

KINDI

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See also printed version of “Statement by Each Submitter”.

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1 Introduction

Lattices as mathematical objects have been studied by early mathematicians such as Gauss or Dirichlet due to its extremely rich combinatorial structure appearing in many areas of mathematics. But in the last 2 decades they have also extensively been utilized in cryptography to build powerful cryptosystems, where the security stems from the worst-case hardness of well studied lattice problems.

Beside the NTRU assumption the main computational assumptions exploited to build those cryptosystems are the hardness of the problems LWE/SIS [1, 16, 12], ring-LWE/ring-SIS [11, 14, 7, 13] and recently also MLWE/MSIS [10], which are equipped with security guarantees based on worst-case lattice problems. However, the efficiency of cryptosystems increases by imposing more structure. Thus, one almost only finds ring instantiations of the respective schemes for use in practice.

The decision problems are widely used to build lattice-based encryption schemes, where the public key and ciphertexts can be represented as LWE instances $\mathbf{A} \cdot \mathbf{s} + \mathbf{e}$. CPA-security is thus obtained almost for free.

We propose trapdoor-based encryption schemes, where the message is injected into the error term. By use of the trapdoor, the secret vector and error terms are recovered during decryption and are thus available for inspection. In many encryption schemes, this is indeed not possible. Since the message is embedded in the error term, small expansion factors can be realized at competitive parameters, i.e. we can encrypt more keys or data per (small) ciphertext bit (e.g. for sign-then-encrypt). Furthermore, it can easily be transformed to ensure CCA security. This work is based on [2, 15].

2 General algorithm specification (part of 2.B.1)

Parameter Definition	
n	power of two
$x^n + 1$	cyclotomic polynomial
$\mathbb{Z}[x]$	set of polynomials with integer coefficients
$\mathbb{Z}_b[x]$	set of polynomials with integer coefficients modulo b
\mathcal{R}	$\mathbb{Z}[x] / \langle x^n + 1 \rangle$
\mathcal{R}_b	$\mathbb{Z}_b[x] / \langle x^n + 1 \rangle$
\mathcal{R}_b^d	set of d polynomials from \mathcal{R}_b
q	modulus
ℓ	module rank
k	$\log q$
$[x]$	represents a polynomial in \mathcal{R} with all coefficients equal to x .
$\lfloor x \rfloor$	rounds x to the nearest integer.
\mathbf{g}	gadget $\mathbf{g} = 2^{k-1}$
\mathbf{g}'	gadget $\mathbf{g} = 2^{k-2}$ used for higher security levels
rsec	coefficient range $\{-\text{rsec}, \dots, \text{rsec} - 1\}$ of the secrets and error used
p	$p = \text{rsec}$ for simplicity
t	number of truncated bits per coefficient of the public key
$\mathbf{A} \in \mathcal{R}_q^{\ell \times \ell}$	public uniform matrix
$\mathbf{r} \in \mathcal{R}_q^\ell$	secret key
$\bar{\mathbf{p}} \in \mathcal{R}_q^\ell$	public key
$\bar{\mathbf{b}} \in \mathcal{R}_q^\ell$	compressed public key
λ	security parameter
δ	decryption failure
μ	seed of size 2λ for $\mathbf{A} \in \mathcal{R}_q^{\ell \times \ell}$
γ	seed of size 2λ for \mathbf{r}, \mathbf{r}'
$\text{MLWE}_{x,y,z}$	MLWE instances over a module of rank x with y samples having uniform errors in $\{-z, \dots, z - 1\}$
Secret key size	$n\ell \log 2p + n\ell(k - t) + 2\lambda$ bits
Public key size	$n\ell(k - t) + 2\lambda$ bits
Message size	$n(\ell + 1) \log 2p$ bits

2.1 Trapdoor based Encryption $\text{Kindi}_{\text{CPA}}$ with Uniform Errors

In this section, we describe our CPA-secure Module-LWE/SIS based encryption scheme $\text{Kindi}_{\text{CPA}}$. It is based on the works [2, 15] and employs trapdoors in order to recover the secret vector and error term from Module-LWE instances. In fact, the scheme embeds the message into the error term and further encrypts a random string (similar to a KEM) in the secret vector, which can be exploited as a key for a symmetric key cipher. We note that our encryption scheme can be seen in some sense as a "simplified" KEM, where $\mathbf{c} = \text{Kindi}_{\text{CPA}}.\text{Encrypt}(\text{pk}, \text{msg}) = (s_1 \leftarrow \mathcal{R}_2, \text{Encrypt}(\text{pk}, \text{msg} || s_1, G(s_1)))$, $\text{msg} || s_1 \leftarrow \text{Decrypt}(\text{sk}, \mathbf{c})$ and $\text{Kindi}_{\text{CPA}}.\text{Decrypt}$ just outputs msg . One part of the message, namely the random string, is always hashed with a random oracle in order to deterministically generate the secret and error term. The encryption engine $\text{Encrypt}(\cdot)$ thus coincides with the deterministic encryption scheme in [9], if msg is for instance set to \perp . In our KEM construction we need s_1 in order to finally deduce the key, thus we take $s_1 \leftarrow \mathcal{R}_2$ out of $\text{Kindi}_{\text{CPA}}.\text{Encrypt}$.

We now give a specification of the parameter space and the algorithms.

2.1.1 Parameter Space and Notation

We operate with the rings $\mathcal{R} = \mathbb{Z}[x]/\langle x^n + 1 \rangle$ and $\mathcal{R}_q = \mathbb{Z}_q[x]/\langle x^n + 1 \rangle$, where $n, q = 2^k$ are powers of two and k is a positive integer. In general, we define $\mathcal{R}_b := \mathbb{Z}_b[x]/\langle x^n + 1 \rangle$ for some positive integer b . Furthermore, we introduce the gadget polynomial $\mathbf{g} = 2^{k-1}$ with all coefficients being zero except for the constant. By ℓ we denote the module rank and the message size per coefficient amounts to $\log_2 \text{rsec}$ bits. Let λ denote the bit security level and define $p := \text{rsec}$ for simplicity. In the implementation, we use rsec instead. By $[x]$ we denote the polynomial with all coefficients equal to x .

