$$\boldsymbol{a}^{(L)}(x) = \boldsymbol{a}_0^{(L)} + \boldsymbol{a}_1^{(L)} \cdot x + \boldsymbol{a}_2^{(L)} \cdot x^2 + \cdots + \boldsymbol{a}_n^{(L)} x^n$$

equals

$$-\boldsymbol{a}_0 + (\boldsymbol{a}_0 - \boldsymbol{a}_1)x + (\boldsymbol{a}_1 - \boldsymbol{a}_2)x^2 + \cdots + (\boldsymbol{a}_{n-2} - \boldsymbol{a}_{n-1})x^{n-1} + \boldsymbol{a}_{n-1}x^n$$

unlift_poly()

Function that unlifts input polynomial $\boldsymbol{a^{(L)}}$ in $\mathbb{Z}_r[x]/\left(N_{n+1}(x)\right)$, obtaining $\boldsymbol{a}$ in $\mathbb{Z}_r[x]/\left(\Phi_{n+1}(x)\right)$.

$$\boldsymbol{a} = \text{unlift_poly}(\boldsymbol{a^{(L)}}, n, r)$$

In mathematical terms, unlifting means:

$$\boldsymbol{a}(x) = \boldsymbol{a}^{(L)}(x)/(x-1)$$

As $\boldsymbol{a}^{(L)} = \text{lift_poly}(\boldsymbol{a}, n, r)$, the coefficients of $\boldsymbol{a}$ can be recursively computed as

$$\boldsymbol{a}_0 = -\boldsymbol{a}_0^L \text{ and } \boldsymbol{a}_i = \boldsymbol{a}_{i-1} - \boldsymbol{a}_i^L \text{ for } 1 \leq i \leq n-1.$$

mult_poly() Function that takes input polynomials $\boldsymbol{a}$ and $\boldsymbol{b}$ of length n and multiplies them in $\mathcal{R}_{n,r} = \mathbb{Z}_r[x]/\left(\xi_{n+1}(x)\right)$ obtaining polynomial $\boldsymbol{c}$.

$$\boldsymbol{c} = \text{mult_poly}(\boldsymbol{a}, \boldsymbol{b}, n, r, Xi)$$

If $Xi = N$, then $\boldsymbol{c} = \text{mult_poly_ntru}(\boldsymbol{a}||0, \boldsymbol{b}, n, r)$. If $Xi = Phi$, then this function lifts input parameter $\boldsymbol{a}$ before calling mult_poly_ntru and unlifts the result, i.e., $\boldsymbol{c} = \text{unlift_poly}(\text{mult_poly_ntru}(\text{lift_poly}(\boldsymbol{a}, n, r), \boldsymbol{b}, n, r), n, r)$.

add_poly() Function that takes input polynomials $\boldsymbol{a}$ and $\boldsymbol{b}$ of length n and adds them component-wise obtaining $\boldsymbol{c}$.

$$\boldsymbol{c} = \text{add_poly}(\boldsymbol{a}, \boldsymbol{b}, n, r, Xi)$$

mult_matrix() Function that multiplies two matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ of dimension $A_row \times A_col$ and $B_row \times B_col$, with entries in $\mathcal{R}_{n,r} = \mathbb{Z}_r[x]/\left(\xi_{n+1}(x)\right)$ obtaining matrix $\boldsymbol{C}$ of dimension $A_row \times B_col$ with entries in $\mathcal{R}_{n,r}$.

$$\boldsymbol{C} = \text{mult_matrix}(\boldsymbol{A}, A_row, A_col, \boldsymbol{B}, B_row, B_col, n, r, Xi)$$

Algorithm 14: mult_matrix($\boldsymbol{A}$, *A_row, A_col*, $\boldsymbol{B}$, *B_row, B_col, n, r, Xi*)

```
for(i = 0; i < A_row; i++)
    for(j = 0; j < B_col; j++)
        C[i, j] = 0
        for(k = 0; k < A_col; k++)
            tmp = mult_poly(A[i, k], B[k, j], n, r, Xi)
            C[i, j] = add_poly(C[i, j], tmp, n, r)
```

transpose_matrix() Function that transposes input matrix $\boldsymbol{A}$ of dimension $A_row \times A_col$ with entries in $\mathbb{Z}[x]/\left(\Phi_{n+1}(x)\right)$, obtaining matrix $\boldsymbol{A_T}$ of dimension $A_col \times A_row$ with entries in $\mathbb{Z}[x]/\left(\Phi_{n+1}(x)\right)$.

$$\boldsymbol{A_T} = \text{transpose_matrix}(\boldsymbol{A}, A_row, A_col, n)$$

For $0 \leq i \leq A_col - 1$ and $0 \leq j \leq A_row - 1$, $\boldsymbol{A}_T(i, j) = \boldsymbol{A}(j, i)$.

round_element Function that rounds a_bits bits long element x from a_bits to b_bits bits using rounding constant h where $a = 2^{a_bits}$ and $b = 2^{b_bits}$, obtaining y

$$y = \text{round_element}(x, a_bits, b_bits, h) = \left\lfloor \frac{x+h}{2^{a_bits - b_bits}} = \right\rfloor = \left\lfloor \frac{b}{a}(x+h) \right\rfloor$$

round_matrix() Function that performs coefficient-wise rounding applying round_element() to all polynomial coefficients in matrix $\boldsymbol{A}$ of dimension $A_row \times A_col$ with elements in $\mathcal{R}_{n,2^{a_bits}} = \mathbb{Z}_{2^{a_bits}}[x]/\left(\xi_{n+1}(x)\right)$, obtaining matrix $\boldsymbol{B}$ of dimension $A_row \times A_col$ with elements in $\mathcal{R}_{n,2^{b_bits}} = \mathbb{Z}_{2^{b_bits}}[x]/\left(\xi_{n+1}(x)\right)$.

$$\boldsymbol{B} = \text{round_matrix}(\boldsymbol{A}, A_row \cdot A_col, n, a_bits, b_bits, h)$$

decompress() Function that decompresses integer x from b_bits to a_bits bits, obtaining y

$$y = \text{decompress}(x, b_bits, a_bits) = x \cdot 2^{a_bits - b_bits}$$

decompress_ matrix() Function that performs coefficient-wise decompression applying decompress to the first mu polynomial coefficients in matrix $\boldsymbol{A}$ of dimension $A_row \times A_col$ with elements in $\mathcal{R}_{n,2^{b_bits}} = \mathbb{Z}_{2^{b_bits}}[x]/\left(\xi_{n+1}(x)\right)$, obtaining vector $\boldsymbol{b}$ of length mu with entries in $\mathbb{Z}_{2^{a_bits}}$.

$$\boldsymbol{b} = \text{decompress_matrix}(\boldsymbol{A}, mu, 1, b_bits, a_bits)$$

permutation_tau_1() Function that computes permutation $\boldsymbol{p1} \in \mathbb{Z}_d^d$ associated to $f_{d,1}^{(1)}$, used to permute the row elements in a fixed master public parameter matrix $\boldsymbol{A_master}$ and obtain the public parameter A.

$$\boldsymbol{p1} = permutation_tau_1(sigma, d)$$

The function is defined as follows:

Algorithm 15: permutation_tau_1($sigma, d$)

```
state = APermutationInit(sigma)
for (i = 0; i < d; i++)
    p1[i] = sample(APermutationGen(2, state), d))
return p1
```

permutation_tau_2() Function that computes permutation $\boldsymbol{p2}$ associated to $f_{d,1}^{(2)}$, used to permute the elements in a master public parameter vector $\boldsymbol{a_master}$ and obtain the public parameter $\boldsymbol{A}$.

$$\boldsymbol{p2} = \text{permutation_tau_2}(sigma, d, len_tau_2)$$

$\boldsymbol{p2}$ is a vector of length d with distinct entries from $\{0, 1, \ldots, len_tau_2 - 1\}$.

The function is defined as follows:

Algorithm 16: permutation_tau_2(*sigma, d, len_tau_2*)

```
state = APermutationInit(sigma)
v = 0
for (i = 0; i < d; i++)
  do
    x = APermutationGen(2,state) mod len_tau_2
  while v[x]! = 0
  v[x] = 1
  p2[i] = x
return p2
```

The operation mod *len_tau_2* applied to x returns the first log_2(len_tau_2) bits of x. For instance, if $x = [0x0, 0x1, 0xC, 0xD]$ and $len_tau_2 = 2^{11}$, then the returned value is $[0x0, 0x1, 0x4, 0x0]$
.

create_A() Function that computes master public parameter $\boldsymbol{A}$ given random *sigma*.

$$\boldsymbol{A} = \text{create_A}(sigma)$$

Internally, depending on the choice of *tau*, create_A computes $\boldsymbol{A}$ using one out of three strategies that provide a trade-off between CPU and memory performance (see Section 2.4.3).

$\mathbf{f^{(0)}_{d,n}}$: Generates the d^2/n coefficients comprising matrix $\boldsymbol{A}$ in 8 blocks so that efficient vectorized implementations (e.g., AVX2) are feasible.

AGenerationInit() is called 8 times with seed *sigma* and 1-byte long index i with $0, 1, 2, ..., 7$. After each initialization, the output of AGenerationGen() is used to fill-in $\boldsymbol{A}$ row-wise. Each element in $\boldsymbol{A}$ is a polynomial, and it is filled-in coefficient-wise, i.e., first coefficient of degree 0, then coefficient of degree 1, till the coefficient of highest degree. For instance, when starting with row j, then first polynomial element 0 in row j, then polynomial element 1 in row j, till all polynomial elements in row j are assigned; then polynomial element 0 in row $j + 1$, then polynomial element 1 in row $j + 1$, till all polynomial elements in row $j + 1$ are assigned, and so on.

When $n = 1$, the generation is defined as follows:

Algorithm 17: create_A($sigma$) for $\mathbf{f^{(0)}_{d,1}}$

```
for i = 0 to 7
    state = AGenerationInit(sigma, i)
    for j = 0 to ⌈d/8⌉ − 1
        for l = 0 to d − 1
            A[i⌈d/8⌉ + j, l] = AGenerationGen(2, state) mod q
return A
```

When $n = d$, the generation is defined as follows:

Algorithm 18: create_A($sigma$) for $\mathbf{f^{(0)}_{d,d}}$

```
for i = 0 to 7
    state = AGenerationInit(sigma, i)
    for j = 0 to ⌈d/8⌉ − 1
        a[i⌈d/8⌉ + j] = AGenerationGen(2, state) mod q
return a
```

The initialization and generation functions can be parellelized by means of AVX instructions.

The above mod q operation means that from the two bytes pseudorandom number x returned by AGenerationGen(2, *state*), the corresponding coefficient is obtaining by taking the first $q_bits = \log_2(q)$ bits of x, i.e., $[x_0, x_1, \ldots x_{q_bits-1}]$ For instance, if AGenerationGen(2, *state*) returns $[0x12, 0x34]$ and $q = 2^{12}$, then the generated coefficient is $[0x12, 0x30]$.

$\mathbf{f^{(1)}_{d,n=1}}$: only applies to $n = 1$. This requires a $d \times d$ master matrix $\boldsymbol{A_master}$ that has been precomputed using the method described for $\mathbf{f^{(0)}_{d,1}}$, and is a public parameter known to all parties in the system. It also requires a permutation vector $\boldsymbol{p1} \in \mathbb{Z}_d^d$ – computed with permutation_tau_1() – to permute the elements in each row in $\boldsymbol{A_master}$ to obtain $\boldsymbol{A}$:

$$\boldsymbol{A}[i, j] = \boldsymbol{A_master}[i, (j + \boldsymbol{p1}[i]) \text{mod } d]$$

$\mathbf{f^{(2)}_{d,1}}$: only applies to $n = 1$. This approach first computes a vector $\boldsymbol{a_master}$ of length len_tau_2 by calling AGeneration(). It then uses a permutation vector $\boldsymbol{p2}$ of length d with distinct entries from $\{0, 1, \ldots,$len_tau_2$-1\}$, obtained by applying permutation_tau_2() to $sigma$, to pick up d sets of d consecutive elements in $\boldsymbol{a_master}$ as rows of $\boldsymbol{A}$.

Algorithm 19: create_A($sigma$) for $\mathbf{f^{(2)}_{d,n=1}}$

```
for i = 0 to 7
    state = AGenerationInit(sigma, i)
    for j = 0 to ⌈d/8⌉ − 1
        a_master[i⌈len_tau_2/8⌉ + j] =
    AGenerationGen(2, state) mod q
p2 = permutation_tau_2(sigma, d, len_tau_2)
for i = 0 to d − 1
    for j = 0 to d − 1
        A[i, j] = a_master[(p2[i] + j) mod len_tau_2]
return A
```

The initialization and generation functions to obtain ***a_master*** can be parallelized by means of AVX instructions.

The above mod q operation means that from the two bytes pseudorandom number x returned by AGenerationGen(2, *state*), the corresponding coefficient is obtaining by taking the first $q_bits = \log_2(q)$ bits of x, i.e., $[x_0, x_1, \ldots x_{q_bits-1}]$ For instance, if AGenerationGen(2, *state*) returns $[0x12, 0x34]$ and $q = 2^{12}$, then the generated coefficient is $[0x12, 0x30]$.

len_tau_2 has a default value 2^{11}, which is the smallest power of two value greater than the d value in any of the Round5 configurations.

secret_key_vector() Function that computes a sparse ternary secret $\boldsymbol{s}$ of dimension $d \times 1$ of hamming weight h.

$$\boldsymbol{s} = \text{secret_key_vector}(dom, s, id)$$

Each secret vector $\boldsymbol{s}$ contains d/n polynomials in $\mathcal{R}_{n,r} = \mathbb{Z}_r[x]/\left(\xi_{n+1}(x)\right)$. Since n can only take values 1 and d, this secret vector can represent two different data structures, both consisting of d elements in $\mathbb{Z}_r$:

- ring case: a single polynomial containing $n = d$ ternary coefficients, with exactly $h/2$ "+1" and $h/2$ "−1" values.
- non-ring case: d polynomials, each of them having a single ternary coefficient, and the vector with exactly $h/2$ "+1" and $h/2$ "−1" values.

Since in both data structures, there are exactly $h/2$ "+1" and $h/2$ "−1" values, this function only computes the h positions in vector $\boldsymbol{s}$ containing the h non-zero elements.

This function uses SKGeneration() to generate 2 byte long pseudorandom values x required to sample the h non-zero positions. This is done by checking whether a position $\boldsymbol{s}[x]$ is occupied already. The ith sampled position is assigned value "-1" if i is odd and "$+1$" if i is even as described below.

Algorithm 20: secret_key_vector(dom, s, id)

```
state = SKGenerationInit(dom, s, id)
s = 0^d
for (i = 0; i < h; i++)
  do
    x= sample(SKGenerationGen(2,state), d)
  while (s[x]! = 0);
  if (is_even(i))
    s[x] = 1;
  else
    s[x] = −1;
```

create_S_T()

Function that computes $n_bar \times d$ secret $\boldsymbol{S}^T$ with hamming weight h per row, using secret_key_vector() internally.

$$\boldsymbol{S_T} = create_S_T(sk)$$

Algorithm 21: create_S_T(sk)

```
domain = "SGEN"
for(id = 0; id < n_bar; id++)
  S_T[i] = secret_key_vector(domain, sk, id)
```

create_R_T()

Function that computes $m_bar \times d$ secret $\boldsymbol{R}^T$ with hamming weight h per row, using secret_key_vector() internally.

$$\boldsymbol{R_T} = create_R_T(rho)$$

Algorithm 22: create_R_T(rho)

```
domain = "RGEN"
for(id = 0; id < m_bar; id++)
  R_T[i] = secret_key_vector(domain, rho, id)
```

sample_mu()

Function that returns the first mu polynomial coefficients of the matrix $\boldsymbol{M}$ containing $\bar{n} \times \bar{m}$ polynomials in $\mathcal{R}_{n,r} = \mathbb{Z}_r[x]/\left(\xi_{n+1}(x)\right)$.

When $n = d$, $\boldsymbol{M}$ contains a single polynomial $\boldsymbol{m}$ and the values returned by *sample_mu* corresponds to the first

mu polynomial coefficients:

$$m_0 + m_1 x + \cdots + m_{mu-1} x^{mu-1}$$

When $n = 1$, $\boldsymbol{M}$ is a $\bar{m} \times \bar{n}$ matrix over $\mathbb{Z}_r$. The returned coefficients are the first mu coefficients of $\boldsymbol{M}$ read out row-wise. That is, if $M_{i,j}$ denotes the entry of $\boldsymbol{M}$ in row i and column j, then

$$\overbrace{\underbrace{M_{0,0}, M_{0,1}, \ldots, M_{0,\bar{n}-1}}_{\text{Row } 0}, \ldots \underbrace{M_{ii-1,0}, M_{ii-1,1}, \ldots, M_{ii-1,jj-1}}_{\text{Row } ii-1}}^{mu \text{ coefficients}},$$

where $mu = ii \cdot \bar{n} + jj$

add_msg() Function that first converts a binary string m of length $mu \cdot b_bits$ into mu elements in $\mathbb{Z}_t$, where $t = 2^{t_bits}$, and adds the result component wise modulo t to a vector $\boldsymbol{x} \in \mathbb{Z}_t$.

$$\boldsymbol{result} = \text{add_msg}(mu, \boldsymbol{x}, m, b_bits, t_bits)$$

The conversion of bits $m[i \cdot b_bits, \ldots, (i+1) \cdot b_bits - 1]$ is done by multiplying this bit string interpreted as an element in $\mathbb{Z}_b$ by t/b so that this is represented in $\mathbb{Z}_t$.

