Single trace HQC shared key recovery with SASCA

Fifth NIST PQC Standardization Conference

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Table of Contents

Table of Contents

Soft Analytical Side-Channel Attacks (SASCA)

Idea : combine several weak physical leaks to obtain strong information

- Introduced by Veyrat-Chravrillon et al. [VCGS14] to attack AES in 2014
- Application against Kyber [PPM17, PP19, HHP+21, HSST23, AEVR23]
  - $\rightarrow$ Information Propagation through NTT

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  → Information Propagation through NTT
- Attack against hash function Keccak [KPP20] in 2020
- First attack against code-based cryptography [GMGL23]

➔ Mainly based on **Belief Propagation** [Mac03, KFL01].

Message passing with Belief Propagation

The goal of Belief Propagation is to compute a **Marginal Distribution** for every **Intermediate values** involved in a given algorithm.

Toy Example : Galois Field Multiplication $v = a \times b \; (= \alpha^{\log(a)+\log(b)})$:

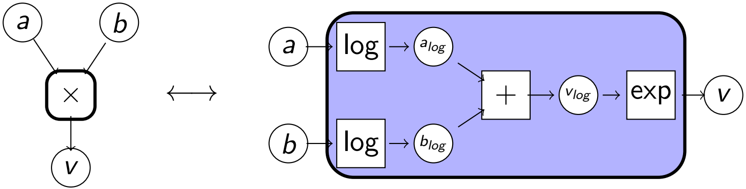

Figure – Graphical representation of a Galois Field Multiplication

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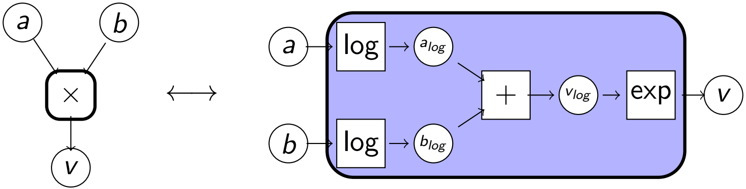

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The Goal is to compute : $\mathbb{P}(a \mid b, v), \mathbb{P}(b \mid a, v), \mathbb{P}(v \mid a, b)$

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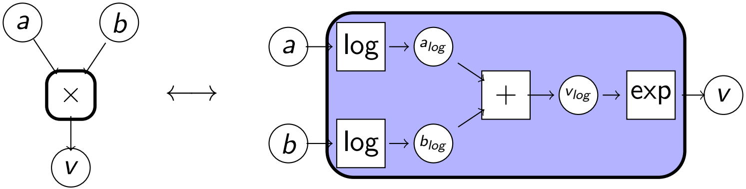

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Sum Product Algorithm [KFL01] gives a solver for this problem.

Table of Contents

Hamming Quasi-Cyclic

Algorithm Keygen

Input : param
Output : (pk, sk)

1: $\mathbf{h} \xleftarrow{\$} \mathcal{R}$
2: $(\mathbf{x}, \mathbf{y}) \xleftarrow{\$} \mathcal{R}_\omega^2$
3: $\mathbf{s} = \mathbf{x} + \mathbf{h}\mathbf{y}$
4: $\mathrm{pk} = (\mathbf{h}, \mathbf{s})$
5: $\mathrm{sk} = (\mathbf{x}, \mathbf{y})$

Algorithm Encrypt

Input : $(\mathrm{pk}, \mathbf{m} \in \mathbb{F}_2^\lambda)$
Output : ciphertext ct

1: $\mathbf{e} \xleftarrow{\$} \mathcal{R}_{\omega_e}$
2: $(\mathbf{r}_1, \mathbf{r}_2) \xleftarrow{\$} \mathcal{R}_{\omega_r}^2$
3: $\mathbf{u} = \mathbf{r}_1 + \mathbf{h}\mathbf{r}_2$
4: $\mathbf{c} = \mathtt{Encode}(\mathbf{m})$
5: $\mathbf{v} = \mathbf{c} + \mathbf{s}\mathbf{r}_2 + \mathbf{e}$
6: $\mathtt{ct} = (\mathbf{u}, \mathbf{v})$

Algorithm Decrypt

Input : (sk, ct)
Output : $\mathbf{m}'$

1: $\mathbf{c} + \mathbf{e}' = \mathbf{v} - \mathbf{u}\mathbf{y}$
2: $\mathbf{m}' = \mathtt{Decode}(\mathbf{c} + \mathbf{e}')$