2.1.2 Secret and Public Keys

Two seeds of size 2λ bits are generated, where $\lambda \geq 128$. The first seed μ is used to generate the public matrix $\mathbf{A} \in \mathcal{R}_q^{\ell \times \ell}$ by use of a PRNG $\in \{\text{Shake128}, \text{Shake256}\}$, which consists of ℓ^2 uniformly distributed ring elements modulo q . This seed is public. The second seed γ of size 2λ bits is secret and serves to generate the private key $\mathbf{r} \in \mathcal{R}_q^\ell$ and the error term \mathbf{r}' each consisting of ℓ ring elements with coefficients sampled uniformly at random from $\{-p, \dots, p-1\}$. In particular, Shake_p generates uniform random integers from $\{0, \dots, 2p-1\}$ with Shake and subtracts p . The uncompressed public key part \mathbf{b} is a module-LWE instance $\mathbf{b} = \mathbf{A} \cdot \mathbf{r} + \mathbf{r}' \in \mathcal{R}_q^\ell$. The public key thus consists of $\text{pk} := (\bar{\mathbf{b}}, \mu)$ and the secret key $\text{sk} := (\mathbf{r}, \bar{\mathbf{p}}, \mu)$ also contains the public key required for the decryption engine when recovering the secret and error terms.

Algorithm 1: $\text{KINDI}_{\text{CPA}}.\text{KeyGen}(1^n, p, k, t, \ell) :$

```

1  $\gamma, \mu \leftarrow \{0, 1\}^n$ 
2  $\mathbf{A} \in \mathcal{R}_q^{\ell \times \ell} \leftarrow \text{Shake}(\gamma)$ 
3  $\mathbf{r}, \mathbf{r}' \in \mathcal{R}_q^\ell \leftarrow \text{Shake}_p(\mu)$ 
4  $\mathbf{b} = \mathbf{A} \cdot \mathbf{r} + \mathbf{r}'$ 
5  $\bar{\mathbf{b}} = \text{Compress}(\mathbf{b}, t)$ 
6  $\text{pk} := (\bar{\mathbf{b}}, \mu), \text{sk} := (\mathbf{r}, \bar{\mathbf{p}}, \mu)$ 
7 return (pk, sk)
```

Algorithm 2: $\text{Compress}(\mathbf{x} \in \mathcal{R}_q^{\ell+1}, t \in \mathbb{N}) :$

```

1 Truncate the  $t$  least significant bits of each coefficient in  $\mathbf{x}$ .
2  $\bar{\mathbf{b}} = \lfloor \mathbf{x}/2^t \rfloor \in \mathcal{R}_{2^{k-t}}^{\ell+1}$ .
3 return  $\bar{\mathbf{b}}$ 
```

Compressing the public key just requires to truncate the least t significant bits. Thus, if the public key is uniform random then so the compressed one.

2.1.3 Encryption

If $\text{coins} = \perp$ (required for the KEM) the encryptor samples a secret binary polynomial s_1 with coefficients from $\{0, 1\}$ uniformly at random, otherwise coins already contains s_1 (for the KEM). In what follows, the matrix $\mathbf{A} \in \mathcal{R}_q^\ell$ is deterministically generated from μ . The public key is retrieved, decompressed by multiplication with 2^t and modified in such a way that the constant polynomial \mathbf{g} is added to \mathbf{p}_1 . The random binary polynomial s_1 is extended via the random oracle \mathbf{G} implemented as **Shake** to $\ell - 1$ uniform random polynomials (s_2, \dots, s_ℓ) with coefficients in the range $\{0, \dots, 2p-1\}$, one random polynomial \bar{s}_1 in the range $\{0, \dots, p-1\}$, i.e. one bit per coefficient less than the other polynomials, and a bit string of size $n(\ell+1) \log 2p$ bits. To obtain a secret polynomial \mathbf{s}_1 over the full range \mathcal{R}_{2p} , we shift \bar{s}_1 by one bit and add s_1 . The message msg is xored with the uniform random string \bar{u} and finally split into $n \log 2p$ bit chunks that are encoded as polynomials \mathbf{u}_i from \mathcal{R}_{2p}^n with $\log 2p$ bits per entry. The error terms are just \mathbf{u}_i translated by p in each coefficient. The ciphertext is computed as a module-LWE instances with the same secret $\mathbf{s} = (s_1 - [p], \dots, s_\ell - [p])$, where each coefficient is translated by p . To enable recovery of s_1 we adjust the last ciphertext sample via subtraction of $\mathbf{g} \cdot [p]$, which vanishes modulo q for $\mathbf{g} = 2^{k-1}$ and $p = 2^x$ with $x \geq 1$.

For $n = 256$ at a post quantum security level of 256 bits, we need $s_1 \leftarrow \mathcal{R}_4$ and $\mathbf{g} = 2^{k-2}$. The coefficients are recovered with the alternative subroutine **Recover'**.

Algorithm 3: $\text{KINDI}_{\text{CPA}}.\text{Encrypt}(\text{pk}, \text{msg} = \{0, 1\}^{n(\ell+1) \log 2p}; \text{coins} = \perp \text{ or } s_1 \in \mathcal{R}_2) :$	
<pre> 1 $s_1 \leftarrow \mathcal{R}_2$ 2 $\mathbf{A} \leftarrow \text{Shake}(\mu)$ 3 $\bar{\mathbf{p}} = \text{Decompress}(\bar{\mathbf{b}}, t)$ 4 $\mathbf{p} = (\bar{\mathbf{p}}_1 + \mathbf{g}, \bar{\mathbf{p}}_2, \dots, \bar{\mathbf{p}}_\ell)$ 5 $\bar{u} \in \{0, 1\}^{n \log p}, \bar{s}_1, (s_2, \dots, s_\ell) \in \{0, 1\}^{n(\ell+1) \log 2p} \times \mathcal{R}_p \times \mathcal{R}_{2p}^{\ell-1} \leftarrow \mathbf{G}(s_1) := \text{Shake}(s_1)$ 6 $\mathbf{s} = (s_1 + 2 \cdot \bar{s}_1 - [p], s_2 - [p], \dots, s_\ell - [p])^\top$ 7 $u = \bar{u} \oplus \text{msg}$ 8 $\mathbf{u} = \text{Encode}(u)$ 9 $\mathbf{e} = (\mathbf{u}_1 - [p], \dots, \mathbf{u}_\ell - [p])^\top, e = \mathbf{u}_{\ell+1} - [p]$ 10 $(\mathbf{c}, c)^\top = (\mathbf{A}^\top \cdot \mathbf{s} + \mathbf{e}, \mathbf{p} \cdot \mathbf{s} + \mathbf{g} \cdot [p] + e) \in \mathcal{R}_q^{\ell+1}$ 11 return (\mathbf{c}, c) </pre>	

