

SECURITY OF CYCLOTOMIC EXTENSIONS AGAINST THE [ELOS] ATTACK ON RLWE

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1. INTRODUCTION

Let $m \geq 1$ be any integer and let $K = \mathbb{Q}(\zeta_m)$. We will show that under a simplifying assumption, the image of a reduced RLWE error distribution $D_{\mathcal{R}} \pmod{\mathfrak{q}}$ for a prime \mathfrak{q} above q , will be non-distinguishable from the uniform distribution $U(\mathbb{F}_q)$. The tool we use is Fourier analysis on finite fields.

First, we introduce a class of distributions indexed by even integers $k \geq 2$, aiming at approximating discrete Gaussians over \mathbb{Z} . Here k plays the role of the standard deviation σ for discrete Gaussians.

Definition 1.1. For any even integer $k \geq 2$, let \mathcal{V}_k denote the distribution over \mathbb{Z} such that

$$\text{Prob}(\mathcal{V}_k = m) = \begin{cases} \binom{k}{m+\frac{k}{2}} & \text{if } |m| \leq \frac{k}{2} \\ 0 & \text{otherwise} \end{cases}$$

When $q > k$, we abuse notations and let $\mathcal{V}_k : \mathbb{F}_q \rightarrow \mathbb{R}$ denote the probability density function of the distribution \mathcal{V}'_k over \mathbb{F}_q defined by the same formula.

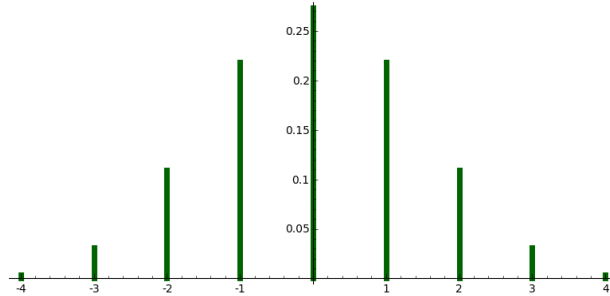


FIGURE 1.1. Probability density function of \mathcal{V}_8

Definition 1.2 (Modified error distribution). Let $K = \mathbb{Q}(\zeta_m)$ with degree n ring of integers R . Let q be a prime and let $k \geq 2$ be an even integer. Then a sample from the distribution $PD_{m,q,k}$ is

$$e = \sum_{i=0}^{n-1} e_i \zeta_m^i \pmod{qR},$$

where the e_i are sampled independently from \mathcal{V}_k .

Assumption Keeping the above notations, $\mathcal{R} = (K, q, \sigma, s)$ be an RLWE instance. We assume that the distributions $PD_{m,q, [\sqrt{2\pi}\sigma]}$ are $D_{\mathcal{R}}$ are “close modulo \mathfrak{q} ”, in the sense that the two distributions $PD_{m,q, [\sqrt{2\pi}\sigma]} \pmod{\mathfrak{q}}$ and $D_{\mathcal{R}} \pmod{\mathfrak{q}}$ are indistinguishable.

We will analyze the distance between $PD_{m,q, [\sqrt{2\pi}\sigma]} \pmod{\mathfrak{q}}$ and the uniform distribution over R/\mathfrak{q} .

2. AFTER INTRODUCTION

We recall the definition and key properties of Fourier transform over finite fields. Suppose f is a real-valued function on \mathbb{F}_q . The *Fourier transform* of f is defined as

$$\hat{f}(s) = \sum_{a \in \mathbb{F}_q} f(a) \bar{\chi}_s(a),$$

where

$$\chi_s(a) := e^{2\pi i as/q}$$

We have the inversion formula:

$$f(a) = \frac{1}{q} \sum_{s \in \mathbb{F}_q} \hat{f}(s) \chi_s(a).$$

Let $\mathbf{1}$ denote the constant function $f \equiv 1$, and let δ denote the characteristic function of the one-point set $\{0\} \subseteq \mathbb{F}_q$.

Proposition 2.1.

- (1) The transform of the δ function is $\hat{\delta} = \mathbf{1}$.
- (2) The transform of $\mathbf{1}$ is $\hat{\mathbf{1}} = q\delta$; if U the uniform distribution over \mathbb{F}_q , then $\hat{U} = \delta$.
- (3) convolution becomes product.

Lemma 2.2. For all even integers $k \geq 2$,

$$\hat{\mathcal{V}}_k(s) = \cos\left(\frac{\pi s}{q}\right)^k, (\forall s \in \mathbb{F}_q).$$

Proof. Routine calculation. □

Now we consider the error distribution we obtained from mapping RLWE errors to \mathbb{F}_q .