For instance, if $t = 2^5$ and $b = 2^2$, and $m[0,1] = [1,1]$, then its bit representation in $\mathbb{Z}_t$ is [0,0,0,1,1] where the left most bit is bit 0 and the right most bit is bit 4. This value is added to the t_bits-bit value $\boldsymbol{x}[i]$.

diff_msg() Function that computes the difference of mu entries in $\boldsymbol{v}$ and $\boldsymbol{x}$ modulo p.

$$\boldsymbol{result} = \text{diff_msg}(mu, \boldsymbol{v}, \boldsymbol{x}, p)$$

xef_compute() Round5's error correction operates on bit strings of size mu bits, of which $kappa$ bits are used to transport a shared secret message (with $kappa \in \{128, 192, 256\}$), and the remaining $xe = mu - kappa$ bits are used to correct errors. Note that $b_bits = 1$ for all parameter sets using error correction. The XEf design is easily scalable, so that it is possible to use the parameter f to control the number of errors guaranteed to be corrected.

$$m1 = \text{xef_compute}(m1, kappa_bytes, f)$$

is the function that given a string $m1$ of length mu, computes the xe parity bits corresponding to the $kappa$ left-most bits of $m1$, and XORs these parity bits with the xe

rightmost bits of $m1$. The xe parity bits consist of the values of $2f$ registers. The lengths $\{l_0, l_1, \ldots, l_{2f-1}\}$ of registers $\{r_0, r_1, \ldots, r_{2f-1}\}$ for the code $XE(kappa, f)$, and the number of parity bits $xe = \sum l_i$ are as follows:

$kappa$	f	register lengths	xe
128	2	$\{11, 13, 14, 15\}$	53
128	4	$\{11, 13, 16, 17, 19, 21, 23, 29\}$	149
128	5	$\{16^{(*)}, 11, 13, 16, 17, 19, 21, 23, 25, 29\}$	190
192	5	$\{24^{(*)}, 13, 16, 17, 19, 21, 23, 25, 29, 31\}$	218
256	5	$\{16^{(*)}, 16, 17, 19, 21, 23, 25, 29, 31, 37\}$	234

Bit j in register r_i of length l_i is computed as:

$$r_i[j] = m1[j] \oplus m1[j+l_i] \oplus \cdots \oplus m1[j + \lfloor \frac{kappa - 1 - j}{l_i} \rfloor \cdot l_i]$$

As in HILA5, register r_0 in the XE5 codes is special – marked with $(*)$ – and computes the register bits as the block-wise XOR of $kappa/l_0$ consecutive string bits.

$$r_0[j] = m1[j \cdot \frac{kappa}{l_0}] \oplus \cdots \oplus m1[(j+1) \cdot \frac{kappa}{l_0} - 1]$$

The output bit string of xef_compute is:

$$m1 \oplus [0^{kappa} || r_0 || r_1 || \ldots || r_{2f-1}]$$

xef_fixerr() Function used for correcting up to f errors in a string of $mu = kappa + xe$ bits. For correcting a bit string $m1 = (m' || r')$, where m' has length $kappa$ and r' has length xe, first $m1 = \text{xef_compute}(m1, kappa_bytes, f)$ is computed. Then $m1 = (m' || r''' = r' \oplus r'')$, where the registers r''_i correspond to the parity bits for the message m'. Next,

$$m = \text{xef_fixerr}(m1, kappa_bytes, f),$$

is computed, where $m = (m[0], \ldots, m[kappa-1])$ is a bit string of length $kappa$ with

$$m[k] = \begin{cases} m'[k] \oplus 1 & \text{if } \sum_{i=0}^{2f-1} r'''_i[f_{r_i}(k)] > f, \\ m'[k] & \text{otherwise.} \end{cases}$$

Here $f_{r_i}(k)$ is the bit in register r_i that depends on message bit k as specified in xef_compute. See Section 2.4.1 for more background.

pack() Function that serializes an input vector $\boldsymbol{input}$ containing $input_length$ components, each of size $input_size$ bits and places it into an output message $output$ of size $\lceil input_length \cdot input_size/8 \rceil$ bytes.

$$output = \text{pack}(\boldsymbol{input}, input_length, input_size)$$

For instance, input vector $[0x8, 0x1, 0xf, 0x2]$ contains 4 elements, each of them 4 bits long is serialized in output vector $[0x81, 0xf2]$. If $input_length \cdot input_size$ is not a multiple of 8, then the most significant bits of the last byte of $output$ are padded with 0s.

pack_pk() Function that serializes the components $sigma$ and $\boldsymbol{B}$ of Round5 public key, using pack() internally.

$$pk = \text{pack_pk}(sigma, ss_size, \boldsymbol{B}, d/n \cdot n_bar \cdot n, p_bits)$$

By definition, $sigma$ is packed in the first ss_size bytes of pk. Next, the $d/n \times \bar{n}$ n-coefficient polynomials in $\boldsymbol{B}$ are packed. Packing is done row-wise (first element 0 in row 0, then element 1 in row 0,..., till the last element in row 0; next the second row till the last row). For each polynomial element, packing starts with the coefficient of degree 0 and ends with the coefficient of degree $n-1$. For each polynomial coefficient having p_bits bits, bit 0 comes first and bit $p_bits - 1$ comes last.

pack_ct() Function that serializes the components $\boldsymbol{U}$ and $\boldsymbol{v}$ of Round5 ciphertext, using pack() internally.

$$ct = \text{pack_ct}(\boldsymbol{U}, d/n \cdot m_bar \cdot n, p_bits, \boldsymbol{v}, mu, t_bits)$$

By definition, $\boldsymbol{U}$ is packed in the first $\lceil d/n \cdot m_bar \cdot n \cdot p_bits/8 \rceil$ bytes of ct. Packing is done row-wise (first element 0 in row 0, then element 1 in row 0,..., till the last element in row 0; next the second row till the last row). For each polynomial element, packing starts with the coefficient of degree 0 and ends with the coefficient of degree $n-1$. For each polynomial coefficient having p_bits bits, bit 0 comes first and bit $p_bits - 1$ comes last. Next, v is packed, starting with $v[0]$ and ending with $v[mu-1]$. Each coefficient of v has t_bits bits and those are also packed following a little endian approach, i.e., first bit 0, then bit 1, till bit $t_bits - 1$.

unpack() Function that deserializes a bit string $input$ of length $\lceil number_elements \cdot element_bits/8 \rceil$ bytes into a vector

of size *number_elements* in which each vector element is in $\mathbb{Z}_{2^{element_bits}}$.

$\boldsymbol{output} = \text{unpack}(input, number_elements, element_bits)$

Bits $\{i * element_bits, \ldots, (i+1) * element_bits - 1\}$ in the input bit string correspond to element $\boldsymbol{output}[i]$ of the deserialized output vector.

unpack_pk() Function that de-serializes the components *sigma* and $\boldsymbol{B}$ of Round5's public-key *pk*, using unpack() internally.

$(sigma, \boldsymbol{B}) = \text{unpack_pk}(pk, sigma_size, B_elements, B_element_bits)$

where the input parameters are the serialized public-key, the size of *sigma*, the number of polynomial coefficients in $\boldsymbol{B}$ and the size in bits of each polynomial coefficient.

unpack_ct() Function that de-serializes the components $\boldsymbol{U}$ and $\boldsymbol{v}$ of Round5's ciphertext *ct*, using unpack() internally.

$(\boldsymbol{U}, \boldsymbol{v}) = \text{unpack_ct}(ct, U_elem, U_elem_size, v_elem, v_elem_size)$

where the input parameters are the serialized ciphertext, the number of polynomial coefficients in $\boldsymbol{U}$, the size in bits of each polynomial coefficient, the number of polynomial coefficients in $\boldsymbol{v}$, and the size in bits of each vector coefficient.

verify() Compares two byte strings $s1$ and $s2$ of equal length l and outputs bit 0 if they are equal.

$$c = \text{verify}(s1, s2, l)$$

conditional_constant_time_memcpy()
Function that copies byte string a of length *a_bytes* starting at memory address *mem* if condition *cond* is true.

$\text{conditional_constant_time_memcpy}(mem, a, a_bytes, cond)$

2.11.7 Implementation of r5_cpa_pke

Round5's INDCPA public-key encryption is specified in Algorithms 1, 2, and 3. Their implementation is described in Algorithms 23, 24, and 25.

Algorithm 23: r5_cpa_pke_keygen

output: $pk : kappa_bytes + \lceil n_bar \cdot d/n \cdot n \cdot p_bits/8 \rceil$ byte string.
: $sk : kappa_bytes$ byte string.

1 $sigma = \text{randombytes}(kappa_bytes)$
2 $\boldsymbol{A} = \text{create_A}(sigma)$
3 $sk = \text{randombytes}(kappa_bytes)$
4 $\boldsymbol{S_T} = \text{create_S_T}(sk)$
5 $\boldsymbol{S} = \text{transpose_matrix}(S_T, n_bar, d/n, n)$
6 $\boldsymbol{B} = \text{mult_matrix}(\boldsymbol{A}, d/n, d/n, \boldsymbol{S}, d/n, n_bar, n, q, Phi)$
7 $\boldsymbol{B} = \text{round_matrix}(\boldsymbol{B}, d/n \cdot n_bar, n, q_bits, p_bits, h1)$
8 $pk = \text{pack_pk}(sigma, kappa_bytes, b_bits, d/n \cdot n_bar \cdot n, p_bits)$
9 **return** pk, sk

Algorithm 24: r5_cpa_pke_encrypt

input: $pk : kappa_bytes + \lceil n_bar \cdot d/n \cdot n \cdot p_bits/8 \rceil$ byte string.
input: $m : kappa_bytes$ byte string that is encrypted.
input: $rho : kappa_bytes$ byte string.
output: $ct : (\lceil m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8 \rceil$ encrypted byte string.

1 $sigma, \boldsymbol{B} = \text{unpack_pk}(pk, kappa_bytes, d/n \cdot n_bar \cdot n, p_bits)$
2 $\boldsymbol{A} = \text{create_A}(sigma)$
3 $\boldsymbol{R_T} = \text{create_R_T}(rho)$
4 $\boldsymbol{A_T} = \text{transpose_matrix}(\boldsymbol{A}, d/n, d/n, n)$
5 $\boldsymbol{R} = \text{transpose_matrix}(\boldsymbol{R_T}, m_bar, d/n, n)$
6 $\boldsymbol{U} = \text{mult_matrix}(\boldsymbol{A_T}, d/n, d/n, \boldsymbol{R}, d/n, m_bar, n, q, Phi)$
7 $\boldsymbol{U} = \text{round_matrix}(\boldsymbol{U}, d/n \cdot m_bar, n, q_bits, p_bits, h2)$
8 $\boldsymbol{U_T} = \text{transpose_matrix}(\boldsymbol{U}, d/n, m_bar, n)$
9 $\boldsymbol{B_T} = \text{transpose_matrix}(\boldsymbol{B}, d/n, n_bar, n)$
10 $\boldsymbol{X} = \text{mult_matrix}(\boldsymbol{B_T}, n_bar, d/n, \boldsymbol{R}, d/n, m_bar, n, p, Xi)$
11 $\boldsymbol{x} = \text{round_matrix}(\boldsymbol{sample_mu(X)}, mu, 1, p_bits, t_bits, h2)$
12 $m1 = (m || 0^{xe})$
13 $m1 = \text{xef_compute}(m1, kappa_bytes, f)$
14 $\boldsymbol{v} = \text{add_msg}(mu, \boldsymbol{x}, m1, b_bits, t_bits)$
15 $ct = \text{pack_ct}(\boldsymbol{U_T}, d/n \cdot m_bar \cdot n, p_bits, \boldsymbol{v}, mu, t_bits)$
16 **return** ct

Algorithm 25: r5_cpa_pke_decrypt

input: sk : $kappa_bytes$ byte string.
: ct : $(\lceil m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8\rceil$ byte string.
output: m : $kappa_bytes$ byte string that has been decrypted.

$\boldsymbol{S_T}$ = create_S_T(sk)
$\boldsymbol{U_T}, \boldsymbol{v}$ = unpack_ct($ct, d/n \cdot m_bar \cdot n, p_bits, mu, t_bits$)
$\boldsymbol{U}$ = transpose_matrix($\boldsymbol{U_T}, m_bar, d/n, n$)
$\boldsymbol{v}$ = decompress_matrix($\boldsymbol{v}, mu, 1, p_bits, t_bits$)
$\boldsymbol{X_prime}$ = mult_matrix($\boldsymbol{S_T}, n_bar, d/n, \boldsymbol{U}, d/n, m_bar, n, p, Xi$)
$\boldsymbol{m2}$ = diff_msg($mu, \boldsymbol{v}, \boldsymbol{sample_mu(X_prime)}, p$)
$\boldsymbol{m2}$ = round_matrix($\boldsymbol{m2}, mu, 1, p_bits, b_bits, h3$)
$m1$ = pack($\boldsymbol{m2}, mu, b_bits$)
$m1$ = xef_compute($m1, kappa_bytes, f$)
return m = xef_fixerr($m1, kappa_bytes, f$)

2.11.8 Implementation of r5_cpa_kem

Round5's main building block is an INDCPA KEM are specified in Algorithms 4, 5, and 6. They are described from an implementation perspective in Algorithms 26, 27, and 28. Note that function HCPAKEM() includes the lengths of its input parameters.

Algorithm 26: r5_cpa_kem_keygen

output: pk : $\lceil kappa_bytes + n_bar \cdot d/n \cdot n \cdot p_bits/8\rceil$ byte string.
: sk : $kappa_bytes$ byte string.

(pk, sk) = r5_cpa_pke_keygen()
return pk, sk

Algorithm 27: r5_cpa_kem_encapsulate

input: pk : $\lceil kappa_bytes + n_bar \cdot d/n \cdot n \cdot p_bits/8\rceil$ byte string.
output: ct : $(\lceil m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8\rceil$ byte string.
output: k : $kappa_bytes$ byte string.

m = randombytes($kappa_bytes$)
rho = randombytes($kappa_bytes$)
ct = r5_cpa_pke_encrypt(pk, m, rho)
k = HCPAKEM($m, kappa_bytes, ct, \lceil m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8\rceil$)
return (ct, k)

Algorithm 28: r5_cpa_kem_decapsulate

input: ct : $(\lceil m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8\rceil$ byte string.
input: sk : $kappa_bytes$ byte string.
output: k : $kappa_bytes$ byte string.

m = r5_cpa_pke_decrypt(sk, ct)
k = HCPAKEM($m, kappa_bytes, ct, \lceil m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8\rceil$)
return k

2.11.9 Implementation of r5_cca_kem

Round5 relies on an INDCCA KEM specified in Algorithms 7, 8, and 9. They are described from an implementation perspective in Algorithms 29, 30, and 31. Note that functions HCCAKEM() and GCCAKEM() also include the lengths of its input parameters.

Algorithm 29: r5_cca_kem_keygen

output: $pk : \lceil kappa_bytes + n_bar \cdot d/n \cdot n \cdot p_bits/8 \rceil$ byte string.
: $sk = sk_cpa_pke||y||pk : \lceil 3 \cdot kappa_bytes + n_bar \cdot d/n \cdot n \cdot p_bits/8 \rceil$ byte string.

1 $(pk, sk_cpa_pke) =$ r5_cpa_pke_keygen
2 $y =$ randombytes$(kappa_bytes)$
3 $sk = sk_cpa_pke||y||pk$
4 **return** (pk, sk)

Algorithm 30: r5_cca_kem_encapsulate

input: $pk : \lceil 3 \cdot kappa_bytes + (n_bar \cdot d/n \cdot n \cdot p_bits)/8 \rceil$ byte string.
output: $ct : \lceil kappa_bytes + (m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8 \rceil$ byte string.
output: $k : kappa_bytes$ byte string.

1 $m =$ randombytes$(kappa_bytes)$
2 $L||g||rho =$ GCCAKEM$(m, kappa_bytes, pk, \lceil kappa_bytes + (n_bar \cdot d/n \cdot n \cdot p_bits)/8 \rceil)$
3 $(\boldsymbol{U_T}, \boldsymbol{v}) =$ r5_cpa_pke_encrypt(pk, m, rho)
4 $ct = \boldsymbol{U_T}||\boldsymbol{v}||g$
5 $k =$ HCCAKEM$(L, kappa_bytes, ct, kappa_bytes + \lceil m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8 \rceil)$
6 **return** ct, k

Algorithm 31: r5_cca_kem_decapsulate

input: $ct : \lceil kappa_bytes + (m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8 \rceil$ byte string.
input: $sk = sk_cpa_pke||y||pk : \lceil 3 \cdot kappa_bytes + n_bar \cdot d/n \cdot n \cdot p_bits/8 \rceil$ byte string.
output: $k : kappa_bytes$ byte string.

1 $m' =$ r5_cpa_pke_decrypt(sk_cpa_pke, ct)
2 $L_prime||g_prime||rho_prime =$ GCCAKEM$(m', kappa_bytes, pk, \lceil kappa_bytes + (n_bar \cdot d/n \cdot n \cdot p_bits)/8 \rceil)$
3 $(\boldsymbol{U_T_prime}, \boldsymbol{v_prime}) =$ r5_cpa_pke_encrypt(pk, m_prime, rho_prime)
4 $ct_prime = \boldsymbol{U_T_prime}||\boldsymbol{v_prime}||g_prime$
5 $fail =$ verify$(ct, ct_prime, \lceil kappa_bytes + (m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8 \rceil)$
6 conditional_constant_time_memcpy$(L_prime, y, kappa_bytes, fail)$
7 $k =$ HCCAKEM$(L_prime, kappa_bytes, ct_prime, kappa_bytes + \lceil m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8 \rceil)$
8 **return** k

2.11.10 Implementation of r5_cca_pke

Round5 relies on an INDCCA PKE specified in Algorithms 10, 11, and 12. They are described from an implementation perspective in Algorithms 32, 33, and 34. These algorithms rely on r5_dem() and r5_dem_inverse() algorithms that in Round5 are implemented by means of AES in GCM mode according to FIPS 197 and SP 800-38D. AES in GCM mode requires both a key and an initialization vector that are derived by means of HR5DEM() from k. This functionality is included in r5_dem() and r5_dem_inverse().

Algorithm 32: r5_cca_pke_keygen

output: $pk : \lceil kappa_bytes + n_bar \cdot d/n \cdot n \cdot p_bits/8 \rceil$ byte string.
: $sk : \lceil 3 \cdot kappa_bytes + n_bar \cdot d/n \cdot n \cdot p_bits/8 \rceil$ byte string.

1 $(pk, sk) =$ r5_cca_kem_keygen()
2 **return** (pk, sk)

Algorithm 33: r5_cca_pke_encrypt

input: $m : m_len$ byte string containing the message to be encrypted.
input: m_len: message length, integer smaller than 2^{64}
input: $pk : \lceil 3 \cdot kappa_bytes + (n_bar \cdot d/n \cdot n \cdot p_bits)/8 \rceil$ byte string.
output: $ct = c1||c2 :$
$\lceil kappa_bytes + (m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8 \rceil + c2_len$ byte string.
output: $clen$: ciphertext length, integer smaller than 2^{64}

1 $(c1, k) =$ r5_cca_kem_encapsulate(pk)
2 $(c2, c2_len) =$ r5_dem$(k, kappa_bytes, m, m_len)$
3 $ct = c1||c2$
4 $clen = \lceil kappa_bytes + (m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8 \rceil + c2_len$
5 **return** $(ct, clen)$

Algorithm 34: r5_cca_pke_decrypt

input: $ct = c1||c2 : \lceil kappa_bytes + (m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8 \rceil + c2_len$ byte string encoding the ciphertext.
input: $clen$: ciphertext length, integer smaller than 2^{64}
input: $sk : \lceil 3 \cdot kappa_bytes + n_bar \cdot d/n \cdot n \cdot p_bits/8 \rceil$ byte string.
output: $m : m_len$ byte string containing the decrypted message.
output: m_len: message length, integer smaller than 2^{64}

1 $c2_len = clen - \lceil kappa_bytes + (m_bar \cdot d/n \cdot n \cdot p_bits + mu \cdot t_bits)/8 \rceil$
2 $k =$ r5_cca_kem_decapsulate$(c1, sk)$
3 $(m, m_len) =$ r5_dem_inverse$(k, kappa_bytes, c2, c2_len)$
4 **return** (m, m_len)

3 Description of contents in digital media

The contents of the digital media is structured as follows. In the root directory the following files and directories can be found:

`README` A file listing the content of the media.

`Supporting_Documentation` Directory with the documentation of our submission.

`Reference_Implementation` Directory with the source code for the reference implementation of our submission.

`Optimized_Implementation` Directory with the source code for the optimized (fixed parameters) implementation of our submission.

`Additional_Implementations` Directory with the source code for additional implementations.

`KAT` Directory with the KAT files.

The contents of each directory is detailed below.

3.1 Supporting documentation

The `Supporting_Documentation` directory contains the documentation of our submission in PDF form.