Algorithm 4: $\text{Decompress}(\mathbf{x} \in \mathcal{R}_q^{\ell+1}, t \in \mathbb{N}) :$	
<pre> 1 $\mathbf{b} = 2^t \cdot \mathbf{x}$ </pre>	

Algorithm 5: $\text{Encode}(u \in \{0, 1\}^{n(\ell+1)\log 2p}) :$

- 1 Pack $\log 2p$ bits of u into each coefficient of $\mathbf{u}_i \in \mathcal{R}$ for $1 \leq i \leq \ell + 1$.
- 2 Each $\mathbf{u}_i \in \mathcal{R}$ contains $n \cdot \log 2p$ bits.
- 3 $\mathbf{u} = (\mathbf{u}_1, \dots, \mathbf{u}_{\ell+1})$
- 4 return \mathbf{u}

Theorem 2.1 *In the random oracle model, assume that there exists a PPT-adversary \mathcal{A} against the scheme, then there exists a reduction \mathcal{D} that breaks $\text{MLWE}_{\ell, \ell+1, p}$ such that $\text{Adv}_{\text{Kindi}(\mathcal{A})}^{\text{CPA}} \leq 3\text{Adv}_{\ell, \ell+1, p}^{\text{MLWE}}(\mathcal{D})$.*

Proof. We proceed in a sequence of hybrids. Thus, let \mathcal{H}_0 be the real IND – CPA game. In \mathcal{H}_1 , the MLWE instance $\mathbf{b} = \mathbf{A} \cdot \mathbf{r} + \mathbf{e}$ in the key generation step is changed to a uniform random value. If there exists an adversary that can distinguish the hybrids \mathcal{H}_0 and \mathcal{H}_1 , then there exists a reduction \mathcal{D}_0 that can distinguish $\text{MLWE}_{\ell, \ell, p}$ from uniform such that $\text{Adv}_{\mathcal{H}_0, \mathcal{H}_1}(\mathcal{D}_0) \leq \text{Adv}_{\ell, \ell, p}^{\text{MLWE}}(\mathcal{D}_0)$. In the hybrid \mathcal{H}_2 , the elements $\bar{u}, \bar{\mathbf{s}}_1, (\mathbf{s}_2, \dots, \mathbf{s}_\ell)$ are replaced by uniform random elements (RO) such that $\mathbf{e}, e, \mathbf{s}$ are again uniform random. Here too, we obtain $\text{Adv}_{\mathcal{H}_1, \mathcal{H}_2}(\mathcal{D}_1) \leq \text{Adv}_{\ell, \ell, p}^{\text{MLWE}}(\mathcal{D}_1)$ for the chosen parameters. Finally, in \mathcal{H}_3 the ciphertexts $\mathbf{c} = \mathbf{A}^\top \cdot \mathbf{s} + \mathbf{e}$ and $c = \mathbf{p} \cdot \mathbf{s} + \mathbf{g} \cdot [p] + e$ are replaced by uniform random elements. If there exists an adversary that can distinguish the hybrids \mathcal{H}_2 and \mathcal{H}_3 , then there exists a reduction \mathcal{D}_2 that can distinguish $\text{MLWE}_{\ell, \ell+1, p}$ from uniform such that $\text{Adv}_{\mathcal{H}_2, \mathcal{H}_3}(\mathcal{D}_2) \leq \text{Adv}_{\ell, \ell+1, p}^{\text{MLWE}}(\mathcal{D}_2)$.

We now analyze the advantage of an adversary in \mathcal{H}_0 , which is given by

$$\begin{aligned} \text{Adv}_{\mathcal{H}_0}(\mathcal{A}) &:= \text{Adv}_{\text{Kindi}}^{\text{CPA}}(\mathcal{A}) = |P[b = b'] \text{ in } \mathcal{H}_0 - 1/2| \\ &\leq \text{Adv}_{\mathcal{H}_0, \mathcal{H}_1}(\mathcal{D}) + \text{Adv}_{\mathcal{H}_1, \mathcal{H}_2}(\mathcal{D}) + \text{Adv}_{\mathcal{H}_2, \mathcal{H}_3}(\mathcal{D}) \leq 3\text{Adv}_{\ell, \ell+1, p}^{\text{MLWE}}(\mathcal{D}). \end{aligned}$$

2.1.4 Decryption

The decryption engine works similar to the encryption engine. First, the least significant bit of the coefficients of \mathbf{s}_1 are recovered via $s_1 = \text{Recover}(\mathbf{v}) \in \mathcal{R}_2$ and $\mathbf{v} = c - \mathbf{c} \cdot \mathbf{r}^\top = 2^{k-1}\mathbf{s}_1 + \mathbf{d} \bmod q = 2^{k-1}s_1 + \mathbf{d} \bmod q$ for some small $\|\mathbf{d}\|_\infty$. This recovery function has also been used for instance in [4] avoiding if-else checks. From s_1 the vectors \bar{u} and \mathbf{s}_i are derived. We obtain $(\mathbf{u}_1 - [p], \dots, \mathbf{u}_{\ell+1} - [p]) = (\mathbf{e}, e) = (\mathbf{c} - \mathbf{A}^\top \cdot \mathbf{s}, c - \mathbf{p} \cdot \mathbf{s}) \bmod q$. The decoder $\text{Decode}(\mathbf{u})$ maps the set of polynomials with coefficients in the range $[0, 2p]$ to a bit string such that the bit string $\mathbf{msg} = \text{Decode}(\mathbf{u}) \oplus \bar{u}$ returns the message.

