

TITLE OF DOCUMENT

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1. χ^2 TEST FOR UNIFORM DISTRIBUTION

We briefly recall the property and usage of the χ^2 test for uniform distributions over a finite set S . Suppose M samples $y_1, \dots, y_M \in S$. We partition S into r subsets

$$S = \sqcup_{j=1}^r S_j,$$

For each $1 \leq j \leq r$, we compute the expected number of samples that would fall in the j -th subset: $c_j := |S_j|M/|S|$. Then we compute the actual number of samples, $t_j := |\{1 \leq i \leq M : y_i \in S_j\}|$. Finally, the χ^2 value is computed as

$$\chi^2(S, y) = \sum_{j=1}^r \frac{(t_j - c_j)^2}{c_j}.$$

Note that degree of freedom in this test is $d = r - 1$. To decide whether the samples are from a uniform distribution, we can either look up a table of χ^2 values, or use an approximation rule: when d is large, the χ^2 distribution can be well-approximated by a normal distribution $N(d, 2d)$; for example, if it turns out that $\chi^2 \notin (d - c\sqrt{2d}, d + c\sqrt{2d})$, then the confidence we have that the samples are not taken from a uniform distribution is $2\Phi(c) - 1$.

2. ATTACK

Now we describe our attack. It relies on the assumption that there exists a prime ideal \mathfrak{q} such that error $e \pmod{\mathfrak{q}}$ is not uniformly distributed in the finite field $F = R/\mathfrak{q}R$. The attack loop through all q^f possibilities of $\bar{s} = s \pmod{\mathfrak{q}}$. For each guess s' , it computes the values $\bar{e}' = \bar{b} - \bar{a}s' \pmod{\mathfrak{q}}$. If the guess is wrong, or if the samples are taken from the uniform distribution instead of an RLWE instance, then \bar{e}' is uniformly distributed in F and it would pass the χ^2 test. On the other hand, if the guess is correct, then we expect the errors \bar{e}' to fail the χ^2 test.

Let $N = q^f$, the number of χ^2 tests we run in the attack. For the attack to be successful, we need the $(N - 1)$ tests corresponding to wrong guess of $s \pmod{\mathfrak{q}}$ to pass, and the one test corresponding to the correct guess to fail. Therefore, we need to choose the confidence interval of our χ^2 test so that it is unlikely for a set of samples coming from uniform distribution to fail the test. In practice, we choose the confidence level to be $\alpha = 1 - \frac{1}{10N}$. Let β denote the probability that the sample errors fails the uniform test with probability α . Then the probability that our algorithm will success is $p = (1 - \frac{1}{10N})^{N-1}\beta$. Note that when N is large, $(1 - \frac{1}{10N})^{N-1}$ is about $e^{-1/10} \approx 0.904$.

Algorithm 1 χ^2 -test attack of RLWE(R, \mathfrak{q})

Require: $R = (K, q, \sigma)$ – an RLWE instance.

$R = \mathcal{O}_K$ – the ring of integers of K .

n : the degree of K .

\mathfrak{q} : a prime ideal in K above q .

N : the cardinality of the finite field R/\mathfrak{q} .

S : a collection of M ($M = \Omega(N)$) RLWE samples $(a, b) \sim R$.

Ensure: a guess of the value $s \pmod{\mathfrak{q}}$, or **NON-RLWE**, or **INSUFFICIENT-SAMPLES**

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1:  $\alpha \leftarrow 1 - \frac{1}{10N}$ .
2:  $\omega \leftarrow \Phi^{-1}((1 + \alpha)/2)$ 
3:  $G = \emptyset$ 
4: for  $s$  in  $F$  do
5:   for  $a, b$  in  $S$  do
6:      $E \leftarrow \emptyset$ .
7:      $\bar{a}, \bar{b} \leftarrow a \pmod{\mathfrak{q}}, b \pmod{\mathfrak{q}}$ .
8:      $\bar{e} \leftarrow \bar{b} - \bar{a}s$ .
9:     add  $e$  to  $E$ .
10:  end for
11:  Run  $\chi^2$  test on  $E$  and obtain the value  $\chi^2(E)$ .
12:  if  $|\chi^2(E) - B - 1| > \omega\sqrt{2B - 2}$  then
13:    add  $s$  to  $G$ 
14:  end if
15: end for
16: if  $G = \emptyset$  then
17:   return NOT RLWE
18: else if  $G = \{g\}$  then
19:   return  $g$ 
20: else
21:   return INSUFFICIENT-SAMPLES
22: end if
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Proof of correctness.

Proposition 2.1. *The algorithm has time complexity $O(q^{2f})$. Let Δ be the statistical distance between $D_{R, \sigma} \pmod{\mathfrak{q}}$ and the uniform distribution on R/\mathfrak{q} . Then algorithm outputs with probability at least 0.904Δ (fixme: do the correct constant).*