`Round5_Submission.pdf` The main submission document.

`Speedtest` Directory with the source files for the application with which we performed our performance measurements (see `speedTest/README` for information).

`Correctness` Directory with source code for analyzing the correctness of parameter sets (see the `README` in this directory for information).

`Parameters` Directory with a script for summarizing the parameter sets (see the `README` in this directory for information).

3.2 Reference, and Optimized implementations

For the reference (found inside directory `Reference_Implementation`), configurable (found inside directory `Configurable_Implementation`), and optimized (found inside directory `Optimized_Implementation`) implementations, the subdirectories `kem` and `encrypt` contain the implementations of our KEM and PKE algorithms, respectively.

Inside those subdirectories a further directory level can be found for each of the algorithm variants and NIST levels. The naming convention for these subdirectories is as shown in the following table:

`R5`	Fixed text
`ND`, or `N1`	To indicate a ring (`ND`), or non-ring (`N1`) variant
_	Fixed text
level	To indicate the NIST level (1, 3, or 5) or 0 for no NIST level.
`KEM` or `PKE`	The type of the algorithm
_	Fixed text
xef	The number of bit-errors to be corrected.
version	Version identifier, `d` for the standard parameters, extttiot for iot parameter sets, etc.

Inside the directories with the variant, you can find the complete source code of that variant:

`Makefile` A makefile with which the KAT generation executable can be created.

`PQCgetKAT_*.c` The NIST source code for the generation of KATs for the variant.

`api.h` The API functions and settings in use for the variant.

`*.h` and `*.c` The header and source code files of our submission.

In table 19 we have listed all submitted KEM and PKE variants.

3.3 Additional implementations

The directory `Additional_Implementations` contains additional implementations of our submission.

`AVX2` Directory with the source code for an AVX2 optimized implementation. This version also has cache attack countermeasures enabled.

`Configurable` Directory with the source code for an optimized, but configurable at runtime, implementation.

3.4 KAT files

The files with the Known Answer Test values can be found in the `KAT` directory. Underneath that directory, the KAT files can be found in subdirectories using the same structure as the implementations.

For instance the KAT files for the "R5N1_3PKE_0d" variant can be found in directory `KAT/encrypt/R5N1_3PKE_0d`.

Inside the KAT file directory, the KAT files can be found named according to the NIST specification, including the number of bytes of the secret key as part of the name and the use of the suffixes `.req`, `.int`, and `.rsp` to denote the request, intermediate output, and response files respectively.

We have provided KAT files for all submitted algorithm variants.

Table 19: Submitted algorithm variants

KEM	**PKE**
R5ND_1KEM_0d	R5ND_1PKE_0d
R5ND_1KEM_5d	R5ND_1PKE_5d
R5ND_3KEM_0d	R5ND_3PKE_0d
R5ND_3KEM_5d	R5ND_3PKE_5d
R5ND_5KEM_0d	R5ND_5PKE_0d
R5ND_5KEM_5d	R5ND_5PKE_5d
R5ND_0KEM_2iot	R5N1_1PKE_0d
R5ND_1KEM_4longkey	R5N1_3PKE_0d
R5N1_1KEM_0d	R5N1_5PKE_0d
R5N1_3KEM_0d	R5N1_3PKE_0smallCT
R5N1_5KEM_0d	

4 IPR Statements

2.D.1 Statement by Each Submitter

I, Hayo Baan, High Tech Campus 5, 5656 AE Eindhoven, The Netherlands, do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5 (formerly Round2 and Hila5), is my own original work, or if submitted jointly with others, is the original work of the joint submitters.

I further declare that (check one):

- ☐ *I do not hold and do not intend to hold any patent or patent application with a claim which may cover the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5;* ***OR*** *(check one or both of the following):*

  - ☐ *to the best of my knowledge, the practice of the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5, may be covered by the following U.S. and/or foreign patents: _____ (describe and enumerate or state "none" if applicable)_____ ;*

  - ■ *I do hereby declare that, to the best of my knowledge, the following pending U.S. and/or foreign patent applications may cover the practice of my submitted cryptosystem, reference implementation or optimized implementations: EP17156214, EP17170508, EP17159296, EP17196812, EP17196926, EP18194118.*

I do hereby acknowledge and agree that my submitted cryptosystem will be provided to the public for review and will be evaluated by NIST, and that it might not be selected for standardization by NIST. I further acknowledge that I will not receive financial or other compensation from the U.S. Government for my submission. I certify that, to the best of my knowledge, I have fully disclosed all patents and patent applications which may cover my cryptosystem, reference implementation or optimized implementations. I also acknowledge and agree that the U.S. Government may, during the public review and the evaluation process, and, if my submitted cryptosystem is selected for standardization, during the lifetime of the standard, modify my submitted cryptosystem's specifications (e.g., to protect against a newly discovered vulnerability).

I acknowledge that NIST will announce any selected cryptosystem(s) and proceed to publish the draft standards for public comment

I do hereby agree to provide the statements required by Sections 2.D.2 and 2.D.3 in the Call For Proposals for any patent or patent application identified to cover the practice of my cryptosystem, reference implementation or optimized implementations and the right to use such implementations for the purposes of the public review and evaluation process.

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consideration by all submitter(s) and owner(s), I understand that rights granted and assurances made under Sections 2.D.1, 2.D.2 and 2.D.3 of the Call For Proposals, including use rights of the reference and optimized implementations, may be withdrawn by the submitter(s) and owner(s), as appropriate.

Signed: Hayo Baan
Title: Software Developer
Date: 5 March 2019
Place: Eindhoven, The Netherlands

2.D.1 Statement by Each Submitter

I, Sauvik Bhattacharya, of High Tech Campus 34, 5656AE Eindhoven, the Netherlands, do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5 (formerly Round2 and Hila5), is my own original work, or if submitted jointly with others, is the original work of the joint submitters.

I further declare that (check one):

> *I do not hold and do not intend to hold any patent or patent application with a claim which may cover the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5;* ***OR*** *(check one or both of the following):*
>
> > *to the best of my knowledge, the practice of the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5, may be covered by the following U.S. and/or foreign patents: _____ (describe and enumerate or state "none" if applicable)_____ ;*
>
> ■ *I do hereby declare that, to the best of my knowledge, the following pending U.S. and/or foreign patent applications may cover the practice of my submitted cryptosystem, reference implementation or optimized implementations: EP17156214, EP17170508, EP17159296, EP17196812, EP17196926, EP18194118.*

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Signed: Sauvik Bhattacharya
Title: Scientist
Date: 4 March 2019
Place: Eindhoven, the Netherlands

2.D.1 Statement by Each Submitter

*I, **Jung Hee Cheon**, of **1, Gwanak-ro, Gwanak-gu, Seoul, Republic of Korea, 08826**, do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5 (formerly Round2 and Hila5), is my own original work, or if submitted jointly with others, is the original work of the joint submitters.*

I further declare that (check one):

- ☐ *I do not hold and do not intend to hold any patent or patent application with a claim which may cover the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5;* ***OR*** *(check one or both of the following):*

  - ■ *to the best of my knowledge, the practice of the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5, may be covered by the following U.S. and/or foreign patents: KR101905689B1;*

  - ■ *I do hereby declare that, to the best of my knowledge, the following pending U.S. and/or foreign patent applications may cover the practice of my submitted cryptosystem, reference implementation or optimized implementations: EP17156214, EP17170508, EP17159296, EP17196812, EP17196926, EP18194118, US16/462091.*

I do hereby acknowledge and agree that my submitted cryptosystem will be provided to the public for review and will be evaluated by NIST, and that it might not be selected for standardization by NIST. I further acknowledge that I will not receive financial or other compensation from the U.S. Government for my submission. I certify that, to the best of my knowledge, I have fully disclosed all patents and patent applications which may cover my cryptosystem, reference implementation or optimized implementations. I also acknowledge and agree that the U.S. Government may, during the public review and the evaluation process, and, if my submitted cryptosystem is selected for standardization, during the lifetime of the standard, modify my submitted cryptosystem's specifications (e.g., to protect against a newly discovered vulnerability).

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Signed: Jung Hee Cheon
Title: Professor
Date: Jan 08, 2020
Place: Seoul National University

2.D.1 Statement by Each Submitter

I, Scott Fluhrer, 31 Massand Rd, North Attleborough, MA, USA, do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5 (formerly Round2 and Hila5), is my own original work, or if submitted jointly with others, is the original work of the joint submitters.

I further declare that (check one):

- ☐ *I do not hold and do not intend to hold any patent or patent application with a claim which may cover the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5;* ***OR*** *(check one or both of the following):*

  - ☐ *to the best of my knowledge, the practice of the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5, may be covered by the following U.S. and/or foreign patents: _____ (describe and enumerate or state "none" if applicable)_____ ;*

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Signed: [redacted]
Title: Principal Engineer
Date: [redacted] 3/11/19
Place: North Attleboro, MA, 02760

2.D.1 Statement by Each Submitter

I, Oscar Garcia-Morchon, High Tech Campus 5, 5656 AE Eindhoven, The Netherlands, do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5 (formerly Round2 and Hila5), is my own original work, or if submitted jointly with others, is the original work of the joint submitters.

I further declare that (check one):

- ☐ *I do not hold and do not intend to hold any patent or patent application with a claim which may cover the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as ____ (print name of cryptosystem)____;* ***OR*** *(check one or both of the following):*

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Signed: Oscar Garcia-Morchon
Title: Senior Cryptography Architect
Date: March 12, 2019
Place: Eindhoven, The Netherlands

2.D.1 Statement by Each Submitter

I, Thijs Laarhoven, Eindhoven University of Technology, The Netherlands, do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5 (formerly Round2 and Hila5), is my own original work, or if submitted jointly with others, is the original work of the joint submitters.

I further declare that (check one):

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Signed: Thijs Laarhoven
Title: dr.ir.
Date: March 4th, 2019
Place: Eindhoven

TLaarhoven

2.D.1 Statement by Each Submitter

I, Rachel Player, Information Security Group, McCrea Buidling, Royal Holloway, University of London, Egham Hill, Egham, Surrey, TW20 0EX, UK, do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5 (formerly Round2 and Hila5), is my own original work, or if submitted jointly with others, is the original work of the joint submitters.

I further declare that (check one):

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made under Sections 2.D.1, 2.D.2 and 2.D.3 of the Call For Proposals, including use rights of the reference and optimized implementations, may be withdrawn by the submitter(s) and owner(s), as appropriate.

Signed: Dr. Rachel Player
Title: Postdoctoral Researcher
Date: 4 March 2019
Place: Egham, UK

R. Player

2.D.1 Statement by Each Submitter

I, Ronald Rietman, Philips Research, High Tech Campus 34, 5656AE Eindhoven, The Netherlands, do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5 (formerly Round2 and Hila5), is my own original work, or if submitted jointly with others, is the original work of the joint submitters.

I further declare that (check one):

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> > *to the best of my knowledge, the practice of the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5, may be covered by the following U.S. and/or foreign patents: _____ (describe and enumerate or state "none" if applicable)_____ ;*
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Signed: Ronald Rietman
Title: Senior scientist
Date: 2019-3-4
Place: Eindhoven

2.D.1 Statement by Each Submitter

I, Markku-Juhani Olavi Saarinen, PQShield Ltd., Prama House, 267 Banbury Road, Oxford OX2 7HQ,United Kingdom, do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5 (formerly Round2 and Hila5), is my own original work, or if submitted jointly with others, is the original work of the joint submitters.

I further declare that (check one):

- ☐ *I do not hold and do not intend to hold any patent or patent application with a claim which may cover the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5;* ***OR*** *(check one or both of the following):*

  - ☐ *to the best of my knowledge, the practice of the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5, may be covered by the following U.S. and/or foreign patents: _____ (describe and enumerate or state "none" if applicable)_____ ;*

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1/2

cryptosystem) is removed from consideration for standardization or withdrawn from consideration by all submitter(s) and owner(s), I understand that rights granted and assurances made under Sections 2.D.1, 2.D.2 and 2.D.3 of the Call For Proposals, including use rights of the reference and optimized implementations, may be withdrawn by the submitter(s) and owner(s), as appropriate.

Signed: Markku-Juhani O. Saarinen

Title: Senior Cryptography Engineer

Date: March 5, 2019

Place: OXFORD, UK

2.D.1 Statement by Each Submitter

*I, **Yongha Son**, of **1, Gwanak-ro, Gwanak-gu, Seoul, Republic of Korea, 08826**, do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5 (formerly Round2 and Hila5), is my own original work, or if submitted jointly with others, is the original work of the joint submitters.*

I further declare that (check one):

- ☐ *I do not hold and do not intend to hold any patent or patent application with a claim which may cover the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5;* ***OR*** *(check one or both of the following):*

  - ■ *to the best of my knowledge, the practice of the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5, may be covered by the following U.S. and/or foreign patents: KR101905689B1;*

  - ■ *I do hereby declare that, to the best of my knowledge, the following pending U.S. and/or foreign patent applications may cover the practice of my submitted cryptosystem, reference implementation or optimized implementations: EP17156214, EP17170508, EP17159296, EP17196812, EP17196926, EP18194118, US16/462091.*

I do hereby acknowledge and agree that my submitted cryptosystem will be provided to the public for review and will be evaluated by NIST, and that it might not be selected for standardization by NIST. I further acknowledge that I will not receive financial or other compensation from the U.S. Government for my submission. I certify that, to the best of my knowledge, I have fully disclosed all patents and patent applications which may cover my cryptosystem, reference implementation or optimized implementations. I also acknowledge and agree that the U.S. Government may, during the public review and the evaluation process, and, if my submitted cryptosystem is selected for standardization, during the lifetime of the standard, modify my submitted cryptosystem's specifications (e.g., to protect against a newly discovered vulnerability).

I acknowledge that NIST will announce any selected cryptosystem(s) and proceed to publish the draft standards for public comment

I do hereby agree to provide the statements required by Sections 2.D.2 and 2.D.3 in the Call For Proposals for any patent or patent application identified to cover the practice of my cryptosystem, reference implementation or optimized implementations and the right to use such implementations for the purposes of the public review and evaluation process.

I acknowledge that, during the post-quantum algorithm evaluation process, NIST may remove my cryptosystem from consideration for standardization. If my cryptosystem (or the derived cryptosystem) is removed from consideration for standardization or withdrawn from

consideration by all submitter(s) and owner(s), I understand that rights granted and assurances made under Sections 2.D.1, 2.D.2 and 2.D.3 of the Call For Proposals, including use rights of the reference and optimized implementations, may be withdrawn by the submitter(s) and owner(s), as appropriate.

Signed: Yongha Son
Title: Professor
Date: Jan 08, 2020
Place: Seoul National University

2.D.1 Statement by Each Submitter

I, Ludo Tolhuizen, High Tech Campus 34, 5656 AE Eindhoven, The Netherlands, do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5 (formerly Round2 and Hila5), is my own original work, or if submitted jointly with others, is the original work of the joint submitters.

I further declare that (check one):

> *I do not hold and do not intend to hold any patent or patent application with a claim which may cover the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5;* ***OR*** *(check one or both of the following):*
>
> > *to the best of my knowledge, the practice of the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5, may be covered by the following U.S. and/or foreign patents: _____ (describe and enumerate or state "none" if applicable)_____ ;*
>
> ■ *I do hereby declare that, to the best of my knowledge, the following pending U.S. and/or foreign patent applications may cover the practice of my submitted cryptosystem, reference implementation or optimized implementations: EP17156214, EP17170508, EP17159296, EP17196812, EP17196926, EP18194118.*

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L. Tolhuizen

Signed: Ludo Tolhuizen
Title: Senior Scientist
Date: March 4, 2019
Place: Eindhoven, The Netherlands

2.D.1 Statement by Each Submitter

I, Mr. JOSÉ LUIS TORRE ARCE, address Avenida BILBAO, nº 9, C.P. 39600 Muriedas (Spain), do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5 (formerly Round2 and Hila5), is my own original work, or if submitted jointly with others, is the original work of the joint submitters.

I further declare that (check one):

- ☐ *I do not hold and do not intend to hold any patent or patent application with a claim which may cover the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as ____ (print name of cryptosystem)____;* ***OR*** *(check one or both of the following):*

  - ☐ *to the best of my knowledge, the practice of the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as ____ (print name of cryptosystem)____, may be covered by the following U.S. and/or foreign patents: _____ (describe and enumerate or state "none" if applicable)_____ ;*

  - ■ *I do hereby declare that, to the best of my knowledge, the following pending U.S. and/or foreign patent applications may cover the practice of my submitted cryptosystem, reference implementation or optimized implementations: EP17156214, EP17170508, EP17159296, EP17196812, EP17196926, EP18194118.*

I do hereby acknowledge and agree that my submitted cryptosystem will be provided to the public for review and will be evaluated by NIST, and that it might not be selected for standardization by NIST. I further acknowledge that I will not receive financial or other compensation from the U.S. Government for my submission. I certify that, to the best of my knowledge, I have fully disclosed all patents and patent applications which may cover my cryptosystem, reference implementation or optimized implementations. I also acknowledge and agree that the U.S. Government may, during the public review and the evaluation process, and, if my submitted cryptosystem is selected for standardization, during the lifetime of the standard, modify my submitted cryptosystem's specifications (e.g., to protect against a newly discovered vulnerability).

I acknowledge that NIST will announce any selected cryptosystem(s) and proceed to publish the draft standards for public comment

I do hereby agree to provide the statements required by Sections 2.D.2 and 2.D.3 in the Call For Proposals for any patent or patent application identified to cover the practice of my cryptosystem, reference implementation or optimized implementations and the right to use such implementations for the purposes of the public review and evaluation process.

I acknowledge that, during the post-quantum algorithm evaluation process, NIST may remove my cryptosystem from consideration for standardization. If my cryptosystem (or the derived

cryptosystem) is removed from consideration for standardization or withdrawn from consideration by all submitter(s) and owner(s), I understand that rights granted and assurances made under Sections 2.D.1, 2.D.2 and 2.D.3 of the Call For Proposals, including use rights of the reference and optimized implementations, may be withdrawn by the submitter(s) and owner(s), as appropriate.

Signed: NAME...JOSÉ LUIS TORRE ARCE
Title: TITLE.....Mr.
Date: DATE.....2019.03.08
Place: PLACE...Santander

2.D.1 Statement by Each Submitter

I, Zhenfei Zhang, 888 Boylston St. Boston, MA, U.S., do hereby declare that the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5 (formerly Round2 and Hila5), is my own original work, or if submitted jointly with others, is the original work of the joint submitters.

I further declare that (check one):

- *I do not hold and do not intend to hold any patent or patent application with a claim which may cover the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5;* ***OR*** *(check one or both of the following):*

  - *to the best of my knowledge, the practice of the cryptosystem, reference implementation, or optimized implementations that I have submitted, known as Round5, may be covered by the following U.S. and/or foreign patents: _____ (describe and enumerate or state "none" if applicable)_____ ;*

  - *I do hereby declare that, to the best of my knowledge, the following pending U.S. and/or foreign patent applications may cover the practice of my submitted cryptosystem, reference implementation or optimized implementations: EP17156214, EP17170508, EP17159296, EP17196812, EP17196926, EP18194118.*

I do hereby acknowledge and agree that my submitted cryptosystem will be provided to the public for review and will be evaluated by NIST, and that it might not be selected for standardization by NIST. I further acknowledge that I will not receive financial or other compensation from the U.S. Government for my submission. I certify that, to the best of my knowledge, I have fully disclosed all patents and patent applications which may cover my cryptosystem, reference implementation or optimized implementations. I also acknowledge and agree that the U.S. Government may, during the public review and the evaluation process, and, if my submitted cryptosystem is selected for standardization, during the lifetime of the standard, modify my submitted cryptosystem's specifications (e.g., to protect against a newly discovered vulnerability).