Algorithm 6: $\text{KINDI}_{\text{CPA}}.\text{Decrypt}(\text{sk}, (\mathbf{c}, c)) :$

```

1  $\mathbf{A} \leftarrow \text{Shake}(\mu)$ 
2  $\bar{\mathbf{p}} = \text{Decompress}(\bar{\mathbf{b}}, t)$ 
3  $\mathbf{p} = (\bar{\mathbf{p}}_1 + \mathbf{g}, \bar{\mathbf{p}}_2, \dots, \bar{\mathbf{p}}_\ell)$ 
4  $\mathbf{v} = c - \mathbf{c} \cdot \mathbf{r}^\top$ 
5  $s_1 = \text{Recover}(\mathbf{v}) \in \mathcal{R}_2$ 
6  $\bar{\mathbf{u}}, \bar{s}_1, (s_2, \dots, s_\ell) \in \{0, 1\}^{n(\ell+1)\log 2p} \times \mathcal{R}_p \times \mathcal{R}_p^{\ell-1} \leftarrow \text{Shake}(s_1)$ 
7  $\mathbf{s} = (s_1 + 2 \cdot \bar{s}_1 - [p], s_2 - [p], \dots, s_\ell - [p])^\top$ 
8  $(\mathbf{e}, e) = (\mathbf{u}_1 - [p], \dots, \mathbf{u}_{\ell+1} - [p]) = (\mathbf{c} - \mathbf{A}^\top \cdot \mathbf{s}, c - \mathbf{p} \cdot \mathbf{s}) \bmod q$ 
9  $\text{msg} = \text{Decode}(\mathbf{u}) \oplus \bar{\mathbf{u}}$ 
10 return  $(\text{msg}, s_1)$ 
```

Algorithm 7: $\text{Decode}(\mathbf{u} \in \mathcal{R}_{2p}^{\ell+1}) :$

```

1 Concatenate the least significant  $\log 2p$  bits of all coefficients in  $\mathbf{u}$  into  $u$ .
2 return  $u \in \{0, 1\}^{n(\ell+1)\log 2p}$ 
```

Algorithm 8: $\text{Recover}(\mathbf{v} \in \mathcal{R}_q) :$

```

1 Let  $v_i$  be in  $\{0, \dots, q-1\}$ .
2 For  $i = 1$  to  $n$  do
3      $b_i = \lfloor v_i / 2^{k-1} \rfloor \bmod 2$ 
4 return  $b \in \mathcal{R}_2$ 
```

Algorithm 9: $\text{Recover}'(\mathbf{v} \in \mathcal{R}_q) :$

```

1 Let  $v_i$  be in  $\{0, \dots, q-1\}$ .
2 For  $i = 1$  to  $n$  do
3      $b_i = \lfloor v_i / 2^{k-2} \rfloor \bmod 4$ 
4 return  $b \in \mathcal{R}_4$ 
```

Theorem 2.2 *Let the coefficients of $\mathbf{r}_j, \mathbf{r}'_j, \mathbf{s}_j - [p]$ and $\mathbf{e}_i = \mathbf{u}_i - [p]$ be uniformly distributed from $\{-p, \dots, p-1\}$ for $1 \leq j \leq \ell$ and $1 \leq i \leq \ell+1$. Then, for*

$$\delta := P[\|\mathbf{w}^\top \cdot \mathbf{s} + e - \mathbf{e} \cdot \mathbf{r}^\top\|_\infty \geq q/4]$$

the algorithm is $(1 - \delta)$ correct, where $\mathbf{w} = \text{Decompress}(\text{Compress}(\mathbf{A} \cdot \mathbf{r} + \mathbf{r}')) - \mathbf{A} \cdot \mathbf{r}$.

Proof. We choose the parameters p and q such that s_1 is correctly recovered. Let $\mathbf{s} =$

$(\mathbf{s}_1 - [p], \dots, \mathbf{s}_\ell - [p])$, then

$$\begin{aligned}
\|\mathbf{v} - 2^{k-1}s_1\|_\infty &= \|c - \mathbf{c}^\top \cdot \mathbf{r} - 2^{k-1}s_1\|_\infty \\
&= \|\mathbf{p} \cdot \mathbf{s} + \mathbf{g} \cdot [p] + e - (\mathbf{A}^\top \cdot \mathbf{s} + \mathbf{e})^\top \cdot \mathbf{r} - 2^{k-1}s_1\|_\infty \\
&= \|\mathbf{g} \cdot (\mathbf{s}_1 - [p]) + \mathbf{g} \cdot [p] + e + \mathbf{w}^\top \cdot \mathbf{s} - \mathbf{e} \cdot \mathbf{r}^\top - 2^{k-1}s_1\|_\infty \\
&= \|\mathbf{w}^\top \cdot \mathbf{s} + e - \mathbf{e} \cdot \mathbf{r}^\top\|_\infty < q/4.
\end{aligned}$$

We note that in case $p = 2^x$, then the term $\mathbf{g} \cdot [p]$ vanishes and is not needed in the computation.

For $n = 256$ and $\lambda = 256$ (key size 2λ bits resisting Grover's search), we have $\mathbf{g} = 2^{k-2}$. We define the correctness requirement with respect to the bound $q/8$ rather than $q/4$, i.e.

$$\delta := P[\|\mathbf{w}^\top \cdot \mathbf{s} + e - \mathbf{e} \cdot \mathbf{r}^\top\|_\infty \geq q/8].$$

2.2 Trapdoor-based CCA-secure KEM $\text{KINDI}_{\text{KEM}}$ with Uniform Errors

The key encapsulation mechanism $\text{KINDI}_{\text{KEM}}$ has the same parameter space as $\text{KINDI}_{\text{CPA}}$. We adopt the transformation [9] in order to realize a KEM by our construction. In fact, we already indicated in Section 2.1 that some of the transformations are already encompassed in our construction. Thus, the construction gets very simple.

The generic construction secure in the quantum random oracle model is given by the following two algorithms, where $\mathbf{G}, \mathbf{H}, \mathbf{H}'$ denote random oracles.

Algorithm 10: QEncaps(pk) :
<pre> 1 $m \leftarrow \mathbf{M}$ 2 $\mathbf{c} := \text{Enc}(\text{pk}, m, \mathbf{G}(m))$ 3 $K := \mathbf{H}(m)$ 4 $d := \mathbf{H}'(m, \mathbf{c})$ 5 return (K, \mathbf{c}, d) </pre>

We state the theorem for tight security, when the computation and check of d is omitted. For that we combine the security implications [9] $\text{IND} - \text{CPA} \implies \text{OW} - \text{PCVA}$ and $\text{OW} - \text{PCVA} \implies \text{IND} - \text{CCA}$.