Definition 2.3. Suppose $\mathbf{a} = a_1, \dots, a_n$ is a vector in \mathbb{F}_q^n . Define the following random variable with values in \mathbb{F}_q

$$e(\mathbf{a}, k, q) := \sum_{i=1}^n a_i e_i \pmod{q}$$

where the e_i are independent variables with distribution \mathcal{V}_k . Let E denote its probability density function: $E(b) = \text{Prob}(e = b)$ for $b \in \mathbb{F}_q$.

Next, using the fact that the probability of a sum of two variables is a convolution, we prove

Lemma 2.4.

$$E_{\hat{\mathbf{a}}, k, q}(s) = \prod_{i=1}^n \cos\left(\frac{a_i \pi s}{q}\right)^k$$

In particular, $\hat{E}(0) = 1$ for all \mathbf{a} , k and q .

Proof. Routine calculation. □

Next we restrict our attention to cyclotomic fields. Let $m \geq 1$ be an integer and let $q \equiv 1 \pmod{m}$ be a prime. Then q splits completely in the cyclotomic field $K = \mathbb{Q}(\zeta_m)$. Let $\alpha \in \mathbb{F}_q$ be a primitive n -th root of unity. Let

$$e = e(\alpha) = \sum_{i=0}^{n-1} e_i \alpha^i.$$

Then $e \leftarrow PD_{m, q, k}$. Let E denote its density function of e . Recall that U denotes the density function of the uniform distribution: $U(a) = 1/q$ for all $a \in \mathbb{F}_q$. Now We can compute $(E - U)(a)$ for any $a \in \mathbb{F}_q$ using the Fourier inversion formula, using the notations in the beginning of this section,

$$\begin{aligned}
E(a) - U(a) &= \frac{1}{q} \sum_{s \in \mathbb{F}_q} (\hat{E}(s) - \hat{U}(s)) \chi_s(a) \\
&= \frac{1}{q} \sum_{s \in \mathbb{F}_q} (\hat{E}(s) - \delta(s)) \chi_s(a) \\
&= \frac{1}{q} \sum_{s \in \mathbb{F}_q, s \neq 0} \hat{E}(s) \chi_s(a).
\end{aligned}$$

Since $|\chi_s(a)| \leq 1$ for all a and all s , we have

Proposition 2.5.

$$|E(a) - 1/q| \leq \frac{1}{q} \sum_{y \in \mathbb{F}_q, y \neq 0} |\hat{E}(y)|, (\forall a \in \mathbb{F}_q)$$

Let $\epsilon(m, q, k, \alpha)$ denote the right hand side of the above inequality, i.e.,

$$\epsilon(m, q, k, \alpha) = \frac{1}{q} \sum_{y \in \mathbb{F}_q, y \neq 0} \prod_{i=0}^{n-1} \cos \left(\frac{\alpha^i \pi y}{q} \right)^k.$$

We let α run over all primitive n -th root of unities in \mathbb{F}_q and define

$$\epsilon(m, q, k) := \max_{\alpha: \varphi_m(\alpha)=0} \epsilon(m, q, k, \alpha)$$

The punchline of our argument is: the value $\epsilon(m, q, k)$ is usually negligibly small. As a result, the distribution $PD_{m,q,k} \pmod{q}$ is computationally indistinguishable from uniform for all q . The following is a table of data, to demonstrate how small it is.

TABLE 2.1. $f = 1$

m	q	$\lceil \log_2(\epsilon(m, q, 2)) \rceil$
244	1709	-230
101	1213	-177
256	3329	-194
256	14081	-208
55	10891	-44
197	3547	-337
96	4513	-35
160	20641	-61
145	19163	-176
101	101	-4
13	1000039	-12
512	7681	-455
512	10753	-431
512	19457	-414

On row -1 and -2 from the above table, we can see the effect of taking the ramified prime, or taking $q \gg n$.

Remark 2.6. It is possible to generalize this cryptanalysis to higher degree primes, where we are looking at general finite fields \mathbb{F}_{q^f} . In this situation we should interpret $\chi_s(a) = e^{2\pi i \text{Tr}(as)/q}$. Separability tells us this is an isomorphism between \mathbb{F}_q and its dual, and we can define the Fourier transform this way. So everything goes through? We just want to add a trace to everything, i.e.,

$$\hat{E}_{\mathbf{a},k,q}(s) = \prod_{i=1}^n \cos \left(\frac{\pi \text{Tr}(a_i s)}{q} \right)^k$$

Note this is well-defined when k is even, which we always assume.

We have a table for degree 2 primes.

TABLE 2.2. $f = 2$

m	q	$\lfloor \log_2(\epsilon(m, q, 2)) \rfloor$
53	211	-61
55	109	-48
63	881	-33
64	127	-37
64	191	-35
64	383	-31

3. REFERENCES

https://en.wikipedia.org/wiki/Fourier_transform_on_finite_groups
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