I acknowledge that NIST will announce any selected cryptosystem(s) and proceed to publish the draft standards for public comment

I do hereby agree to provide the statements required by Sections 2.D.2 and 2.D.3 in the Call For Proposals for any patent or patent application identified to cover the practice of my cryptosystem, reference implementation or optimized implementations and the right to use such

implementations for the purposes of the public review and evaluation process.

I acknowledge that, during the post-quantum algorithm evaluation process, NIST may remove my cryptosystem from consideration for standardization. If my cryptosystem (or the derived cryptosystem) is removed from consideration for standardization or withdrawn from consideration by all submitter(s) and owner(s), I understand that rights granted and assurances made under Sections 2.D.1, 2.D.2 and 2.D.3 of the Call For Proposals, including use rights of the reference and optimized implementations, may be withdrawn by the submitter(s) and owner(s), as appropriate.

3/11/2019

Signed: Zhenfei Zhang
Title: Cryptography engineer
Date: March 11, 2019
Place: 888 Boylston st. Boston, MA

2.D.2 Statement by Patent (and Patent Application) Owner(s)

If there are any patents (or patent applications) identified by the submitter, including those held by the submitter, the following statement must be signed by each and every owner, or each owner's authorized representative, of each patent and patent application identified.

I, ***Jung Hee Cheon****, of 1,* ***Gwanak-ro, Gwanak-gu, Seoul, Republic of Korea, 08826****, am the owner or authorized representative of the owner (print full name, if different than the signer) of the following patent(s) and/or patent application(s):* ***KR101905689B1, US16/462091****, and do hereby commit and agree to grant to any interested party on a worldwide basis, if the cryptosystem known as* ***Round5 (formerly Round2 and Hila5)*** *is selected for standardization, in consideration of its evaluation and selection by NIST, a non-exclusive license for the purpose of implementing the standard (check one):*

- ☑ *without compensation and under reasonable terms and conditions that are demonstrably free of any unfair discrimination,* **OR**
- ☐ *under reasonable terms and conditions that are demonstrably free of any unfair discrimination.*

I further do hereby commit and agree to license such party on the same basis with respect to any other patent application or patent hereafter granted to me, or owned or controlled by me, that is or may be necessary for the purpose of implementing the standard.

I further do hereby commit and agree that I will include, in any documents transferring ownership of each patent and patent application, provisions to ensure that the commitments and assurances made by me are binding on the transferee and any future transferee.

I further do hereby commit and agree that these commitments and assurances are intended by me to be binding on successors-in-interest of each patent and patent application, regardless of whether such provisions are included in the relevant transfer documents.

I further do hereby grant to the U.S. Government, during the public review and the evaluation process, and during the lifetime of the standard, a nonexclusive, nontransferrable, irrevocable, paid-up worldwide license solely for the purpose of modifying my submitted cryptosystem's specifications (e.g., to protect against a newly discovered vulnerability) for incorporation into the standard.

Signed: Jung Hee Cheon
Title: Professor
Date: Jan 9, 2020
Place: Seoul

2.D.2 Statement by Patent (and Patent Application) Owner(s)

If there are any patents (or patent applications) identified by the submitter, including those held by the submitter, the following statement must be signed by each and every owner, or each owner's authorized representative, of each patent and patent application identified.

I, ***Joohee Lee****, of 1,* ***Gwanak-ro, Gwanak-gu, Seoul, Republic of Korea, 08826****, am the owner or authorized representative of the owner (print full name, if different than the signer) of the following patent(s) and/or patent application(s):* ***KR101905689B1, US16/462091****, and do hereby commit and agree to grant to any interested party on a worldwide basis, if the cryptosystem known as* ***Round5 (formerly Round2 and Hila5)*** *is selected for standardization, in consideration of its evaluation and selection by NIST, a non-exclusive license for the purpose of implementing the standard (check one):*

- ☑ *without compensation and under reasonable terms and conditions that are demonstrably free of any unfair discrimination,* **OR**
- ☐ *under reasonable terms and conditions that are demonstrably free of any unfair discrimination.*

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I further do hereby grant to the U.S. Government, during the public review and the evaluation process, and during the lifetime of the standard, a nonexclusive, nontransferrable, irrevocable, paid-up worldwide license solely for the purpose of modifying my submitted cryptosystem's specifications (e.g., to protect against a newly discovered vulnerability) for incorporation into the standard.

Signed: Joohee Lee
Title: Ms.
Date: Jan. 9 / 2020
Place: Seoul National University

2.D.2 Statement by Patent (and Patent Application) Owner(s)

If there are any patents (or patent applications) identified by the submitter, including those held by the submitter, the following statement must be signed by each and every owner, or each owner's authorized representative, of each patent and patent application identified.

I, Jako Eleveld , of High Tech Campus 5, 5656 AE Eindhoven, The Netherlands, am the owner or authorized representative of the owner Koninklijke Philips N.V. of the following patent(s) and/or patent application(s): EP17156214, EP17170508, EP17159296, EP17196812, EP17196926, EP18194118 and do hereby commit and agree to grant to any interested party on a worldwide basis, if the cryptosystem known as Round5 (formerly Round2 and Hila5) is selected for standardization, in consideration of its evaluation and selection by NIST, a non-exclusive license for the purpose of implementing the standard (check one):

> ~~*without compensation and under reasonable terms and conditions that are demonstrably free of any unfair discrimination,*~~ **OR**
>
> ■ *under reasonable terms and conditions that are demonstrably free of any unfair discrimination.*

I further do hereby commit and agree to license such party on the same basis with respect to any other patent application or patent hereafter granted to me, or owned or controlled by me, that is or may be necessary for the purpose of implementing the standard.

I further do hereby commit and agree that I will include, in any documents transferring ownership of each patent and patent application, provisions to ensure that the commitments and assurances made by me are binding on the transferee and any future transferee.

I further do hereby commit and agree that these commitments and assurances are intended by me to be binding on successors-in-interest of each patent and patent application, regardless of whether such provisions are included in the relevant transfer documents.

I further do hereby grant to the U.S. Government, during the public review and the evaluation process, and during the lifetime of the standard, a nonexclusive, nontransferrable, irrevocable, paid-up worldwide license solely for the purpose of modifying my submitted cryptosystem's specifications (e.g., to protect against a newly discovered vulnerability) for incorporation into the standard.

Signed: Jako Eleveld
Title: Head of IP Licensing
Date: 27 FEB 2019
Place: Eindhoven, The Netherlands

2.D.3 Statement by Reference/Optimized Implementations' Owner(s)

The following must also be included:

I, Ali El Kaafarani, of Prama House, 267 Banbury Rd, Oxford OX2 7HQ, UK, am the owner or authorized representative of the owner PQShield Ltd. of the submitted reference implementation and optimized implementations and hereby grant the U.S. Government and any interested party the right to reproduce, prepare derivative works based upon, distribute copies of, and display such implementations for the purposes of the post-quantum algorithm public review and evaluation process, and implementation if the corresponding cryptosystem is selected for standardization and as a standard, notwithstanding that the implementations may be copyrighted or copyrightable.

Signed: Ali El Kaafarani
Title: CEO of PQShield.
Date: 04/03/2019
Place: OXFORD, UK.

2.D.3 Statement by Reference/Optimized Implementations' Owner(s)

The following must also be included:

I, Jako Eleveld , High Tech Campus 5, 5656 AE Eindhoven, The Netherlands, am the owner or authorized representative of the owner Koninklijke Philips N.V. of the submitted reference implementation and optimized implementations and hereby grant the U.S. Government and any interested party the right to reproduce, prepare derivative works based upon, distribute copies of, and display such implementations for the purposes of the post-quantum algorithm public review and evaluation process, and implementation if the corresponding cryptosystem is selected for standardization and as a standard, notwithstanding that the implementations may be copyrighted or copyrightable.

Signed: Jako Eleveld
Title: Head of IP Licensing
Date: 27 FEB 2019
Place: Eindhoven, The Netherlands

A Formal security of Round5

This appendix contains details on the formal security analysis of Round5.

The appendix is organized as follows: Section A.1 introduces notions of security based on indistinguishability of ciphertexts or encapsulated keys. Section A.2 gives results (existing and new) on the hardness of our underlying problem, or rather its two specific instances we use – the Learning with Rounding problem with sparse ternary secrets ($\texttt{LWR}_{\text{spt}}$) and the Ring Learning with Rounding problem with sparse ternary secrets ($\texttt{RLWR}_{\text{spt}}$).

In Section A.3 it is shown that r5_cpa_pke is IND-CPA secure under the assumption of the hardness of (Ring) Learning with Rounding, assuming that the function $\boldsymbol{f}_{d,n}^{(\tau)}$ can be modeled as a random oracle, and that f_S and f_R can be modeled as pseudo-random functions. The analysis applies for LWR and for RLWR with equal reduction polynomials. In Section A.4 the security of an LWE-variant of Round5 with different polynomials is analyzed. Sections A.5 and A.6 contain the first main result of this section – a ROM proof of IND-CPA security for r5_cpa_kem (Theorem A.5.2), and a ROM proof of IND-CCA security of r5_cca_pke (Theorems A.6.1 and A.6.2), assuming the hardness of the above problems. Finally, Section A.7 and Theorem A.7.1 contain the second main result of this reduction: a proof of the hardness for $\texttt{LWR}_{\text{spt}}$, the underlying problem of our schemes for the non-ring case (i.e., for $n = 1$) in the form of a polynomial-time reduction to it from the Learning with Errors (LWE) problem with secrets uniformly chosen from $\mathbb{Z}_q^d$ and errors drawn according to a Gaussian distribution.

A.1 Security Definitions

Security requirements for public-key encryption and key-encapsulation schemes are based on whether static or ephemeral keys are used. (Static) public-key encryption (PKE) schemes, and nominally ephemeral key-encapsulation mechanisms that allow key caching that provide security against adaptive chosen ciphertext attack (corresponding to IND-CCA2 security) are considered to be sufficiently secure [84, Section 4.A.2]. On the other hand, a purely ephemeral key encapsulation mechanism (KEM) that provides semantic security against chosen plaintext attack, i.e., IND-CPA security, is considered to be sufficiently secure [84, Section 4.A.3].

Definition A.1.1 (Distinguishing advantage)**.** *Let $\mathcal{A}$ be a randomized algorithm that takes as input elements from a set X with output in $\{0,1\}$. Let D_1 and D_2 two probability distributions on X. The advantage of $\mathcal{A}$ for distinguishing between D_1 and D_2, denoted by $Adv_{D_1,D_2}(\mathcal{A})$, is defined as*

$$Adv_{D_1,D_2}(\mathcal{A}) = |Pr[\mathcal{A}(x) = 1 \mid x \leftarrow D_1] - Pr[\mathcal{A}(x) = 1 \mid x \leftarrow D_2]\,|$$

Table 20: IND-CPA game for PKE

1. $(pk, sk) = \texttt{KeyGen}(\lambda)$.
2. $b \xleftarrow{\$} \{0, 1\}$
3. $(m_0, m_1, st) = \mathcal{A}(pk)$ such that $|m_0| = |m_1|$.
4. $c = \texttt{Enc}(pk, m_b)$
5. $b' = \mathcal{A}(pk, c, st)$
6. **return** $[b' = b]$

Definition A.1.2 (IND-CPA Secure PKE)**.** *Let PKE=(Keygen, Enc, Dec) be a public key encryption scheme with message space $\mathcal{M}$. Let λ be a security parameter. The IND-CPA game is defined in Table 20, and the IND-CPA advantage of an adversary $\mathcal{A}$ against PKE is defined as*

$$Adv_{PKE}^{IND\text{-}CPA}(\mathcal{A}) \ = \mid Pr[\textsf{IND-CPA}^{\mathcal{A}} \Rightarrow 1] - \frac{1}{2} \mid .$$

Definition A.1.3 (IND-CCA Secure PKE)**.** *Let PKE=(Keygen, Enc, Dec) be a public key encryption scheme with message space $\mathcal{M}$. Let λ be a security parameter. Let $\mathcal{A}$ be an adversary against PKE. The IND-CCA game is defined as Table 20, with the addition that $\mathcal{A}$ has access to a decryption oracle $\texttt{Dec}(\cdot) = \texttt{Dec}(sk, \cdot)$ that returns $m' = \texttt{Dec}(sk, \texttt{Enc}(pk, m'))$, and the restriction that $\mathcal{A}$ cannot query $\texttt{Dec}(\cdot)$ with the challenge c. The IND-CCA advantage of $\mathcal{A}$ against PKE is defined as*

$$Adv_{PKE}^{IND\text{-}CCA}(\mathcal{A}^{\texttt{Dec}(\cdot)}) \ = \mid Pr[\textsf{IND-CCA}^{\mathcal{A}} \Rightarrow 1] - \frac{1}{2} \mid .$$

Table 21: IND-CPA game for KEM

1. $(pk, sk) = \texttt{KeyGen}(\lambda)$.
2. $b \xleftarrow{\$} \{0, 1\}$
3. $(c, K_0) = \texttt{Encaps}(pk)$
4. $K_1 \xleftarrow{\$} \mathcal{K}$
5. $b' = \mathcal{A}(pk, c, K_b)$
6. **return** $[b' = b]$

Definition A.1.4 (IND-CPA Secure KEM)**.** *Let KEM=(Keygen, Encaps, Decaps) be a key encapsulation mechanism with key space $\mathcal{K}$. Let λ be a security parameter. The IND-CPA game is defined in Table 21, and the IND-CPA advantage of an adversary $\mathcal{A}$ against KEM is defined as*

$$Adv_{KEM}^{IND\text{-}CPA}(\mathcal{A}) \ = \mid Pr[\textsf{IND-CPA}^{\mathcal{A}} \Rightarrow 1] - \frac{1}{2} \mid .$$

Definition A.1.5 (IND-CCA Secure KEM)**.** *Let KEM=(Keygen, Encaps, Decaps) be a key encapsulation mechanism with key space $\mathcal{K}$. Let λ be a security parameter. Let $\mathcal{A}$ be an adversary against KEM. The IND-CCA game is defined in Table 21, with the addition that $\mathcal{A}$ has access to a decapsulation oracle $\texttt{Decaps}(\cdot) = \texttt{Decaps}(sk, \cdot)$ that returns $K' = \texttt{Decaps}(sk, c')$ where $(c', K') = \texttt{Encaps}(pk)$, and the restriction that $\mathcal{A}$ cannot query $\texttt{Decaps}(\cdot)$ with the challenge c. The IND-CCA advantage of $\mathcal{A}$ against KEM is defined as*

$$Adv_{KEM}^{IND\text{-}CCA}(\mathcal{A}^{\texttt{Decaps}(\cdot)}) = \mid Pr[\textsf{IND-CCA}^{\mathcal{A}} \Rightarrow 1] - \frac{1}{2} \mid .$$

In the random oracle model [23] (both for IND-CPA and IND-CCA games), the adversary is given access to a random oracle H that it can query up to a polynomial number q_H of times. In a post-quantum setting, it can be assumed that the adversary has access to a quantum accessible random oracle H_Q [27] that can be queried up to q_{H_Q} times on arbitrary superpositions of input strings.

A.2 Hardness Assumption (Underlying Problem)

In this section, we detail the underlying problem on whose hardness the security of our schemes are established. Depending on whether the system parameter n is chosen to be 1 or d (see Section 2.4.3), the proposed public-key encryption and key-encapsulation mechanism are instantiated either as non-ring (LWR) based or ring (RLWR) based schemes. The security of the proposals are therefore based on the hardness of the Decision-General Learning with Rounding problem with sparse-ternary secrets, i.e., $\texttt{dGLWR}_{\text{spt}}$ (see Section 2.3). We first recall hardness results for LWR before introducing our own results on the hardness of $\texttt{dLWR}_{\text{spt}}$. We then recall hardness results of RLWR.

Provable Security in the non-ring case: The hardness of the LWR problem has been studied in [20, 10, 26, 19] and established based on the hardness of the Learning with Errors (LWE) problem [92]. The most recent work are two independent reductions to LWR from LWE: the first, due to Bai et al. [19, Theorem 6.4] preserves the dimension n between the two problems but decreases the number of LWR samples that may be queried by an attacker by a factor (p/q); the second due to Bogdanov et al. [26, Theorem 3] preserves the number of samples between the two problems but increases the LWR dimension by a factor $\log q$. We follow the approach of Bai since it results in a smaller LWR dimension, leading to smaller bandwidth requirements and better performance. We note that the requirements on the number of samples is met, as $\boldsymbol{A}$ is a $d/n \times d/n$ matrix.

Bai et al.'s reduction [19, Theorem 6.4] is an essential component that we use in Section A.7 to prove a reduction from $\texttt{dLWE}_{n,m',q,D_\alpha}(\mathcal{U}(\mathbb{Z}_q))$ to $\texttt{dLWR}_{n,m,q,p}(\mathcal{U}(\mathcal{H}_n(h)))$, i.e., to $\texttt{dLWR}_{\text{spt}}$.

Provable Security in the ring case: Next, we recall hardness results for the ring case, i.e., for Decision-RLWR [20]. To the best of our knowledge, the

only existing result on the hardness of Decision-RLWR is due to [20, Theorem 3.2], who show that Decision-RLWR is at least as hard as Decision-RLWE as long as the underlying ring and secret distribution remain the *same* for the two problems, the RLWE noise is sampled from *any* (balanced) distribution in $\{-B, \ldots, B\}$, and q is super-polynomial in n, i.e., $q \geq pBn^{\omega(1)}$. The last condition may be too restrictive for practical schemes. Hence, although [20, Theorem 3.2] is relevant for the provable (IND) security of our schemes' ring-based instantiations, it remains to be seen whether the above reduction can be improved to be made practical.

A.3 IND-CPA Security of r5_cpa_pke

In this section it is shown that the public-key encryption scheme r5_cpa_pke is IND-CPA secure, based on the hardness of the decision GLWR problem with sparse-ternary secrets (Theorem A.3.2). In Section A.6 this result will be used to show that r5_cca_pke is IND-CCA Secure. The proof is restricted to the case that $\xi(x) = \Phi_{n+1}(x)$. In the proof, we assume that the function $\boldsymbol{f}_{d,n}^{(\tau)}$ can be modeled as a random oracle, and that f_S and f_R can be modeled as pseudo-random functions.