Theorem 2.3 *Let \mathbf{M} denote the message space. Furthermore, for any IND – CCA adversary that makes $q_{\mathbf{G}}$ queries to the random oracle \mathbf{G} , $q_{\mathbf{H}}$ queries to the random oracle \mathbf{H} , and $q_{\mathbf{D}}$*

Algorithm 11: QDecaps(sk, c) :

```

1  $m' \leftarrow \text{Dec}(\text{sk}, \text{c})$ 
2  $\text{c}' := \text{Enc}(\text{pk}, m', G(m'))$ 
3 if  $\text{c}' = \text{c} \wedge H'(m', \text{c}) = d$ 
4   return  $K := H(m', \text{c})$ 
5 else
6   return  $K := H(s, \text{c})$ 

```

queries to the decapsulation oracle, there exists an IND – CPA adversary such that

$$\text{Adv}_{\text{KEM}}^{\text{IND-CCA}}(\mathcal{B}) \leq q_G \cdot \delta + \frac{2 \cdot q_G + q_H}{|\mathbf{M}|} + 3\text{Adv}_{\text{PKE}}^{\text{IND-CPA}}(\mathcal{A}) \quad (1)$$

and the running time of A is about that of B .

This reduction is tight. Thus, we can tightly reduce it from $\text{MLWE}_{\ell, \ell+1, p}$.

For security in the quantum random oracle model, which requires d , there is an alternative theorem in [9].

2.3 Key Generation

The key generation step just outputs the keys of $\text{KINDI}_{\text{CPA}}$.

Algorithm 12: $\text{KINDI}_{\text{CCA-KEM}}.\text{KeyGen}(1^n, p, k, d, \ell)$:

```

1  $(\text{pk}, \text{sk}) \leftarrow \text{KINDI}_{\text{CPA}}.\text{KeyGen}(1^n, p, k, d, \ell)$ 
2 return  $(\text{pk}, \text{sk})$ 

```

2.4 Encapsulation

The encapsulation mechanism slightly differs from the generic construction. We do not need to input $G(s_1)$ but rather just s_1 . In fact, the encryption engine $\text{KINDI}_{\text{CPA}}.\text{Encrypt}$ does this implicitly within the algorithm as it applies $G(s_1)$ to deterministically deduce the secret and error polynomials. At the same time s_1 is encrypted (see $\text{KINDI}_{\text{CPA}}.\text{Encrypt}$). As in the generic construction, we compute the key $K \in \{0, 1\}^{2\lambda}$ and $d \in \{0, 1\}^{2\lambda}$. Due to the fact that KINDI has a large message container, we can also encrypt d and send a ciphertext that is as large as in $\text{KINDI}_{\text{CPA}}$. Finally, the ciphertext is output. We implement the different random oracles as $H(s_1) := \text{Shake}(s_1 || \text{padding})$, $H'(s_1, \text{c}) := \text{Shake}(s_1, \text{c})$ and $G(s_1) := \text{Shake}(s_1)$, where we use a one byte padding = 4.

Algorithm 13: $\text{KINDI}_{\text{CCA-KEM}}.\text{Encaps}(\text{pk}) :$

```

1  $s_1 \leftarrow \{0, 1\}^n$ 
2  $d \leftarrow H(s_1)$ 
3  $(\mathbf{c}, c)^\top \leftarrow \text{KINDI}_{\text{CPA}}.\text{Encrypt}(\text{pk}, d; s_1)$ 
4  $K \leftarrow H'(s_1, (\mathbf{c}, c))$ 
5 return  $K$ 

```

2.5 Decapsulation

The decapsulation mechanism implicitly performs many steps of the generic construction within $\text{KINDI}_{\text{CPA}}.\text{Decrypt}$. For instance, it is not required to encrypt s'_1 again once recovered from the ciphertext as we prove below. It is only necessary, to check that the decrypted d is equal to the computed d' . In case, the check is correct the key is deduced, otherwise it outputs a random key for some uniform random $s \in \{0, 1\}^{2\lambda}$.

Algorithm 14: $\text{KINDI}_{\text{CCA-KEM}}.\text{Decaps}(\text{sk}, (\mathbf{c}, c, d)) :$

```

1  $(d', s'_1) \leftarrow \text{KINDI}_{\text{CPA}}.\text{Decrypt}(\text{sk}, (\mathbf{c}, c))$ 
2 if  $d' = d$ 
3   return  $H'(s'_1, (\mathbf{c}, c))$ 
4 else
5   return  $H'(s, (\mathbf{c}, c))$ 

```

In the following lemma we show that it suffices to only check $d' = d$ in order to satisfy the conditions from [9] for key decapsulation.

Lemma 2.4 *If $d' = d$ is satisfied, then $s'_1 = s_1$ and $(\mathbf{c}, c) = \text{KINDI}_{\text{CPA}}.\text{Encrypt}(\text{pk}, d; s'_1)$.*

Proof. If $d' = d$, then $G(s_1) = G(s'_1)$, which means that s'_1 has been correctly recovered. As a result, we have that \mathbf{c}, c is uniquely generated from \mathbf{s} and $\mathbf{u} = \text{Encode}(\bar{u} \oplus d)$ with

$$\bar{\mathbf{u}}, \bar{s}_1, (\mathbf{s}_2, \dots, \mathbf{s}_\ell) \leftarrow G(s'_1)$$

and $\mathbf{s}_1 = s_1 + 2\bar{s}_1$.

We note that if $\text{KINDI}_{\text{CPA}}$ is $(1 - \delta)$ correct, then so is the resulting $\text{KINDI}_{\text{CCA-KEM}}$.

3 List of parameter sets (part of 2.B.1)

3.1 Parameter set encrypt/KINDI – 256 – 3 – 4 – 2

Public key encryption with $n = 256$, $\ell = 3$, $p = 4$, $t = 2$ and $q = 2^{14}$.

3.2 Parameter set encrypt/KINDI – 512 – 2 – 2 – 2

Public key encryption with $n = 512$, $\ell = 2$, $p = 2$, $t = 2$ and $q = 2^{13}$.

3.3 Parameter set encrypt/KINDI – 512 – 2 – 4 – 1

Public key encryption with $n = 512$, $\ell = 2$, $p = 4$, $t = 1$ and $q = 2^{14}$.

3.4 Parameter set encrypt/KINDI – 256 – 5 – 2 – 2

Public key encryption with $n = 256$, $\ell = 5$, $p = 2$, $t = 2$ and $q = 2^{14}$.

3.5 Parameter set encrypt/KINDI – 512 – 3 – 2 – 1

Public key encryption with $n = 512$, $\ell = 3$, $p = 2$, $t = 1$ and $q = 2^{13}$.