For the purpose of the exposition of the proof, we define the public-key encryption scheme r5*_cpa_pke, which differs from r5_cpa_pke only in the generation of the public matrix $\boldsymbol{A}$: it is generated uniformly, instead of from the seed σ. Both r5*_cpa_pke_keygen and and r5*_cpa_pke_encrypt(pk, m, ρ) thus do not involve σ, but only $\boldsymbol{A}$. Referring to Table 20, we take for `KeyGen` the function r5*_cpa_pke_keygen, and for `Enc` the function r5*_cpa_pke_encrypt(pk, m, ρ) with uniform choice for ρ. That is

$$\rho \xleftarrow{\$} \{0,1\}^{\kappa}; \texttt{Enc}(pk, m) = \text{r5*_cpa_pke_encrypt}(pk, m, \rho).$$

Let n, m, p, q, d, h be positive integers with $n \in \{1, d\}$. The hard problem underlying the security of our schemes is decision-GLWR with sparse-ternary secrets (see Section 2.3). For the above parameters, we define the GLWR oracle $O_{m,\chi_S,\boldsymbol{s}}$ for a secret distribution χ_S that returns m GLWR samples as follows:

$$O_{m,\chi_S,\boldsymbol{s}} : \boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{m \times d/n},\ \boldsymbol{s} \leftarrow \chi_S;\ \text{return}\ (\boldsymbol{A}, \mathrm{R}_{q \to p}(\boldsymbol{A}\boldsymbol{s})) \tag{41}$$

The decision-GLWR problem with sparse-ternary secrets is to distinguish between the distributions $\mathcal{U}(\mathcal{R}_{n,q}^{m \times d/n}) \times \mathcal{U}(\mathcal{R}_{n,p})$ and $O_{m,\chi_S,\boldsymbol{s}}$, with $\boldsymbol{s}$ common to all samples and $\chi_S := \mathcal{U}(\mathcal{H}_{n,d/n}(h))$. For an adversary $\mathcal{A}$, we define

$$\mathrm{Adv}_{d,n,m,q,p}^{\texttt{dGLWR}_{\text{spt}}}(\mathcal{A}) =$$

$$|\Pr\left[\mathcal{A}(\boldsymbol{A}, \boldsymbol{b}) = 1 \mid (\boldsymbol{A}, \boldsymbol{b}) \xleftarrow{\$} O_{m,\chi_S,\boldsymbol{s}}\right] - \Pr\left[\mathcal{A}(\boldsymbol{A}, \boldsymbol{b}) = 1 \mid \boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{m \times d/n}, \boldsymbol{b} \xleftarrow{\$} \mathcal{R}_{n,p}^{m}\right]|$$

For an extended form of the decision-GLWR problem with the secret in form of a matrix consisting of $\overline{n}$ independent secret vectors, we define a similar oracle

$O_{m,\chi_S,\overline{n},\boldsymbol{S}}$ as follows:

$$O_{m,\chi_S,\overline{n},\boldsymbol{S}} : \boldsymbol{A} \xleftarrow{\$} \mathcal{U}\left(\mathcal{R}_{n,q}^{m\times d/n}\right),\ \boldsymbol{S} \leftarrow (\chi_S)^{\overline{n}};\ \text{return}\ (\boldsymbol{A}, \mathrm{R}_{q\to p}(\boldsymbol{AS})) \tag{42}$$

The advantage of an adversary for this extended form of the decision-GLWR problem is defined in a similar manner as above.

The following theorem A.3.1 shows the IND-CPA security of r5*_cpa_pke under the assumption that f_S and f_R are pseudo-random functions, and that the Decision-GLWR problem with sparse-ternary secrets is hard.

Theorem A.3.1. *Let p, q, t be integers such that $t|p|q$, let $z = \max(p, tq/p)$, and let $\xi(x) = \Phi_{n+1}(x)$. For every IND-CPA adversary $\mathcal{A}$, if $Adv^{IND\text{-}CPA}_{CPA\text{-}PKE}(\mathcal{A})$ is the advantage in winning the IND-CPA game for r5*_cpa_pke, then there exist distinguishers $\mathcal{B}, \mathcal{C}, \mathcal{D}, \mathcal{E}$ with essentially equal running times as $\mathcal{A}$ such that*

$$\begin{aligned} Adv^{IND\text{-}CPA}_{CPA\text{-}PKE}(\mathcal{A}) \leq Adv^{\mathtt{PRF}}_{f_S}(\mathcal{B}) + Adv^{\mathtt{PRF}}_{f_R}(\mathcal{C}) + \overline{n} \cdot Adv^{\mathtt{dGLWR}_{spt}}_{d,n,d/n,q,p}(\mathcal{D}) + \\ Adv^{\mathtt{dGLWR}_{spt}}_{d,n,d/n+\overline{n},q,z}(\mathcal{E}) \end{aligned} \tag{43}$$

In this equation, $Adv^{\mathtt{PRF}}_{f_S}(\mathcal{B})$ denotes the advantage of $\mathcal{B}$ for distinguishing between the distribution of $f_S(s)$ with $s \xleftarrow{\$} \{0,1\}^\kappa$, and the uniform distribution of vectors of length $\overline{n}$ with entries from $\mathcal{H}_{n,d/n}(h)$. Similarly, $Adv^{\mathtt{PRF}}_{f_R}(\mathcal{C})$ denotes the denotes the advantage of $\mathcal{C}$ for distinguishing between the distribution of $f_R(r)$ with $r \xleftarrow{\$} \{0,1\}^\kappa$, and the uniform distribution of vectors of length $\overline{m}$ with entries from $\mathcal{H}_{n,d/n}(h)$. Finally, $Adv^{\mathtt{dGLWR}_{spt}}_{d,n,m,q_1,q_2}(\mathcal{Z})$ is the advantage of adversary $\mathcal{Z}$ in distinguishing m GLWR samples (with sparse-ternary secrets) from uniform, with the GLWR problem defined for the parameters d, n, q_1, q_2.

Proof. Theorem A.3.1 is proven via a sequence of IND-CPA games shown in Tables 22 to 25, following the methodology of Peikert et al. in [85, Lemma 4.1] and that of [31, Theorem 3.3]. Steps for combining samples using rounding from q to p and samples using rounding from p to t are due to [46].

Game G_0 is the actual IND-CPA game for the public-key encryption scheme r5*_cpa_pke. For convenience, the steps of r5*_cpa_pke_encrypt(pk, m, ρ) are written out explicitly. Moreover, we write χ_S for the uniform distribution on $\mathcal{H}_{n,d/n}(h)$.

In Game G_1, $\boldsymbol{M}_\beta$ is the matrix that has zero coefficients in all positions not picked up by Sample$_\mu$ and satisfies $ECC_Enc_{\kappa,f}(m_\beta) = \text{Sample}_\mu(\boldsymbol{M}_\beta)$. Clearly,

$$\Pr(S_0) = \Pr(S_1) \tag{44}$$

Games G_1 and G_2 only differ in the generation of the secret matrix $\boldsymbol{S}$. We define a distinguisher $\mathcal{B}$ as follows. Upon input $\boldsymbol{S} \in (\mathcal{H}_{n,d/n}(h))^{1\times\overline{n}}$, $\mathcal{B}$ performs the steps in Game G_1, except for Step 2, where the given input $\boldsymbol{S}$ is used. It is easy to see that

$$\mathrm{Adv}^{\mathtt{PRF}}_{f_S}(\mathcal{B}) = |\ \Pr(S_2) - \Pr(S_3)\ |\ . \tag{45}$$

Table 22: IND-CPA games for r5*_cpa_pke: games G_0 and G_1

Game G_0	**Game G_1**
1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$	1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$
2. $s \xleftarrow{\$} \{0,1\}^{\kappa}$; $\boldsymbol{S} = f_S(s)$	2. $s \xleftarrow{\$} \{0,1\}^{\kappa}$; $\boldsymbol{S} = f_S(s)$
3. $\boldsymbol{B} = \mathrm{R}_{q \to p}(\langle \boldsymbol{AS} \rangle_{\Phi_{n+1}})$	3. $\boldsymbol{B} = \mathrm{R}_{q \to p}(\langle \boldsymbol{AS} \rangle_{\Phi_{n+1}})$
4. Choose $\beta \xleftarrow{\$} \{0,1\}$.	4. Choose $\beta \xleftarrow{\$} \{0,1\}$.
5. $(m_0, m_1, st) = \mathcal{A}(\boldsymbol{A}, \boldsymbol{B})$	5. $(m_0, m_1, st) = \mathcal{A}(\boldsymbol{A}, \boldsymbol{B})$
6. $\rho \xleftarrow{\$} \{0,1\}^{\kappa}$; $\boldsymbol{R} = f_R(\rho)$	6. $\rho \xleftarrow{\$} \{0,1\}^{\kappa}$; $\boldsymbol{R} = f_R(\rho)$
7. $\boldsymbol{U} = \mathrm{R}_{q \to p, h_2}(\langle \boldsymbol{A}^T \boldsymbol{R} \rangle_{\Phi_{n+1}})$	7. $\boldsymbol{U} = \mathrm{R}_{q \to p, h_2}(\langle \boldsymbol{A}^T \boldsymbol{R} \rangle_{\Phi_{n+1}})$
8. $\boldsymbol{v} = \langle \mathrm{Sample}_{\mu}\left(\mathrm{R}_{p \to t, h_2}(\langle \boldsymbol{B}^T \boldsymbol{R} \rangle_{\xi})\right) + \frac{t}{b} ECC_Enc_{\kappa,f}(m_\beta) \rangle_t$	8. $\boldsymbol{V} = \langle \left(\mathrm{R}_{p \to t, h_2}(\langle \boldsymbol{B}^T \boldsymbol{R} \rangle_{\xi})\right) + \frac{t}{b} \boldsymbol{M_\beta} \rangle_t$
9. $\beta' = \mathcal{A}\left((\boldsymbol{A}, \boldsymbol{B}), (\boldsymbol{U}, \boldsymbol{v}), st\right)$	9. $\beta' = \mathcal{A}\left((\boldsymbol{A}, \boldsymbol{B}), (\boldsymbol{U}, \mathrm{Sample}_{\mu}(\boldsymbol{V}), st\right)$
10. **return**$[(\beta' = \beta)]$.	10. **return**$[(\beta' = \beta)]$.

Games G_2 and G_3 only differ in the generation of $\boldsymbol{B}$. Consider the following algorithm. On input $(\boldsymbol{A}, \boldsymbol{B}) \in \mathcal{R}_{n,q}^{d/n \times d/n} \times \mathcal{R}_{n,p}^{d/n \times \overline{n}}$, run steps 3-10 from game G_3. As $(\mathbf{A}, \mathbf{B})$ is distributed like $O_{m,\chi_S,\overline{n},\boldsymbol{S}}$ in game G_3 and uniformly in game G_4, we conclude that there is a distinguisher $\mathcal{X}$ such that

$$\mathrm{Adv}_{O_{m,\chi_S,\overline{n},\boldsymbol{S},\mathcal{U}(\mathcal{R}_{n,q}^{d/n \times d/n} \times \mathcal{R}_{n,p}^{d/n \times \overline{n}})}}(\mathcal{X}) = \mid \Pr(S_3) - \Pr(S_4)) \mid \tag{46}$$

By using a standard hybrid argument, we infer that there is a distinguisher $\mathcal{E}$ such that

$$\mathrm{Adv}_{O_{m,\chi_S,\overline{n},\boldsymbol{S},\mathcal{U}(\mathcal{R}_{n,q}^{d/n \times d/n} \times \mathcal{R}_{n,p}^{d/n \times \overline{n}})}}(\mathcal{X}) \leq \overline{n} \cdot \mathrm{Adv}_{O_{m,\chi_S,\overline{1},\boldsymbol{s},\mathcal{U}(\mathcal{R}_{n,q}^{d/n \times d/n} \times \mathcal{R}_{n,p}^{d/n \times 1})}}(\mathcal{E}) \tag{47}$$

Games G_3 and G_4 only differ in the generation of the secret matrix $\boldsymbol{R}$. Similarly as with games G_1 and G_2, we infer that there is a distinguisher $\mathcal{C}$ such that

$$\mathrm{Adv}_{f_R}^{\mathsf{PRF}}(\mathcal{C}) = \mid \Pr(S_3) - \Pr(S_4) \mid . \tag{48}$$

We next consider Games G_4 and G_5. As p divides q, $\langle \boldsymbol{B}_q \rangle_p$ is uniformly distributed. By definition of the rounding function,

$$\boldsymbol{V'} \equiv \lfloor \frac{t}{p}(\langle \boldsymbol{B_q}^T \boldsymbol{R} \rangle_{\xi} + h_2 \boldsymbol{J}) \rfloor + \frac{t}{b} \boldsymbol{M}_{\beta} \pmod{\frac{tq}{p}}.$$

As p divides q and $\boldsymbol{B}_q \equiv \langle \boldsymbol{B_q} \rangle_p \pmod{p}$, we have that

$$\boldsymbol{V'} \equiv \lfloor \frac{t}{p}(\langle \boldsymbol{B_q}^T \rangle_p \boldsymbol{R} \rangle_{\xi} + h_2 \boldsymbol{J}) \rfloor + \frac{t}{b} \boldsymbol{M}_{\beta} \pmod{t}.$$

Table 23: IND-CPA games for r5*_cpa_pke: games G_2 and G_3

Game G_2	**Game G_3**
1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$	1 $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$
2. $\boldsymbol{S} \xleftarrow{\$} \chi_S^{\overline{n}}$	2. -
3. $\boldsymbol{B} = \mathrm{R}_{q \to p}(\langle \boldsymbol{AS} \rangle_{\Phi_{n+1}})$	3. $\boldsymbol{B} \xleftarrow{\$} \mathcal{R}_{n,p}^{d/n \times \overline{n}}$
4. Choose $\beta \xleftarrow{\$} \{0,1\}$.	4. Choose $\beta \xleftarrow{\$} \{0,1\}$.
5. $(m_0, m_1, st) = \mathcal{A}(\boldsymbol{A}, \boldsymbol{B})$.	5. $(m_0, m_1, st) = \mathcal{A}(\boldsymbol{A}, \boldsymbol{B})$.
6. $\rho \xleftarrow{\$} \{0,1\}^\kappa$; $\boldsymbol{R} = f_R(\rho)$	6. $\rho \xleftarrow{\$} \{0,1\}^\kappa$; $\boldsymbol{R} = f_R(\rho)$
7. $\boldsymbol{U} = \mathrm{R}_{q \to p, h_2}(\langle \boldsymbol{A}^T \boldsymbol{R} \rangle_{\phi_{n+1}})$	7. $\boldsymbol{U} = \mathrm{R}_{q \to p, h_2}(\langle \boldsymbol{A}^T \boldsymbol{R} \rangle_{\phi_{n+1}})$
8. $\boldsymbol{V} = \langle \big(\mathrm{R}_{p \to t, h_2}(\langle \boldsymbol{B}^T \boldsymbol{R} \rangle_\xi)\big) + \frac{t}{b} \boldsymbol{M}_\beta \rangle_t$	8. $\boldsymbol{V} = \langle \big(\mathrm{R}_{p \to t, h_2}(\langle \boldsymbol{B}^T \boldsymbol{R} \rangle_\xi)\big) + \frac{t}{b} \boldsymbol{M}_\beta \rangle_t$
9. $\beta' = \mathcal{A}\left((\boldsymbol{A}, \boldsymbol{B}), (\boldsymbol{U}, \mathrm{Sample}_\mu(\boldsymbol{V})), st\right)$	9. $\beta' = \mathcal{A}\left((\boldsymbol{A}, \boldsymbol{B}), (\boldsymbol{U}, \mathrm{Sample}_\mu(\boldsymbol{V})), st\right)$
10. **return**$[(\beta' = \beta)]$.	10. **return**$[(\beta' = \beta)]$.

As a result, the pairs $(\boldsymbol{B}, \boldsymbol{V})$ in Game G_4 and $(\langle \boldsymbol{B}_q \rangle_p, \langle \boldsymbol{V}' \rangle_t)$ in Game G_5 have the same distribution, and so

$$\Pr(S_4) = \Pr(S_5). \tag{49}$$

We now consider games G_5 and G_6. We will use the following lemma.

Lemma A.3.1. *Let a, b, c be positive integers such that $a|b|c$. Then for any $x \in \mathbb{R}$*

$$\lfloor \frac{a}{c} x \rfloor = \lfloor \frac{a}{b} \lfloor \frac{b}{c} x \rfloor \rfloor$$

Proof Write $m = \frac{c}{b}$ and $n = \frac{b}{a}$. It is sufficient that to show that

$$\lfloor \frac{x}{mn} \rfloor = \lfloor \frac{1}{n} \lfloor \frac{x}{m} \rfloor \rfloor.$$

We write $x = mn \lfloor \frac{x}{mn} \rfloor + y$ with $0 \le y < mn$. Obviously, $\frac{1}{n} \lfloor \frac{x}{m} \rfloor = \lfloor \frac{x}{mn} \rfloor + \frac{1}{n} \lfloor \frac{y}{m} \rfloor$. As $0 \le y < mn$, it holds that $0 \le \frac{y}{m} < n$ and so $0 \le \lfloor \frac{y}{m} \rfloor \le n - 1$. $\square$

Applying the above lemma, we infer that $(\boldsymbol{U}, \boldsymbol{V'})$ in Game G_5 and $(\boldsymbol{U'}, \boldsymbol{V"})$ in Game G_6 are related as $\boldsymbol{U} = \lfloor \frac{p}{z} \boldsymbol{U'} \rfloor$ and $\boldsymbol{V'} \equiv \lfloor \frac{tq}{pz} \boldsymbol{V"} \rfloor \pmod{\frac{tq}{p}}$. As a result,

$$\Pr(S_5) = \Pr(S_6). \tag{50}$$

In Game G_7, the variable $\begin{bmatrix} \mathrm{R}_{q \to z, h_2}(\langle \boldsymbol{A^T R} \rangle_{\phi_{n+1}}) \\ \mathrm{R}_{q \to z, h_2}(\langle \boldsymbol{B^T R} \rangle_\xi) \end{bmatrix}$ from Game G_6 is replaced by the $(d/n + \overline{n}) \times \overline{m}$ matrix $\begin{bmatrix} \boldsymbol{U"} \\ \boldsymbol{W'} \end{bmatrix}$ with entries uniformly drawn from $\mathcal{R}_{n,z}$.

Table 24: IND-CPA games for r5*_cpa_pke: games G_4 and G_5

Game G_4	**Game G_5**
1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$	1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$
2. -	2. -
3. $\boldsymbol{B} \xleftarrow{\$} \mathcal{R}_{n,p}^{d/n \times \overline{n}}$	3. $\boldsymbol{B}_q \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times \overline{n}}$
4. Choose $\beta \xleftarrow{\$} \{0,1\}$.	4. Choose $\beta \xleftarrow{\$} \{0,1\}$.
5. $(m_0, m_1, st) = \mathcal{A}(\boldsymbol{A}, \boldsymbol{B})$.	5. $(m_0, m_1, st) = \mathcal{A}(\boldsymbol{A}, \langle(\boldsymbol{B_q}\rangle_p)$.
6. $\boldsymbol{R} \xleftarrow{\$} \chi_S^{\overline{m}}$	6. $\boldsymbol{R} \xleftarrow{\$} \chi_S^{\overline{m}}$
7. $\boldsymbol{U} = \mathrm{R}_{q \to p, h_2}(\langle \boldsymbol{A}^T \boldsymbol{R} \rangle_{\Phi_{n+1}})$	7. $\boldsymbol{U} = \mathrm{R}_{q \to p, h_2}(\langle \boldsymbol{A}^T \boldsymbol{R} \rangle_{\Phi_{n+1}})$
8. $\boldsymbol{V} = \langle \big(\mathrm{R}_{p \to t, h_2}(\langle \boldsymbol{B}^T \boldsymbol{R} \rangle_\xi)\big) + \frac{t}{b} \boldsymbol{M}_\beta \rangle_t$	8. $\boldsymbol{V'} = \langle \big(\mathrm{R}_{q \to tq/p, h_2}(\langle \boldsymbol{B_q}^T \boldsymbol{R} \rangle_\xi)\big) + \frac{t}{b} \boldsymbol{M}_\beta \rangle_{tq/p}$
9. $\beta' = \mathcal{A}\left((\boldsymbol{A}, \boldsymbol{B}), (\boldsymbol{U}, \mathrm{Sample}_\mu(\boldsymbol{V})), st\right)$	9. $\beta' = \mathcal{A}\left((\boldsymbol{A}, \langle \boldsymbol{B} \rangle_q), (\boldsymbol{U}, \mathrm{Sample}_\mu(\langle \boldsymbol{V'} \rangle_t)), st\right)$
10. **return**$[(\beta' = \beta)]$.	10. **return**$[(\beta' = \beta)]$.