3.6 Parameter set kem/KINDI – 256 – 3 – 4 – 2

Key encapsulation mechanism with $n = 256$, $\ell = 3$, $p = 4$, $t = 2$ and $q = 2^{14}$.

3.7 Parameter set kem/KINDI – 512 – 2 – 2 – 2

Key encapsulation mechanism with $n = 512$, $\ell = 2$, $p = 2$, $t = 2$ and $q = 2^{13}$.

3.8 Parameter set kem/KINDI – 512 – 2 – 4 – 1

Key encapsulation mechanism with $n = 512$, $\ell = 2$, $p = 4$, $t = 1$ and $q = 2^{14}$.

3.9 Parameter set kem/KINDI – 256 – 5 – 2 – 2

Key encapsulation mechanism with $n = 256$, $\ell = 5$, $p = 2$, $t = 2$ and $q = 2^{14}$.

3.10 Parameter set kem/KINDI – 512 – 3 – 2 – 1

Key encapsulation mechanism with $n = 512$, $\ell = 3$, $p = 2$, $t = 1$ and $q = 2^{13}$.

4 Design rationale (part of 2.B.1)

We propose a simple and highly efficient trapdoor-construction, where the public key \mathbf{B} represents an MLWE instance endowed with a trapdoor \mathbf{T} . Roughly spoken, ciphertexts are generated as MLWE instances $\mathbf{B}^\top \cdot \mathbf{s} + \mathbf{e}$, where \mathbf{s} and $\mathbf{e} = \mathbf{u} \oplus \mathbf{msg}$ are vectors of uniform random polynomials. The message is simply xored to the error polynomials such that large amounts of data can be encrypted at very competitive parameters, for instance useful in sign-then-encrypt scenarios or for the transmission of encrypted key bundles etc. Different to other proposals, the decryption engine can recover all $\mathbf{s}, \mathbf{e} = \mathbf{u} \oplus \mathbf{msg}$ and thus \mathbf{msg} by means of the trapdoor \mathbf{T} . This further allows to inspect the secret and error polynomials and use all of the information stored therein. Our proposal not only encrypts arbitrary messages, but also outputs by construction a uniform random string s_1 for free that can act as a key for a symmetric key cipher as required in a KEM. In other words, the random coins used to encrypt the message can be recovered by use of the trapdoor.

We choose to implement random oracles with the FIPS 202 standardized **Shake**. It is also used in other lattice-based schemes such as Frodo and Kyber. The matrix \mathbf{A} is generated by use of a $\text{PRNG} \in \{\text{Shake128}, \text{Shake256}\}$ and a uniform random input string μ of size 2λ bits. In fact, we only use **Shake256** except for one parameter set namely $n = 256$ and $\ell = 3$. For the optimized variants we use the Keccak code package¹ that allows via AVX2 to compute 4 independent streams of random values on 4 inputs of the same length. Each input $\text{input}_i = \mu || i$ is obtained by the seed concatenated with a one byte number $0 \leq i \leq 3$ resulting in independent uniform random streams. Thus, we do not store \mathbf{A} but rather derive it from μ each time we need it. Since we work modulo 2^k , each k bit chunk is considered as a little endian integer representing one coefficient. Similarly, we generate uniform secrets and errors just from $\text{Shake}(s_1)$. Our choice for p to be a power of two allows us to proceed as with the matrix \mathbf{A} taking the required bits from **Shake** for \bar{u}, \bar{s}_1 and $\mathbf{s}_2, \dots, \mathbf{s}_\ell$. For the random oracle \mathbf{G} we use the same padding scheme in our optimized variant. The message is xored to \bar{u} prior to encoding.

However, for the computation of $d \in \{0, 1\}^{2\lambda}$ in the KEM we append 4 to s_1 before invoking $\mathbf{H} := \text{PRNG}$. We implement $\mathbf{H}' := \text{PRNG}$ without any padding in the reference implementation. For the optimized variant we split the large ciphertext into 4 inputs and invoke **Shake** outputting 4 streams of size 2λ bits each. The outputs are subsequently concatenated to s_1 serving as input to one regular **Shake** call.

We mark the end of a message by a one byte padding. For polynomial multiplication in $O(n \log n)$ we make use of the FFT transformation, which is a divide-and-conquer algorithm. Our AVX2 optimized variant processes 4 coefficients at once. Furthermore, we precompute tables containing powers of the complex root of unity. Modulo $q = 2^k$ operations are obtained almost for free as it just requires to take the k least significant bits.

The ciphertexts, compressed public keys and secret keys are stored in little endian format. The $k - t$ bit coefficients of the compressed public key are appended to each other before

¹<https://keccak.team/>

the seed μ is concatenated to the resulting string. For the secret key we proceed similarly.

5 Detailed performance analysis (2.B.2)

5.1 Description of platform

We implemented both our CPA/CCA secure schemes on a machine that is specified by an Intel Core i5-6200U processor (Skylake) operating at 2.3GHz and 8GB of RAM running on one core. We used Ubuntu 17.10 64-bit (Kernel 4.13.0-17) and gcc version 7.2.0 with compilation flags

- Reference: `-fomit-frame-pointer -Ofast -march=native`
- AVX Version: `-fomit-frame-pointer -Ofast -msse2avx -mavx2 -march=native`

5.2 Time

The following measurements are for `kem` and `encrypt`. The difference in running times between `kem` and `encrypt` stems from 3 additional invocations of `Shake` for `kem`. We took the average over 1 Mio measurements.

Kindi-256-3-4-2:

- Reference Implementation:
 - Key generation in cycles: 203096
 - Encryption/Encaps in cycles: $(\text{encrypt}, \text{kem}) = (247793, 260137)$
 - Decryption/Decaps in cycles: $(\text{encrypt}, \text{kem}) = (312211, 323947)$
- AVX Implementation:
 - Key generation in cycles: 104308
 - Encryption/Encaps in cycles: $(\text{encrypt}, \text{kem}) = (122648, 133888)$
 - Decryption/Decaps in cycles: $(\text{encrypt}, \text{kem}) = (151723, 162070)$

We note that in case we use `Shake256` key generation increases by about 3000-6000 cycles, encryption by about 3000-8000 cycles, encaps by about 8000-10000, decryption by 5000-6000 cycles and decaps by about 7000-10000 cycles (for the reference implementation and AVX implementation). The decryption failure rate is here $\delta = 2^{-192}$. In the AVX implementation, encryption is carried out at a speed of 320 cycles per message byte or 68 cycles per ciphertext byte, whereas decryption is accomplished at a rate of 396 cycles per message byte or 84 cycles per ciphertext byte.