As $h_2 = \frac{q}{2z}$, $\mathrm{R}_{q \to z, h_2} = \mathrm{R}_{q \to z}$. Moreover, if $\xi = \Phi_{n+1}$, the first variable in fact equals $\mathrm{R}_{q \to z}(\langle \begin{bmatrix} \boldsymbol{A}^T \\ \boldsymbol{B}^T \end{bmatrix} \boldsymbol{R} \rangle_\phi)$. We infer that there exists a distinguisher $\mathcal{E}$ such that

$$\mathrm{Adv}_{d,n,d/n+\overline{n},q,z}^{\mathtt{dGLWR}_{\mathrm{spt}}}(\mathcal{A} \circ \mathcal{Z}) = \mid \Pr(S_6) - \Pr(S_7) \mid \tag{51}$$

As all inputs to $\mathcal{A}$ in Game G_7 are uniformly distributed, $\Pr(S_7) = \frac{1}{2}$, and so

$$\mathrm{Adv}_{\text{CPA-PKE}}^{\text{IND-CPA}}(\mathcal{A}) = \mid \Pr(S_0) - \Pr(S_7) \mid = \mid \sum_{i=0}^{6} \Pr(S_i) - \Pr(S_{i+1}) \mid \leq \sum_{i=0}^{6} |\Pr(S_i) - \Pr(S_{i+1})|. \tag{52}$$

By combining (44)-(52), Theorem A.3.1 follows. □

We now are in a position to prove IND-CPA security for r5_cpa_pke.

Theorem A.3.2. *Let p, q, t be integers such that $t|p|q$, and let $\xi(x) = \Phi_{n+1}(x)$. If the Decision-GLWR problem with sparse ternary secrets is hard, f_S and f_R are pseudo-random functions, and $\boldsymbol{f}_{d,n}^{(\tau)}$ can be modeled as a random oracle, then the public-key scheme r5_cpa_pke is IND-CPA secure.*

Proof. This is a direct consequence of a combination of Theorem A.3.1 with a standard random oracle argument. □

A.3.1 Discussion

The above proof of IND-CPA security for r5_cpa_pke requires that $\boldsymbol{f}_{d,n}^{(\tau)}$ can be modeled as a random oracle. This assumption is plausible for $\tau = 0$, but not for the case $\tau = 1$, since $\boldsymbol{f}_{d,n}^{(1)}$ generates $\boldsymbol{A}$ by permuting a fixed matrix. It is not clear whether $\boldsymbol{f}_{d,n}^{(2)}$ can be modeled as a random oracle.

Table 25: IND-CPA games for r5*_cpa_pke: games G_6 and G_7

Game G_6	**Game G_7**
1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$	1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$
2. -	2.-
3. $\boldsymbol{B_q} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times \overline{n}}$	3. $\boldsymbol{B_q} \xleftarrow{\$} \mathcal{R}_{n,p}^{d/n \times \overline{n}}$
4. Choose $\beta \xleftarrow{\$} \{0,1\}$.	4. Choose $\beta \xleftarrow{\$} \{0,1\}$.
5. $(m_0, m_1, st) = \mathcal{A}(\boldsymbol{A}, \langle(\boldsymbol{B_q}\rangle_p)$.	5. $(m_0, m_1, st) = \mathcal{A}(\boldsymbol{A}, \langle\boldsymbol{B_q}\rangle_p)$.
6. $\boldsymbol{R} \xleftarrow{\$} \chi_S^{\overline{m}}$	6. -
7. $\boldsymbol{U'} = \mathrm{R}_{q\to z,h_2}(\langle \boldsymbol{A}^T\boldsymbol{R}\rangle_{\Phi_{n+1}})$	7. $\boldsymbol{U"} \xleftarrow{\$} \mathcal{R}_{n,z}^{d/n \times \overline{m}}$
with $z = \max(p, tq/p)$	
8. $\boldsymbol{V''} = \langle\big(\mathrm{R}_{q\to z,h_2}(\langle \boldsymbol{B_q}^T\boldsymbol{R}\rangle_\xi)\big) + \frac{pz}{qb}\boldsymbol{M}_\beta\rangle_z$	8. $\boldsymbol{W} \xleftarrow{\$} \mathcal{R}_{n,z}^{\overline{n}\times\overline{m}}$; $\boldsymbol{V'''} = \langle\boldsymbol{W} + \frac{pz}{qb}\boldsymbol{M}_\beta\rangle_z$
9. $\beta' = \mathcal{A}((\boldsymbol{A}, \langle\boldsymbol{B_q}\rangle_p), (\langle\lfloor\frac{p}{z}\boldsymbol{U'}\rfloor\rangle_p,$	9. $\beta' = \mathcal{A}((\boldsymbol{A}, \langle\boldsymbol{B_q}\rangle_p), (\langle\lfloor\frac{p}{z}\boldsymbol{U"}\rfloor\rangle_p,$
$\mathrm{Sample}_\mu(\langle\lfloor\frac{tq}{pz}\boldsymbol{V''}\rfloor\rangle_t), st)$	$\mathrm{Sample}_\mu(\langle\lfloor\frac{tq}{pz}\boldsymbol{V'''}\rfloor\rangle_t), st)$
10. **return**$[(\beta' = \beta)]$.	10. **return**$[(\beta' = \beta)]$.

A.4 IND-CPA Security for RLWE-based Round5 variant with different reduction polynomials

As described in Section 2.4.1, the merged parameters of Round5 require that the reduction polynomial $\xi(x)$ used in the computation of the ciphertext component $\boldsymbol{v}$ and in decryption equals $x^{n+1} - 1$. The proof of the IND-CPA security of r5_cpa_pke presented in Section A.3, however, only applies if $\xi(x) = \Phi_{n+1}(x)$. The reason is that otherwise the replacement of $(\boldsymbol{U'}, \boldsymbol{V''})$ by random matrices in the transition from game G_6 to game G_7 cannot be directly related to the difficulty of GLWR with one single reduction polynomial.

Next we argue why this construction is secure: First, Round5 uses function *Sample*$_\mu$ that selects μ coefficients out of $n + 1$. We show how it prevents known distinguishing attacks such as the "*Evaluate at 1*" attack [62]. Second, we discuss an extension of the IND-CPA security proof in Section A.3 for a RLWE-variant of Round5. The existence of this proof for the RLWE case gives strong confidence in the Round5 parameters using error correction. Finally, we discuss why this proof does not directly translate to an RLWR based design and a simple design change in Round5 that would make it work, but that we have not introduced since it does not bring major benefits from a concrete security viewpoint.

Distinguishing attack at $x = 1$. In this section, the well-known "Evaluate at $x = 1$" distinguishing attack [62] is described that can be applied if $\xi(x) = x^{n+1} - 1$ and $\mu = n + 1$. Next, it is argued that this attack cannot be applied in Round5 if $\mu \leq n$. As a shorthand, $N(x)$ is written instead of $x^{n+1} - 1$.

Consider a pair of polynomials $(b(x), v(x))$ with $b(x)$ uniformly distributed on $\mathbb{Z}_p[x]/(x^{n+1}-1)$ and $v(x) = \langle \text{Sample}_\mu(\lfloor \frac{t}{p}(\langle b(x)r(x)\rangle_{N(x)} + h_2)\rfloor) + \frac{t}{b}m(x)\rangle_t$ with $r(x)$ drawn independently and uniformly from the ternary polynomials of degree at most $n-1$ satisfying $r(1) = 0$, and $m(x)$ drawn according to some distribution on $\mathbb{Z}_b[x]/(x^\mu - 1)$. We then have that $v(x) \equiv \lfloor \text{Sample}_\mu(\frac{t}{p}(\langle b(x)r(x)\rangle_{N(x)} + h_2)\rfloor) + \frac{t}{b}m(x) \pmod t$, and so $w(x) = \frac{p}{t}v(x)$ satisfies

$$w(x) \equiv \text{Sample}_\mu(\langle b(x)r(x)\rangle_{N(x)}) + \frac{p}{t} \cdot h_2 \sum_{i=0}^{\mu-1} x^i - \frac{p}{t}\epsilon(x) + \frac{p}{b}m(x) \pmod p.$$

where $\epsilon(x)$ is the result of rounding downwards, so all components of $\frac{p}{t}\epsilon(x)$ are in $[0, \frac{p}{t}) \cap \mathbb{Z}$. As $(x-1)$ divides both $r(x)$ and $N(x)$, it follows that $x-1$ divides $\langle b(x)r(x)\rangle_{N(x)}$, and so if $\mu = n+1$, then

$$w(1) \equiv \frac{p}{t} \cdot h_2 \cdot (n+1) - \frac{p}{t}\sum_{i=0}^{n} \epsilon_i + \frac{p}{b}m(1) \pmod p.$$

For large n, the value of $\frac{p}{t}\sum_{i=0}^{n} \epsilon_i$ is close to its average, i.e., close to $n\frac{p}{2t}$. As a result, has maxima at values $\frac{p}{t}h_2(n+1) - n\frac{p}{2t} + \frac{p}{b}k$ for $0 \le k \le b-1$. So $w(1)$ can serve as a distinguisher between the above distribution and the uniform one. Now assume that $\mu < n+1$. We take $\mu = n$, which is the case giving most information to the attacker. Writing $f(x) = \langle b(x)r(x)\rangle_{N(x)} = \sum_{i=0}^{n} f_i x^i$, it holds that

$$w(1) \equiv \sum_{i=0}^{n-1} f_i + \frac{p}{t} \cdot h_2 \cdot n - \frac{p}{t}\epsilon(1) + \frac{p}{b}m(1) \pmod p.$$

As shown above, $f(1) = 0$, and so $\sum_{i=0}^{n-1} f_i = -f_n$. Hence, under the assumption that f_n is distributed uniformly modulo p, also $w(1)$ is distributed uniformly modulo p. The latter assumption is supported by [86].

Requirements for IND-CPA Security – Design rationale. An IND-CPA security proof is feasible for a RLWE variant of r5_cpa_pke, i.e., a Round5 variant where the noise is independently generated. This proof is presented below and gives confidence in Round5's design and choices made.

The proof requires the secrets to be a multiple of $(x-1)$ and also the noise polynomial for the ciphertext component v to be a multiple of $(x-1)$ (this is used in an essential step of the proof, specifically in the map Ψ in (61)) This last requirement is the reason why this proof does not apply to Round5 with $\xi(x) = x^{n+1} - 1$ using RLWR defined as *component-wise rounding*. This deterministic component-wise rounding does not allow enforcing that the noisy "rounding" polynomials are multiples of $(x-1)$.

Round5's design can be adapted to use a slightly different type of rounding informally named as "rounding to the root lattice" [48, 49, 80] - that allows the IND-CPA proof to work. This alternate rounding technique is described in

Algorithm 35: round_to_root(a, q, p)

```
b ← ⌊(p/q) a⌋
for i ← 0 to n − 1 do
    e_i ← (idx = i ∈ ℤ, val = (p/q) a − ⌊(p/q) a⌋ ∈ ℚ)
end
Sort e in descending order of e.val.
k ← p ⌈b(1)/p⌉ − b(1)
for i ← 0 to k − 1 do
    b_{e_i.idx} ← b_{e_i.idx} + 1
end
return b
```

Algorithm 35, that takes as input an $a \in \mathbb{Z}_q[x]$, integer moduli q, p where $p < q$ and returns a $b \in \mathbb{Z}_p[x]$ satisfying $b(1) \equiv 0 \pmod{p}$.

Rounded noise introduced in b using Algorithm 35 is a polynomial whose coefficients sum to zero, so that the IND-CPA proof given below can be directly translated to the RLWR case. However, this modification – going from component-wise rounding to rounding to the root lattice – would introduce additional complexity with no clear concrete security benefits. First, Sample_μ gets rid of $n + 1 - \mu$ coefficients so that knowing k is irrelevant. Second, concrete security attacks use the norm of the noise that hardly changes here. Because of these two reasons, we argue that the current Round5 design (and the rounding used in it) is sound and secure, and further modifications are not required.

IND-CPA Proof for RLWE-based variant of Round5. We now present the proof of IND-CPA security for the RLWE variant of r5_cpa_pke. We restrict ourselves to the case $B = 1$, that is, one single bit is extracted from each symbol. Our proof uses elements from [28, Sec E1].

The following notation will be used. We write $\phi(x) = 1 + x + \ldots + x^n$, and $N(x) = x^{n+1} - 1$, where $n + 1$ is prime. Moreover, $R_\phi = \mathbb{Z}_q[x]/\phi(x)$, and

$$R_0 = \{f(x) = \sum_{i=0}^{n} f_i x^i \in \mathbb{Z}_q[x] \mid \sum_{i=0}^{n} f_i \equiv 0 \pmod{q}\} \tag{53}$$

As $N(x) = (x - 1)\phi(x)$, it holds that $\langle (x-1)f(x)\rangle_{N(x)} = (x-1)\langle f(x)\rangle_{\phi(x)}$ for any $f \in \mathbb{Z}[x]$. As a result, $f(x) \mapsto (x - 1)f(x)$ is a bijection from R_ϕ to R_0.

In the proof, the following lemma will be used.

Lemma A.4.1. *Let q and $n + 1$ be relatively prime, and let $(n + 1)^{-1}$ be the multiplicative inverse of $n + 1$ in $\mathbb{Z}_q$. The mapping $\mathcal{F}$ defined as*

$$\mathcal{F} : (\sum_{i=0}^{n-1} f_i x^i) \mapsto \sum_{i=0}^{n-1} f_i x^i - (n+1)^{-1} \cdot \left(\sum_{i=0}^{n-1} f_i\right) \cdot \phi(x)$$

is a bijection from R_ϕ to R_0.

Proof. It is easy to see that $\mathcal{F}$ maps R_ϕ to R_0. To show that $\mathcal{F}$ is a bijection, let $g(x) = \sum_{i=0}^{n} g_i x^i \in R_0$, and let $f(x) = \sum_{i=0}^{n} \langle g_i - g_n \rangle_q x^i$. Clearly, $f \in \mathbb{Z}_q[x]$ has degree at most $n-1$, and by direct computation, $\mathcal{F}(f(x)) = g(x)$. □

In the description below, $\mathcal{S}$ denotes a set of secrets such that

$$\mathcal{S} \subset \{f(x) = \sum_{i=0}^{n-1} f_i x^i \in \mathbb{Z}_q[x] \mid \sum_{i=0}^{n-1} f_i \equiv 0 \pmod{q}\}, \tag{54}$$

Moreover, $\mathcal{M}$ denotes a message space, and ECC_Enc and ECC_Dec are error correcting encoding and decoding algorithms such that

$$\{ECC_Enc(m) \mid m \in \mathcal{M}\} \subset \{f(x) = \sum_{i=0}^{n} f_i x^i \in \mathbb{Z}_2[x] \mid \sum_{i=0}^{n} f_i \equiv 0 \pmod{2}\}. \tag{55}$$

Moreover, χ denotes a probability distribution on R_ϕ.

For understanding Algorithm 38 below, note that as $(x-1)|s(x)$, we have that $su' \equiv sa'r + se_1 \pmod{N}$, and, as $(x-1)|r(x)$, that $rb' \equiv ra's + re_0 \pmod{N}$. As a consequence,

$$\zeta \equiv v - su' \equiv \frac{q}{2} ECC_Enc(m) + (x-1)e_2 + re_0 - se_1 \pmod{N}, \text{ whence}$$

$$\lfloor \frac{2}{q}\zeta \rceil \equiv ECC_Enc(m) + \lfloor \frac{2}{q}((x-1)e_2 + re_0 - se_1) \rceil \pmod{N}.$$

Algorithm 36: CPA-PKE.Keygen()

```
a' ←$ R_φ, s ←$ S, e_0 ← χ
b' = ⟨a's + e_0⟩_φ
pk = (a', b')
sk = s
return (pk, sk)
```

Algorithm 37: CPA-PKE.Enc($pk = (a', b'), m \in \mathcal{M}$)

```
r ←$ S, e_1, e_2 ←$ χ
u' = ⟨a'r + e_1⟩_φ
v = ⟨(q/2) ECC_Enc(m) + b'r + (x − 1)e_2⟩_N
ct = (u', v)
return ct
```

We are now in a position to prove the following result.