Kindi-512-2-2-2:

- Reference Implementation:
 - Key generation in cycles: 214064
 - Encryption/Encaps in cycles: (`encrypt,kem`)=(280420,306043)
 - Decryption/Decaps in cycles: (`encrypt,kem`)=(377962,397147)
- AVX Implementation:
 - Key generation in cycles: 113082
 - Encryption/Encaps in cycles: (`encrypt,kem`)=(142950,160150)
 - Decryption/Decaps in cycles: (`encrypt,kem`)=(187097,202458)

The decryption failure rate is here $\delta = 2^{-284}$. In the AVX implementation, encryption is carried out at a speed of 373 cycles per message byte or 57 cycles per ciphertext byte, whereas decryption is accomplished at a rate of 488 cycles per message byte or 75 cycles per ciphertext byte.

Kindi-512-2-4-1:

- Reference Implementation:
 - Key generation in cycles: 215542
 - Encryption/Encaps in cycles: (`encrypt,kem`)=(285832,307999)
 - Decryption/Decaps in cycles: (`encrypt,kem`)=(382958,402041)
- AVX Implementation:
 - Key generation in cycles: 114356
 - Encryption/Encaps in cycles: (`encrypt,kem`)=(142961,160905)
 - Decryption/Decaps in cycles: (`encrypt,kem`)=(186397,202330)

The decryption failure rate is here $\delta = 2^{-165}$. In the AVX implementation, encryption is carried out at a speed of 248 cycles per message byte or 53 cycles per ciphertext byte, whereas decryption is accomplished at a rate of 324 cycles per message byte or 69 cycles per ciphertext byte.

Kindi-256-5-2-2:

- Reference Implementation:
 - Key generation in cycles: 519010
 - Encryption/Encaps in cycles: (`encrypt,kem`)=(595043,623436)

- Decryption/Decaps in cycles: $(\text{encrypt}, \text{kem}) = (701763, 723922)$
- AVX Implementation:
 - Key generation in cycles: 249776
 - Encryption/Encaps in cycles: $(\text{encrypt}, \text{kem}) = (280265, 298163)$
 - Decryption/Decaps in cycles: $(\text{encrypt}, \text{kem}) = (328537, 342016)$

The decryption failure rate is here smaller than $\delta = 2^{-216}$. In the AVX implementation, encryption is carried out at a speed of 731 cycles per message byte or 104 cycles per ciphertext byte, whereas decryption is accomplished at a rate of 857 cycles per message byte or 122 cycles per ciphertext byte.

Kindi-512-3-2-1:

- Reference Implementation:
 - Key generation in cycles: 429952
 - Encryption/Encaps in cycles: $(\text{encrypt}, \text{kem}) = (530173, 562640)$
 - Decryption/Decaps in cycles: $(\text{encrypt}, \text{kem}) = (672720, 698041)$
- AVX Implementation:
 - Key generation in cycles: 216600
 - Encryption/Encaps in cycles: $(\text{encrypt}, \text{kem}) = (256730, 282120)$
 - Decryption/Decaps in cycles: $(\text{encrypt}, \text{kem}) = (325113, 339830)$

The decryption failure rate is here $\delta = 2^{-276}$. In the AVX implementation, encryption is carried out at a speed of 502 cycles per message byte or 77 cycles per ciphertext byte, whereas decryption is accomplished at a rate of 636 cycles per message byte or 97 cycles per ciphertext byte.

5.3 Space

The secret key, public key and ciphertext sizes can be computed straightforwardly. They are the same for the encryption scheme and the KEM.

The ciphertext size is $n(\ell + 1)k/8$ bytes, whereas the public key \mathbf{pk} amounts to $(n\ell(k - t) + 2\lambda)/8$ bytes including the seed μ for the matrix \mathbf{A} . The secret key amounts to $(n\ell(k - t + \log 2p) + 2\lambda)/8$ bytes including the size of the public key. The message size for encryption amounts to $n\ell(\log 2p)/8 - 1$ bytes, where one byte is used for the padding. Thus, we obtain the following.

Kindi-256-3-4-2:

- Ciphertext size: 1792 bytes
- Public key size: 1184 bytes
- Secret key size: 1472 bytes
- Message size: 383 bytes
- Message expansion factor: 4.7

Kindi-512-2-2-2:

- Ciphertext size: 2496 bytes
- Public key size: 1456 bytes
- Secret key size: 1712 bytes
- Message size: 383 bytes
- Message expansion factor: 6.5

Kindi-512-2-4-1:

- Ciphertext size: 2688 bytes
- Public key size: 1728 bytes
- Secret key size: 2112 bytes
- Message size: 575 bytes
- Message expansion: 4.7

Kindi-256-5-2-2:

- Ciphertext size: 2688 bytes
- Public key size: 1984 bytes
- Secret key size: 2304 bytes
- Message size: 383 bytes
- Message expansion factor: 7

Kindi-512-3-2-3:

- Ciphertext size: 3328 bytes
- Public key size: 2368 bytes
- Secret key size: 2752 bytes
- Message size: 511 bytes
- Message expansion: 6.5

5.4 How parameters affect performance

The main parameters governing the performance and security level of the schemes are n, ℓ, q and $p = rsec$. For increasing parameters n, p or ℓ the security of the overall system is increased while simultaneously decreasing the performance level via n and ℓ or increasing the secret key size at a higher decryption failure rate via p . For increasing q and all other parameters being fixed, the decryption failure rate and the security of the system decrease while the ciphertext and public key sizes increase.

5.5 Optimizations

In principal, it is possible to generate the private and public keys just by use of the secret seed γ and the public seed μ . If in applications, the running time is of interest, then all keys and the matrix \mathbf{A} are stored rather than the seeds. In case, key sizes are more important than running time, then one may store only the seeds and generate the respective keys during decryption or decapsulation. Furthermore, it is possible to compress the ciphertext in case the message container is not fully exhausted, i.e. one can compress the coefficients of \mathbf{c}_i if the respective error terms do not contain message bits. For the simplicity of our construction, we did not include these modifications.

6 Expected strength (2.B.4) in general

6.1 Security definitions

The KEM is designed for IND-CCA2 security and PKE ensures CPA security. See Section 7 for quantitative estimates of the security of specific parameter sets.

6.2 Rationale

See Section 8 for an analysis of known attacks. This analysis also presents the rationale for these security estimates.

7 Expected strength (2.B.4) for each parameter set

7.1 Parameter set encrypt/KINDI – 256 – 3 – 4 – 2

Classical security	PQ-security	Category
181	164	2

7.2 Parameter set encrypt/KINDI – 512 – 2 – 2 – 2

Classical security	PQ-security	Category
229	207	4

7.3 Parameter set encrypt/KINDI – 512 – 2 – 4 – 1

Classical security	PQ-security	Category
255	232	4

7.4 Parameter set encrypt/KINDI – 256 – 5 – 2 – 2

Classical security	PQ-security	Category
270	251	5

7.5 Parameter set encrypt/KINDI – 512 – 3 – 2 – 1

Classical security	PQ-security	Category
365	330	5

7.6 Parameter set kem/KINDI – 256 – 3 – 4 – 2

Classical security	PQ-security	Category
181	164	2

7.7 Parameter set kem/KINDI – 512 – 2 – 2 – 2

Classical security	PQ-security	Category
229	207	4

7.8 Parameter set kem/KINDI – 512 – 2 – 4 – 1

Classical security	PQ-security	Category
255	232	4

7.9 Parameter set kem/KINDI – 256 – 5 – 2 – 2

Classical security	PQ-security	Category
270	251	5

7.10 Parameter set kem/KINDI – 512 – 3 – 2 – 1

Classical security	PQ-security	Category
365	330	5

8 Analysis of known attacks (2.B.5)

We give a summary of the most relevant attacks against our MLWE based encryption schemes. To this end, MLWE instances are considered as regular LWE instances of dimension $\ell \cdot n$ with $(\ell + 1) \cdot n$ samples. To date, there exist no better cryptanalytic algorithms to attack MLWE for concrete parameters than the ones on regular LWE. The best way to attack our encryption schemes is to mount a key recovery attack or to consider attacks against the ciphertext. Since we chose the same parameter for the ciphertext and public key, we need only to consider attacks against the ciphertext since it further contains an additional ring sample as compared to the public key. We apply the conservative methodology of [3] in order to estimate the attack complexity or to choose reasonable parameters. Currently, the best way to attack the system is carried out with the primal and dual attacks using BKZ. This lattice reduction algorithm reduces the basis of the lattice using polynomial calls to an SVP oracle in a smaller dimension. For the computation of the attack complexity only one call to the SVP oracle is taken into account. All other factors are also removed leading to very conservative estimates.

In the classical setting the best-known attack bound is $2^{0.292b}$ deduced from lattice sieving whereas in the post-quantum setting the SVP solver requires $2^{0.265b}$ with quantum sieving. Here b denotes the block size. The best plausible security estimates rely on building lists of

size $2^{0.2075b}$.

The primal attack on our cryptosystem consists in finding a unique solution $(\mathbf{s}, \mathbf{e}, 1)$ for the SIS instance $[\mathbf{P}^\top \mid \mathbf{I} \mid -\mathbf{c}] \cdot \mathbf{x} \equiv \mathbf{0} \pmod{q}$ for $\mathbf{x} \in \mathbb{Z}^{n(2\ell+1)+1}$ and \mathbf{pk} considered as a matrix $\mathbf{P} = [\mathbf{A} \mid \mathbf{p}^\top] \in \mathbb{Z}_q^{n\ell \times (n\ell+1)}$ and $\mathbf{c} \in \mathbb{Z}_q^{n(\ell+1)}$.

For the dual attack the attacker tries to find a short vector in the dual lattice that is employed to distinguish MLWE samples from uniform random samples in order to break decision-MLWE.

We do not need to take (quantum) hybrid attacks [8] into account as they often only get significant for sparse binary or trinary secrets and errors, which is never the case for the chosen parameters. Those attacks are based on Howgrave-Graham's Hybrid Attack combining lattice reduction with guessing techniques such as brute-force or meet-in-the-middle attacks.

Algebraic attacks such as finding short generators do not apply in our setting as the parameters required for a successful attack are far from being practical [5, 6].

9 Advantages and limitations (2.B.6)

The encryption scheme KINDI is a simple and flexible trapdoor-based encryption scheme, which by use of the trapdoor allows to retrieve back the error term and secret key from Module-LWE based ciphertexts. By this, it is possible to inspect all the constituents, if they comply with the allowed parameters in order to detect, for instance, inadmissible error terms. Furthermore, lattice-based trapdoor-constructions are used in many areas of cryptography, not only for encryption or KEMs. Thus, KINDI may serve as a basis for new primitives. For instance, when using a slightly modified $\text{KINDI}_{\text{CPA}}$ in combination with a random oracle tag $\mathbf{mac} = H(\mathbf{s}, \mathbf{e})$, we already obtain a scheme that can be employed in CCA2-secure scenarios, since an adversary needs to know the unique inputs in order to compute \mathbf{mac} or differently spoken a correct ciphertext requires already to show knowledge of all its inputs via the \mathbf{mac} .

In addition, KINDI allows to encrypt huge amount of data at once resulting in low message expansion factors as compared to other proposals since the error serves to transport the message. This is particularly interesting for sign-then-encrypt scenarios or for the transport of key bundles etc. For appropriate parameters signatures (uniform or Gauss) could also act as the error term, in this case the encryption scheme needs not to compute \bar{u} . Our proposal always by construction encrypts both a uniform random key s_1 and arbitrary messages. Thus, it inherently tends to act as a KEM. Due to this, we see that many steps from [9] are already implicit in our CPA-secure construction resulting in very small overhead. In fact, even the generation of s_1 in $\text{KINDI}_{\text{CCA-KEM}}$ is implicitly accomplished in the encryption engine. Due to uniform random secrets and error vectors generated by SHAKE and the applied operations our implementations are constant-time.

There exist a wide range of parameters for various security levels. Increasing the parameters allows to encrypt more data at once without losing efficiency. For $r_{\text{sec}} = 1$ we obtain binary errors, in this case we can even apply the NTT transform.

Our $\text{KINDI}_{\text{CCA-KEM}}$ can easily be deployed into the TLS protocol as shown by Google for **NewHope** or in constrained devices or can be transformed into an authenticated key exchange protocol using known transformations.

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