Algorithm 38: CPA-PKE.Dec(sk, ct)

1 $\zeta = \langle v - su' \rangle_N$
2 $\hat{m} = ECC_Dec\langle \lfloor \frac{2\zeta}{q} \rceil \rangle_2)$
3 **return** $\hat{m}$

Theorem A.4.1. *For every IND-CPA adversary $\mathcal{A}$ with advantage A, there exist algorithms C and E such that*

$$A \leq Adv_1(C) + Adv_3(E). \tag{56}$$

Here Adv_1 refers to the advantage of distinguishing between the uniform distribution on $(\mathbb{Z}_q[x]/\phi(x))^2$ and the R-LWE distribution

$$(a', b' = \langle a's + e_0 \rangle_\phi) \text{ with } a' \xleftarrow{\$} R_\phi, s \xleftarrow{\$} \mathcal{S}, e_0 \leftarrow \chi \tag{57}$$

Similarly, Adv_3 refers to the advantage of distinguishing between the uniform distribution on $(\mathbb{Z}_q[x]/\phi(x))^4$ and the distribution of two R-LWE samples with a common secret, given by

$$(a', b'', u', v') \text{ with } a', b'' \xleftarrow{\$} \mathbb{Z}_q[x]/\phi(x), u = \langle a'r + e_1 \rangle_\phi, \tag{58}$$

$$v = \langle b"r + e_2 \rangle_\phi \text{ with } r \xleftarrow{\$} \mathcal{S}, e_1, e_2 \leftarrow \chi \tag{59}$$

Proof. We prove the theorem using a sequence of IND-CPA games. We denote by S_i the event that the output of game i equals 1.
Game G_0 is the original IND-CPA game. In Game G_1, the public key (a', b') is replaced by a pair (a', b') uniformly drawn from R_ϕ^2. It can be shown that there exists an algorithm $\mathcal{C}$ for distinguishing between the uniform distribution on R_ϕ^2 and the R-LWE distribution of pairs (a', b') with $a' \xleftarrow{\$} R_\phi$, $b' = \langle as' + e_0 \rangle_\phi$ with $s \xleftarrow{\$} \mathcal{S}$ and $e_0 \leftarrow \chi$ such that

$$\mathrm{Adv}_1(\mathcal{C}) = |\Pr(S_0) - \Pr(S_1)|.$$

In Game G_2, the values $u' = \langle a'r + e_1 \rangle_\phi$ and $\hat{v} = \langle b'r + (x-1)e_2 \rangle_N$ used in the generation of v are simultaneously substituted with uniform random variables from R_ϕ and R_0, respectively. it can be shown that there exists an adversary $\mathcal{D}$ with the same running time as that of $\mathcal{A}$ such that

$$\mathrm{Adv}_2(\mathcal{D}) = |\Pr(S_1) - \Pr(S_2)|.$$

Here Adv_2 refers to the advantage of distinguishing between the uniform distribution on $R_\phi^3 \times R_0$ and the distribution

$$(a', b', u', v) = (a', b', \langle a'r + e_1 \rangle_\phi, \langle b'r + (x-1)e_2 \rangle_N) \text{ with } a', b' \xleftarrow{\$} R_\phi, r \xleftarrow{\$} \mathcal{S}, e_1, e_2 \xleftarrow{\$} \chi. \tag{60}$$

Because of (55), the value of the ciphertext v in Game G_2 is independent of bit b, and therefore $\Pr(S_2) = 1/2$. As a final step, we define $\Psi : R_\phi^3 \times R_0 \to R_\phi^4$ as

$$\Psi(a'(x), b'(x), u'(x), v(x)) = (a'(x), b''(x), u'(x), v'(x)) \text{ with} \tag{61}$$

$$b''(x) = \frac{\mathcal{F}(b'(x))}{x-1}, v'(x) = \frac{v(x)}{x-1} \tag{62}$$

As $\mathcal{F}$ is a bijection from R_ϕ to R_0 (see Lemma A.4.1) and $f(x) \mapsto \frac{f(x)}{x-1}$ is a bijection from R_0 to R_ϕ, it follows that Ψ is a bijection. Writing $b(x) = \mathcal{F}(b'(x))$, we infer that

$$b(x)r(x) = b'(x)r(x) - (n+1)^{-1}b'(1)\phi(x)r(x) \equiv b'(x)r(x) \pmod{N(x)},$$

where the latter equivalence holds as $r(x)$ is a multiple of $(x-1)$, and so

$$v(x) = \langle b'(x)r(x) + (x-1)e_2(x)\rangle_N = \langle b(x)r(x) + (x-1)e_2(x)\rangle_N.$$

As $r(x)$ is a multiple of $x-1$, it follows that $v(x) \in R_0$ and that

$$v'(x) = \frac{v(x)}{x-1} \equiv \langle b''(x)r(x) + e_2(x)\rangle_\phi \text{ where } b''(x) = \frac{b(x)}{x-1}.$$

As a result, the advantage of $\mathcal{E} = \Psi \circ \mathcal{D}$ in distinguishing between the uniform distribution on R_Φ^4 and the distribution

$$(a', b'', u', v') \text{ with } a, b'' \xleftarrow{\$} R_\phi, u'(x) = \langle a'r + e_1\rangle_\phi \text{ and } v' = \langle b''r + e_2\rangle_\phi$$

is equal to $\mathrm{Adv}_2(D)$. Note that (a, u') and $(b", v')$ are two R-LWE samples with common secret $r(x) \in \mathcal{S}$, with $a', b"$ chosen uniformly in $\mathcal{R}_\phi$ and independent noise polynomials $e_1(x)$ and $e_2(x)$.
As $Pr(S_2) = \frac{1}{2}$, we conclude that

$$Adv(\mathcal{A}) = |\Pr(S_0) - \Pr(S_2)| \leq \sum_{i=0}^{1} |\Pr(S_i) - \Pr(S_{i+1})| = \mathrm{Adv}_1(\mathcal{C}) + \mathrm{Adv}_2(\mathcal{E}).$$

□

A.5 IND-CPA Security of r5_cpa_kem

This section presents a proof that r5_cpa_kem is IND-CPA secure, based on the hardness of the decision GLWR problem with sparse-ternary secrets. Similar to the proof of Theorem A.3.2, we first prove IND-CPA security for r5*_cpa_kem, in which $\boldsymbol{A}$ is generated uniformly instead of from a seed (Theorem A.5.1). The IND-CPA security for r5_cpa_kem, that is, Theorem A.5.2, follows from this result under the assumption that $\boldsymbol{f}_{d,n}^{(\tau)}$ can be modeled as a random oracle. The proof is restricted to the case $\xi(x) = \Phi_{n+1}(x)$.

Theorem A.5.1. *Let b, p, q, t be powers of two such that $b|t|p|q$, and let $z = \max(p, tq/p)$. Furthermore, assume that $\xi(x) = \Phi_{n+1}(x)$. For every IND-CPA adverseary $\mathcal{A}$, if $Adv^{IND\text{-}CPA}_{r5_cpa_kem}(\mathcal{A})$ in winning the IND-CPA game for r5*_cpa_kem game, then there exist distinghuishers $\mathcal{B}, \mathcal{C}, \mathcal{D}, \mathcal{E}, \mathcal{F}$ with essentially equal running times as $\mathcal{A}$ such that*

$$\begin{aligned} Adv^{IND\text{-}CPA}_{r5_cpa_kem}(\mathcal{A}) \leq Adv^{PRF}_{f_S}(\mathcal{B}) + Adv^{PRF}_{f_R}(\mathcal{C}) + \\ \overline{n} \cdot Adv^{\texttt{dGLWR}_{spt}}_{d,n,d/n,q,p}(\mathcal{D}) \ + Adv^{\texttt{dGLWR}_{spt}}_{d,n,d/n+\overline{n},q,z}(\mathcal{E}) + Adv^{PRF}_{H}(\mathcal{F}). \end{aligned} \tag{63}$$

In this equation, $Adv^{\texttt{PRF}}_{f_S}(\mathcal{B})$ denotes the advantage of $\mathcal{B}$ for distinguishing between the distribution of $f_S(s)$ with $s \xleftarrow{\$} \{0,1\}^\kappa$, and the uniform distribution of vectors of length $\overline{n}$ with entries from $\mathcal{H}_{n,d/n}(h)$. Similarly, $Adv^{\texttt{PRF}}_{f_R}(\mathcal{C})$ denotes the denotes the advantage of $\mathcal{C}$ for distinguishing between the distribution of $f_R(r)$ with $r \xleftarrow{\$} \{0,1\}^\kappa$, and the uniform distribution of vectors of length $\overline{m}$ with entries from $\mathcal{H}_{n,d/n}(h)$. Furthermore, $Adv^{\texttt{dGLWR}_{spt}}_{d,n,m,q_1,q_2}(\mathcal{Z})$ is the advantage of adversary $\mathcal{Z}$ in distinguishing m GLWR samples (with sparse-ternary secrets) from uniform, with the GLWR problem defined for the parameters d, n, q_1, q_2. Finally, $Adv^{PRF}_{H}(\mathcal{F})$ is the advantage of $\mathcal{F}$ in distinguishing the uniform distribution on $\{0,1\}^\kappa$ and the distribution of $H(x)$ with $x \xleftarrow{\$} \{0,1\}^{\kappa+\lambda_1}$ with $\lambda_1 = d \cdot \overline{n} \log_2(p) + \mu \log_2(t)$.

Proof. The proof for Theorem A.5.1, proceeds via a similar sequence of games as in the proof of Theorem A.3.1, shown in Tables 26 to 29. Again, S_i denotes the event that the output in game G_i equals 1. As the sequence of games is very similar to that used in the proof of Theorem A.3.1, we focus on the essential difference, which is game G_7. Games G_6 and G_6 only differ in the generation of k_0. As p, q, t all are powers of two and $z = \max(\frac{tq}{p}, p)$, p divides z and tq divides pz. As a result, in games G_6 and G_7, $\lfloor \frac{p}{z} \boldsymbol{U}'' \rfloor$ is uniformly distributed on $\mathcal{R}^{d/n \times \overline{m}}_{n,p}$. Also, as $\boldsymbol{W}'''$ in games G_6 and G_7 is uniformly distributed on $\mathcal{R}^{\overline{n} \times \overline{m}}_{n,z}$, the vector $\lfloor \frac{tq}{pz} \boldsymbol{v}''' \rfloor$ is uniformly distributed on $\mathbb{Z}_{\frac{tq}{p}}$. As t divides $\frac{tq}{p}$, the vector $\langle \lfloor \frac{tq}{pz} \boldsymbol{v}''' \rfloor \rangle_t$ is uniformly distributed on $\mathbb{Z}_t$. We conclude that the input to H in game G_7 is uniform. Therefore, there exists a distinguisher between the uniform distribution on $\{0,1\}^\kappa$ and the distribution of $H(x)$ with $x \xleftarrow{\$} \{0,1\}^{\kappa+\lambda_1}$ (where $\lambda_1 = d \cdot \overline{n} \log_2(p) + \mu \log_2(t)$) with advantage equal to $\mid \Pr(S_6) - \Pr(S_7) \mid$. As the input to $\mathcal{A}$ in game G_7 is uniform, $\Pr(S_7) = \frac{1}{2}$. □

We are now in a position to prove IND-CPA security for r5_cpa_kem.

Theorem A.5.2. *Let b, p, q, t be powers of two such that $b|t|p|q$, and let $\xi(x) = \Phi_{n+1}(x)$. If the Decision-GLWR problem with sparse ternary secrets is hard, f_S,f_R and H (with input length $d \cdot \overline{n} \log_2(p) + \mu \log_2(t)$) are pseudo-random functions, and $\boldsymbol{f}^{(\tau)}_{d,n}$ can be modeled as a random oracle, then the public-key scheme r5_cpa_pke is IND-CPA secure.*

Proof. This is a direct consequence of a combination of Theorem A.5.1 with a standard random oracle argument. □

Table 26: IND-CPA games for r5*_cpa_kem: Games G_0 and G_1

Game G_0	**Game G_1**
1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$	1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$
2. $s \xleftarrow{\$} \{0,1\}^{\kappa}$; $\boldsymbol{S} = f_S(s)$	2. $s \xleftarrow{\$} \chi_S^{\overline{n}}$
3. $\boldsymbol{B} = \mathrm{R}_{q \to p}(\langle \boldsymbol{AS} \rangle_{\Phi_{n+1}})$	3. $\boldsymbol{B} = \mathrm{R}_{q \to p}(\langle \boldsymbol{AS} \rangle_{\Phi_{n+1}})$
4. Choose $b \xleftarrow{\$} \{0,1\}$.	4. Choose $b \xleftarrow{\$} \{0,1\}$.
5. $(ct = (\boldsymbol{U}, \boldsymbol{v}), k_0) = \text{r5_cpa_kem_encapsulate}\,(\boldsymbol{A}, \boldsymbol{B})$.	5. $(ct = (\boldsymbol{U}, \boldsymbol{v}), k_0) = \text{r5_cpa_kem_encapsulate}\,(\boldsymbol{A}, \boldsymbol{B})$.
6. $k_1 \xleftarrow{\$} \{0,1\}^{\kappa}$.	6. $k_1 \xleftarrow{\$} \{0,1\}^{\kappa}$.
7. $b' = \mathcal{A}\,((\boldsymbol{A}, \boldsymbol{B}), ct, k_b)$.	7. $b' = \mathcal{A}\,((\boldsymbol{A}, \boldsymbol{B}), ct, k_b)$.
8. Output $[(b' = b)]$.	8. Output $[(b' = b)]$.

Table 27: IND-CPA games for r5*_cpa_kem: Games G_2 and G_3

Game G_2	**Game G_3**
1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$	1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$, $\boldsymbol{B} \xleftarrow{\$} \mathcal{R}_{n,p}^{d/n \times \overline{n}}$.
2. -	2. Choose $b \xleftarrow{\$} \{0,1\}$
3. $\boldsymbol{B} \xleftarrow{\$} \mathcal{R}_{n,p}^{d/n \times \overline{n}}$	3. $m \xleftarrow{\$} \{0,1\}^{\kappa}, \boldsymbol{\zeta} = ECC_Enc_{\kappa,f}(m)$
4. Choose $b \xleftarrow{\$} \{0,1\}$.	4. $\boldsymbol{R} \xleftarrow{\$} \left(\mathcal{H}_{n,d/n}\,(h)\right)^{1 \times \overline{m}}$.
5. $(ct = (\boldsymbol{U}, \boldsymbol{v}), k_0) = \text{r5_cpa_kem_encapsulate}\,(\boldsymbol{A}, \boldsymbol{B})$.	5. $\boldsymbol{U} = \mathrm{R}_{q \to p, h_2}(\langle \boldsymbol{A}^T \boldsymbol{R} \rangle_{\Phi_{n+1}})$
6. –	6. $\boldsymbol{W} = \mathrm{R}_{p \to t, h_2}(\langle \boldsymbol{B}^T \boldsymbol{R} \rangle_{\xi})$
7. –	7. $\boldsymbol{v} = \langle \mathrm{Sample}_{\mu}(\boldsymbol{W}) + \frac{t}{b}\boldsymbol{\zeta} \rangle_t$
8. –	8. $k_0 = H\,(m \| (ct = (\boldsymbol{U}, \boldsymbol{v})))$.
9. $k_1 \xleftarrow{\$} \{0,1\}^{\kappa}$.	9. $k_1 \xleftarrow{\$} \{0,1\}^{\kappa}$.
10. $b' = \mathcal{A}\,((\boldsymbol{A}, \boldsymbol{B}), ct, k_b)$.	10. $b' = \mathcal{A}\,((\boldsymbol{A}, \boldsymbol{B}), ct, k_b)$.
11. Output $[(b' = b)]$.	11. Output $[(b' = b)]$.

A.6 IND-CCA security of r5_cca_pke

In this section, it is shown that r5_cca_pke is IND-CCA secure. As r5_cca_pke is constructed from r5_cca_kem and a secure data-encapsulation mechanism as proposed by Cramer and Shoup [44], it is sufficient to show the IND-CCA security of r5_cca_kem. Indeed, as stated in Theorem A.6.1, when the hash functions G and H in Algorithms 8 and 9 are modeled as random oracles, the key-encapsulation mechanism r5_cca_kem defined in Section 2.4.5 is IND-CCA secure, assuming the hardness of the decision GLWR problem with sparse-ternary secrets.

Table 28: IND-CPA games for r5*_cpa_kem: Games G_4 and G_5

Game G_4	**Game G_5**
1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$, $\boldsymbol{B} \xleftarrow{\$} \mathcal{R}_{n,p}^{d/n \times \overline{n}}$.	1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$, $\boldsymbol{B}_q \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times \overline{n}}$.
2. Choose $b \xleftarrow{\$} \{0,1\}$.	2. Choose $b \xleftarrow{\$} \{0,1\}$.
3. $m \xleftarrow{\$} \{0,1\}^{\kappa}, \boldsymbol{\zeta} = ECC_Enc_{\kappa,f}(m)$	3. $m \xleftarrow{\$} \{0,1\}^{\kappa}, \boldsymbol{\zeta} = ECC_Enc_{\kappa,f}(m)$
4. $\boldsymbol{R} \xleftarrow{\$} \left(\mathcal{H}_{n,d/n}(h)\right)^{1 \times \overline{m}}$.	4. $\boldsymbol{R} \xleftarrow{\$} \left(\mathcal{H}_{n,d/n}(h)\right)^{1 \times \overline{m}}$
5. $\boldsymbol{U} = \mathrm{R}_{q \to p,h_2}(\langle \boldsymbol{A}^T \boldsymbol{R} \rangle_{\Phi_{n+1}})$	5. $\boldsymbol{U'} = \mathrm{R}_{q \to z,h_2}(\langle \boldsymbol{A}^T \boldsymbol{R} \rangle_{\Phi_{n+1}})$
6. $\boldsymbol{W'} = \mathrm{R}_{q \to tq/p,h_2}(\langle \boldsymbol{B}_q^T \boldsymbol{R} \rangle_{\xi})$	6. $\boldsymbol{W}" = \mathrm{R}_{q \to z,h_2}(\langle \boldsymbol{B}_q^T \boldsymbol{R} \rangle_{\xi})$
7. $\boldsymbol{v'} = \langle \mathrm{Sample}_{\mu}(\boldsymbol{W'}) + \frac{t}{b}\boldsymbol{\zeta} \rangle_{tq/p}$	7. $\boldsymbol{v}" = \langle \mathrm{Sample}_{\mu}(\boldsymbol{W}") + \frac{pz}{qb}\boldsymbol{\zeta} \rangle_{z}$
8. $k_0 = H\left(m \| ct = (\boldsymbol{U}, \langle \boldsymbol{v'} \rangle_t)\right)$.	8. $k_0 = H\left(m \| ct = \left(\lfloor \frac{p}{z}\boldsymbol{U'} \rfloor, \langle \lfloor \frac{tq}{pz}\boldsymbol{v}" \rfloor \rangle_t\right)\right)$.
9. $k_1 \xleftarrow{\$} \{0,1\}^{\kappa}$.	9. $k_1 \xleftarrow{\$} \{0,1\}^{\kappa}$.
10. $b' = \mathcal{A}\left((\boldsymbol{A}, \langle \boldsymbol{B}_q \rangle_p), ct, k_b\right)$.	10. $b' = \mathcal{A}(\left((\boldsymbol{A}, \langle \boldsymbol{B}_q \rangle_p), (\lfloor \frac{p}{z}\boldsymbol{U'} \rfloor, \langle \lfloor \frac{tq}{pz}\boldsymbol{v}" \rfloor \rangle_t), k_b\right)$.
11. Output $[(b' = b)]$.	11. Output $[(b' = b)]$.

Theorem A.6.1. *For any adversary $\mathcal{A}$ that makes at most q_H queries to the random oracle H, at most q_G queries to the random oracle G, and at most q_D queries to the decryption oracle, there exists an adversary $\mathcal{B}$ such that*

$$Adv_{CCA\text{-}KEM}^{IND\text{-}CCA}(\mathcal{A}) \leq 3 \cdot Adv_{CPA\text{-}PKE}^{IND\text{-}CPA}(\mathcal{B}) + q_G \cdot \delta + \frac{2q_G + q_H + 1}{2^{\mu B}} \tag{64}$$

when r5_cpa_pke and r5_cca_kem both have a probability of decryption/decapsulation failure that is at most δ.

Proof. The proof of Theorem A.6.1 proceeds via two transformation reductions due to [63]. First, Lemma A.6.1 establishes that the OW-PCA [4] security of the deterministic public-key encryption scheme PKE_1 obtained from the public-key encryption scheme PKE via transformation T [63], tightly reduces to IND-CPA security of PKE_1. This lemma is a special case of [63, Theorem 3.2] with $q_v = 0$, since by definition OW-PCA security is OW-PCVA[5] security where the attacker is not allowed to query the ciphertext validity checking oracle.

Lemma A.6.1 (Adapted from [63, Theorem 3.2])**.** *Assume PKE to be δ correct. Then, for any OW-PCA adversary $\mathcal{B}$ that issues at most q_G queries to the random oracle G, q_P queries to a plaintext checking oracle P_{CO}, there exists an IND-CPA adversary $\mathcal{C}$ such that*

$$Adv_{PKE_1}^{OW\text{-}PCA}(\mathcal{B}) \leq q_G \cdot \delta + \frac{2q_G + 1}{|\mathcal{M}|} + 3 \cdot Adv_{PKE}^{IND\text{-}CPA}(\mathcal{C}) \tag{65}$$

where $\mathcal{M}$ is the message/plaintext space of the public-key encryption schemes PKE and PKE_1.

[4] The security notion of One-Way against Plaintext Checking Attacks.
[5] The security notion of OW-PCA, with access to a ciphertext Validity checking oracle.

Table 29: IND-CPA games for r5*_cpa_kem: Games G_6 and G_7

Game G_6	**Game G_7**
1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$, $\boldsymbol{B_q} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times \overline{n}}$.	1. $\boldsymbol{A} \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times d/n}$, $\boldsymbol{B}_q \xleftarrow{\$} \mathcal{R}_{n,q}^{d/n \times \overline{n}}$.
2. Choose $b \xleftarrow{\$} \{0,1\}$.	2. Choose $b \xleftarrow{\$} \{0,1\}$.
3. $m \xleftarrow{\$} \{0,1\}^\kappa, \boldsymbol{\zeta} = ECC_Enc_{\kappa,f}(m)$	3. $m \xleftarrow{\$} \{0,1\}^\kappa, \boldsymbol{\zeta} = ECC_Enc_{\kappa,f}(m)$
4. -	4. -
5. $\boldsymbol{U}$" $\xleftarrow{\$} \mathcal{R}_{n,z}^{d/n \times \overline{m}}$	5. $\boldsymbol{U}$" $\xleftarrow{\$} \mathcal{R}_{n,z}^{d/n \times \overline{m}}$
6. $\boldsymbol{W}''' \xleftarrow{\$} R_{n,z}^{\overline{n} \times \overline{m}}$	6. $\boldsymbol{W}''' \xleftarrow{\$} R_{n,z}^{\overline{n} \times \overline{m}}$
7. $\boldsymbol{v}''' = \langle \text{Sample}_\mu(\boldsymbol{W}''') + \frac{pz}{qb}\boldsymbol{\zeta}\rangle_z$	7. $\boldsymbol{v}''' = \langle \text{Sample}_\mu(\boldsymbol{W}''') + \frac{pz}{qb}\boldsymbol{\zeta}\rangle_z$
8. $k_0 = H\left(m \| ct = \left(\lfloor \frac{p}{z}\boldsymbol{U}" \rfloor, \langle \lfloor \frac{tq}{pz}\boldsymbol{v}''' \rfloor \rangle_t\right)\right)$.	8. $k_0 \xleftarrow{\$} \{0,1\}^\kappa$
9. $k_1 \xleftarrow{\$} \{0,1\}^\kappa$.	9. $k_1 \xleftarrow{\$} \{0,1\}^\kappa$.
10. $b' = \mathcal{A}(\left((\boldsymbol{A}, \langle \boldsymbol{B}_q \rangle_p), (\lfloor \frac{p}{z}\boldsymbol{U}" \rfloor, \langle \lfloor \frac{tq}{pz}\boldsymbol{v}''' \rfloor \rangle_t), k_b\right)$.	10. $b' = \mathcal{A}(\left((\boldsymbol{A}, \langle \boldsymbol{B}_q \rangle_p), (\lfloor \frac{p}{z}\boldsymbol{U}" \rfloor, \langle \lfloor \frac{tq}{pz}\boldsymbol{v}''' \rfloor \rangle_t), k_b\right)$.
11. Output $[(b' = b)]$.	11. Output $[(b' = b)]$.

Next, combination of Lemma A.6.1 and the reduction in [63, Theorem 3.4] shows that the IND-CCA security of a KEM with implicit rejection that is constructed using a non-deterministic PKE (like r5_cca_kem), tightly reduces to the IND-CPA security of said PKE. □

Direct application of [63, Theorem 4.6], similarly as in [31, Theorem 4.2], shows that r5_cca_kem is IND-CCA secure in the quantum random oracle model. The resulting security bound however is not tight.

Theorem A.6.2. *For any quantum adversary $\mathcal{A}$ that makes at most q_H queries to the quantum random oracle H, at most q_G queries to the quantum random oracle G, and at most q_D (classical) queries to the decapsulation oracle, there exists a quantum adversary $\mathcal{B}$ such that*

$$Adv_{CCA\text{-}KEM}^{IND\text{-}CCA}(\mathcal{A}) \leq 4q_H\sqrt{q_D \cdot q_H \cdot \delta + q_G \cdot \sqrt{Adv_{CPA\text{-}PKE}^{IND\text{-}CPA}(\mathcal{B})}} \tag{66}$$

A.7 Hardness of Sparse-Ternary LWR

In this section, we prove the hardness of the Decision-LWR problem with sparse-ternary secrets assuming that the small modulus p divides the large modulus q. Figure 4 provides an overview of the reductions involved in the proof of the main result, Theorem A.7.1.

Theorem A.7.1. *Let $k, p, q \geq 1$ and $m \geq n \geq h \geq 1$ be integers such that p divides q, and $k \geq m' = \frac{q}{p} \cdot m$. Let $\epsilon \in (0, \frac{1}{2})$, and $\alpha, \delta > 0$ such that*

$$\alpha \geq q^{-1}\sqrt{(2/\pi)\ln(2n(1+\epsilon^{-1}))}, \ \binom{n}{h}2^h \geq q^{k+1} \cdot \delta^{-2}, \text{ and } m = O(\frac{\log n}{\alpha\sqrt{10h}})$$

Figure 4: Summary of reductions used in Theorem A.7.1. "SPT" refers to a variant of the problem in question where the secret is sparse-ternary, instead of uniform in $\mathbb{Z}_q^d$.

There exist three (transformation) reductions from $\mathtt{dLWE}_{k,m',q,D_\alpha}$ *to* $\mathtt{dLWE}_{n,m',q,D_{\alpha\sqrt{10h}}}(\mathcal{U}(\mathcal{H}_n(h)))$ *such that for any algorithm for the latter problem with advantage* ζ*, at least one of the reductions produces an algorithm for the former with advantage at least*

$$(\zeta-\delta)/(3m') - 41\epsilon/2 - \sum_{s|q, s \text{ prime}} s^{-k-1}.$$

Moreover, there is a reduction from $\mathtt{dLWE}_{n,m',q,D_{\alpha\sqrt{10h}}}(\mathcal{U}(\mathcal{H}_n(h)))$ *to* $\mathtt{dLWR}_{n,m,q,p}(\mathcal{U}(\mathcal{H}_n(h)))$.

Proof. Combination of Lemma A.7.1 and Lemma A.7.4 with $\alpha' = \alpha\sqrt{10h}$. □

Theorem A.7.1 implies the hardness of the sparse-ternary LWR problem $\mathtt{LWR}_{\mathrm{spt}}$ based on the hardness of the $\mathtt{LWE}$ problem with uniformly random secrets in $\mathbb{Z}_q$ and Gaussian errors.

Step 1: Reduction from LWE with secrets in $\mathbb{Z}_q$ and Gaussian errors to Sparse-ternary LWE: In [40, Theorem 1], specializing [38, Theorem 4], it is shown that if $\binom{n}{h}2^h > q^{k+1}$ and $\omega > \alpha\sqrt{10h}$, then the $\mathtt{dLWE}_{n,m,q,D_\omega}(\mathcal{U}(\mathcal{H}_n(h)))$ problem is at least as hard as the $\mathtt{dLWE}_{k,m,q,D_\alpha}$ problem. More formally, generalizing [35, Theorem 4.1], the following holds.

Lemma A.7.1. *Let $k, q \geq 1$ and $m \geq n \geq h \geq 1$ be integers, and let $\epsilon \in (0, \frac{1}{2})$, and $\alpha, \delta > 0$ such that*

$$\alpha \geq q^{-1}\sqrt{(2/\pi)\ln(2n(1+\epsilon^{-1}))}, \text{ and } \binom{n}{h}2^h \geq q^{k+1} \cdot \delta^{-2}$$

There exist three (transformation) reductions from $\mathtt{dLWE}_{k,m,q,D_\alpha}$ to $\mathtt{dLWE}_{n,m,q,D_{\alpha\sqrt{10h}}}(\mathcal{U}(\mathcal{H}_n(h)))$ such that for any algorithm for the latter problem with advantage ζ, at least one of the reductions produces an algorithm for the former with advantage at least

$$(\zeta - \delta)/(3m) - 41\epsilon/2 - \sum_{s|q, s \text{ prime}} s^{-k-1}.$$

Step 2: Reduction from Sparse-ternary LWE to Sparse-ternary LWR: Bai et al. provide in [19, Theorem 6.4] a reduction from LWE with Gaussian noise to LWR, that is based on two independent reductions It can readily be seen that one of these reductions [19, Theorem 6.3] holds for any secret distribution with support on $\mathbb{Z}_q^{n*} = \{(x_1, \ldots, x_n) \in \mathbb{Z}_q^n \mid \gcd(x_1, x_2, \ldots, x_n, q) = 1\}$, and therefore can be applied to the case when the secret is chosen from $\{-1, 0, 1\}^n$. The other reduction [19, Theorem 5.1] however, implicitly assumes the secret to be chosen uniformly at random from $\mathbb{Z}_q^n$. Below, we describe an extension of [19, Theorem 5.1] that describes a reduction from LWE with Gaussian noise and sparse ternary secrets reduces to LWR with sparse-ternary secrets. Below, we will describe such an extension. U_B denotes the continuous uniform distribution in $[-B, \ldots, B]$.

Lemma A.7.2 (Adapted from [19, Theorem 5.1])**.** *Let n, m, q be positive integers. Let $\alpha, B > 0$ be real numbers with $B = \Omega(m\alpha/\log n)$ and $Bq \in \mathbb{Z}$. Let $m > \log\left(\binom{n}{h}2^h\right)/\log(\alpha + B)^{-1} \geq 1$. Then there is a polynomial time reduction from $\mathtt{LWE}_{n,m,q,D_\alpha}(\mathcal{U}(\mathcal{H}_n(h)))$ to $\mathtt{LWE}_{n,m,q,\phi}(\mathcal{U}(\mathcal{H}_n(h)))$ with $\phi = \frac{1}{q}\lfloor qU_B \rceil$.*

Proof. The reduction proceeds similar to that of [19, Theorem 5.1], relying on five steps. Steps 1, 3, 4 below proceed exactly as in [19, Theorem 5.1]. For steps 2 and 5, we mention our adaptations in order to prove the reduction for the case of sparse-ternary secrets, and the resulting conditions. We omit details for brevity.

1. A reduction from $\mathtt{dLWE}_{n,m,q,D_\alpha}$ to $\mathtt{dLWE}_{n,m,q,\psi}$, with $\psi = D_\alpha + U_B$.
2. A reduction from $\mathtt{dLWE}_{n,m,q,\psi}$ to $\mathtt{sLWE}_{n,m,q,\psi}$. We adapt the corresponding step in [19, Theorem 5.1] to work for the uniform distribution on $\mathcal{H}_n(h)$ instead of the uniform distribution on $\mathbb{Z}_q^n$. This results in the bound on m as stated in the lemma.
3. A reduction from $\mathtt{sLWE}_{n,m,q,\psi}$ to $\mathtt{sLWE}_{n,m,q,U_B}$.
4. A reduction from $\mathtt{sLWE}_{n,m,q,U_B}$ to $\mathtt{sLWE}_{n,m,q,\phi}$, with $\phi = \frac{1}{q}\lfloor qU_B \rceil$.

5. A reduction from $\texttt{sLWE}_{n,m,q,\phi}$ to $\texttt{dLWE}_{n,m,q,\phi}$. Since the modulus q is not a prime, the argument from [19, Theorem 5.1] cannot be applied. Instead, we extend an argument due to Regev (see, e.g, [92]) to prove the search-to-decision reduction, which requires that Bq is an integer. We first state an easy lemma.

   Lemma A.7.3. *Let $a > 1$, and let ϕ be the discrete probability distribution obtained by rounding the continuous uniform probability on $[-a, a]$ to the closest integer. If a is an integer, then $\sum_{k\,even} \phi(k) = \sum_{k\,odd} \phi(k) = \frac{1}{2}$.*

   Proof. For $|k| \leq \lfloor a \rfloor - 1$, the interval $[k - \frac{1}{2}, k + \frac{1}{2}]$ is a subset of $-[a, a]$, so that $\sum_{k \equiv 1 - \lfloor a \rfloor \pmod 2} \phi(k) = \sum_{j=0}^{\lfloor a \rfloor - 1} \phi(2j - \lfloor a \rfloor + 1) = \frac{\lfloor a \rfloor}{2a}$. □

   We are now in a position to extend Regev's reduction. Let ϕ be a probability distribution on $\mathbb{Z}_q$ such that $\sum_k \phi(2k) = \sum_k \phi(2k+1) = \frac{1}{2}$. For each $\mathbf{s} \in \mathbb{Z}_q^n$, the probability distribution $A_{\mathbf{s},\phi}$ on $\mathbb{Z}_q^n \times \mathbb{Z}_q$ is obtained by choosing $\mathbf{a} \in \mathbb{Z}_q^n$ uniformly, choosing e according to ϕ, and outputting $(\mathbf{a}, (\mathbf{a}, \mathbf{s}) + e)$ where the additions are modulo q. If qB is integer, then a distinguisher for $\texttt{dLWE}_{n,m,q,\phi}(D_s)$ can be used to construct a solver for $\texttt{sLWE}_{n,m,q,\phi}(D_s)$ for any secret distribution D_s supported on $\{-1, 0, 1\}^n$, where ϕ is the discrete noise $\frac{1}{q}\lfloor qU_B \rfloor$. Note that if Bq is integer, the noise ϕ is distributed as $\phi(k) = \frac{1}{2B}$ for $|k| \leq B - 1$, and $\phi(B) = \phi(-B) = \frac{1}{4B}$. We now show that if Bq is integer, then a distinguisher for deciding between uniform samples $(\mathbf{a}, u) \in U(\mathbb{Z}_q^n) \times U(Z_q)$ and samples $(\mathbf{a}, b)$ from $A_{\mathbf{s},\phi}$ for some unknown $s \in \mathcal{S} \subset \{-1, 0, 1\}^n$ can be used for solving. We show how to find s_1, the first coordinate of a secret. For each $k \in \mathbb{Z}_q$, we consider the following transformation. For each pair $(\mathbf{a}, b)$, we choose a random $r \in \mathbb{Z}_q$ and output $(\mathbf{a}', b') = (\mathbf{a} + (r, 0, \ldots, 0), b + rk)$. Clearly, this transformation takes the uniform distribution to itself. So let us now assume that $b = (\mathbf{a}, \mathbf{s}) + e$ for some $s \in \mathcal{S}$ and some error e. Then $b' = (\mathbf{a}', \mathbf{s}) + r(k - s_1) + e$. If $k = s_1$, then $(\mathbf{a}', b')$ is from $A_{\mathbf{s},\phi}$. If $|k - s_1| = 1$, then $r(k - s_1)$ is uniform over $\mathbb{Z}_q$, and so $(\mathbf{a}', \mathbf{b})$ follows the uniform distribution. Finally, we can have that $|k - s_1| = 2$. We consider $k - s_1 = 2$, the other case being similar. We then have that $b' = (\mathbf{a}, \mathbf{s}) + 2r + e \pmod q$. If q is odd, then $2r$ is uniformly distributed on $\mathbb{Z}_q$, so that $(\mathbf{a}', \mathbf{b})$ is uniformly distributed. If q is even, then $2r$ is distributed uniformly on the even elements of $\mathbb{Z}_q$. With our specific error distribution, e is even with probability $\frac{1}{2}$, so that $2r + e$ is distributed uniformly on $\mathbb{Z}_q$. So also in this case, $(\mathbf{a}', b)$ is distributed uniformly.

   □

Finally, we state the reduction from $\texttt{dLWE}_{n,m,q,D_\alpha}$ to $\texttt{dLWR}_{n,m,q,p}$, for the sparse-ternary secret distribution.

Lemma A.7.4. *Let p, q be positive integers such that p divides q. Let $\alpha' > 0$. Let $m' = m \cdot (q/p)$ with $m = O(\log n/\alpha')$ for $m' \geq m \geq n \geq 1$. There is a*

polynomial time reduction from $\texttt{dLWE}_{n,m',q,D_{\alpha'}}$ *to* $\texttt{dLWR}_{n,m,q,p}$*, both defined for the sparse-ternary secret distribution.*

Proof. Let $B = q/2p$. The reduction has two steps:

1. A reduction from $\texttt{dLWE}_{n,m',q,D_{\alpha'}}$ to $\texttt{dLWE}_{n,m',q,\phi}$, where $B = \Omega(m'\alpha'/\log n)$. due to Lemma A.7.2.

2. A reduction from $\texttt{dLWE}_{n,m',q,\phi}$ to $\texttt{dLWR}_{n,m,q,p}$, due to [19, Theorem 6.3].

As $m' = m \cdot (q/p) = (q/p)O(\frac{\log n}{\alpha'})$, it follows that $B = q/2p = \Omega(m'\alpha'/\log n)$, so that Lemma A.7.2 indeed is applicable. □

Note that the conditions imposed by Lemma]A.7.2 imply that $1/\alpha$ must at least grow linearly in n. This is a common bottleneck in all known LWE to LWR reductions [19, 26, 20].

B HMAX computation

In this appendix, we show how to compute HMAX, the number of calls to a uniform source $\mathcal{U}$ on $\{0, 1, \ldots, 2^{16}-1\}$, required to generate a secret of Hamming weight h with sufficiently high probability, cf. Section 2.9.4.

Let $bp(w)$ be the probability of transitioning from a secret key of Hamming weight w to a secret key of Hamming weight $w+1$. Clearly, $bp(w)$ equals the product of the probability r of getting a suitable value and the probability $(d-w)/d$ that that suitable value has not been allocated yet. As a sampled 16-bits value is suitable if and only if it is smaller than $d\lfloor\frac{2^{16}}{d}\rfloor$, we have that $r = \frac{d}{2^{16}} \cdot \lfloor\frac{2^{16}}{d}\rfloor$, and so

$$bp(w) = \frac{d}{2^{16}} \cdot \lfloor\frac{2^{16}}{d}\rfloor \cdot \frac{d-w}{d}.$$

For non-negative i and w, we denote by $wp^{(i)}(w)$ the probability that the secret key has Hamming weight w after i calls to $\mathcal{U}$. Prior to the first call to $\mathcal{U}$, the secret has Hamming weight 0, so

$$wp^{(0)}(0) = 1 \text{ and } wp^{(0)}(w) = 0 \text{ for } w > 0.$$

The secret has Hamming weight w after $i \geq 1$ calls to $\mathcal{U}$ if it already had Hamming weight w after $i-1$ calls and the newly sampled element does not increase the Hamming weight, or if it had Hamming weight $w-1$ after $i-1$ calls and the newly sampled element does increase the Hamming weight. Consequently, for $i \geq 1$,

$$wp^{(i)}(w) = wp^{(i-1)}(w) \cdot (1 - bp(w)) + wp^{(i-1)}(w-1) * bp(w-1).$$

With the above formula, $wp(^{(i)}(w)$ can be computed recursively. We choose as HMAX the smallest i for which $\sum_{w \geq h} wp^{(i)}(w) \geq 1 - 2^{-\kappa}$.

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