Hamming Quasi-Cyclic

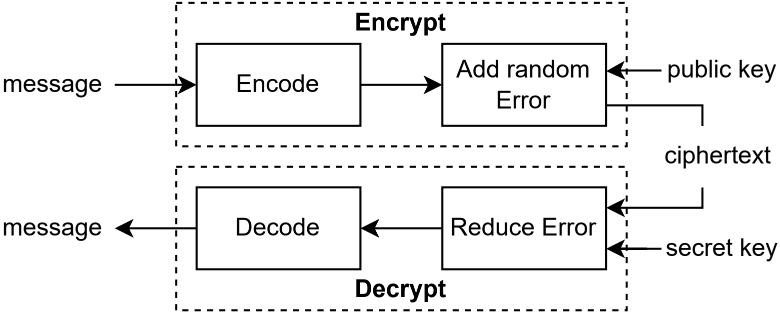

Figure – Hamming Quasi-Cyclic Overview

- Decryption Failure Rate (DFR) is ensured by the error correction capability and analysis of the hamming weight distribution of the error **e**' [AGZ20]
- Most of the Side-Channel Attacks against HQC target the **decoding step**.

Concatenated code structure

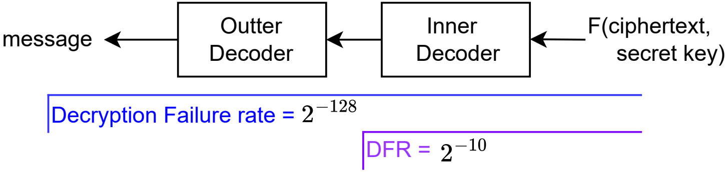

Figure – HQC Concatenated codes structure

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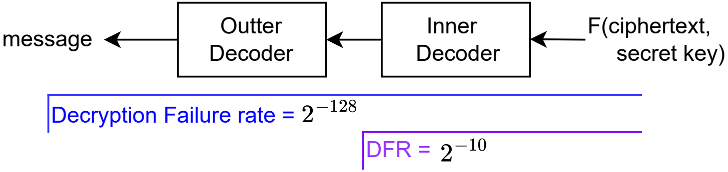


Figure – HQC Concatenated codes structure

(i) **Secret key** recovery attacks : [SHR+22, GLG22a, BMG+24]

(ii) **Shared key** (message) recovery attacks : [GLG22b, GMGL23, BMG+24]

Reed-Solomon Syndrome Computation

Algorithm Compute Syndromes from HQC RS Decoder from [AMAB+23]

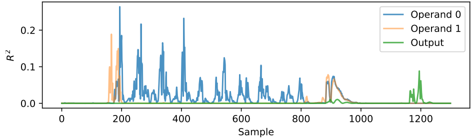
Require: parameters : k, n the dimension and length of the code
Require: parity check matric $H \in \mathbb{F}_q^{(n-k,n)}$
Require: codeword $c \in \mathbb{F}_q^{n_1}$
Ensure: $s := H^T \times c$ the syndrome of c

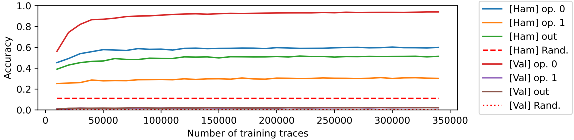
```
1: Initialize s to 0^(n-k)
2: for i from 0 to n - k do
3:     for j from 1 to n do
4:         s[i] = s[i] ⊕ c[j] × H[i, j - 1]        ▷ × is the Galois Field multiplication
5:     s[i] = s[i] ⊕ c[0]
```

Table of Contents

Templates on the Galois field multiplication operands

Galois field multiplication based on FFT strategy [BGTZ08]





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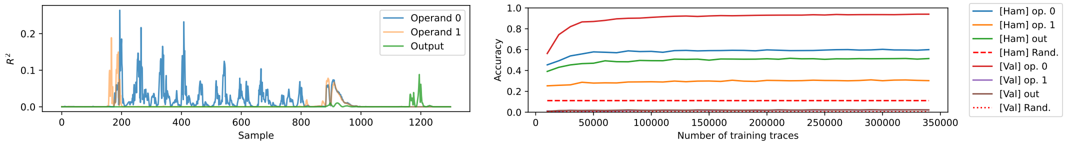


	Value template accuracy	Hamming weight template accuracy
Input 1	**0.9389**	0.5929
Input 2	0.0211	**0.3035**
Output	0.0221	**0.5178**

Table – Hamming weight and value templates accuracies on `gf_mul`. Each attack has been performed 400 times. 10%/90% validation/training segmentation.

Outer Decoder syndrome computation graphical representation

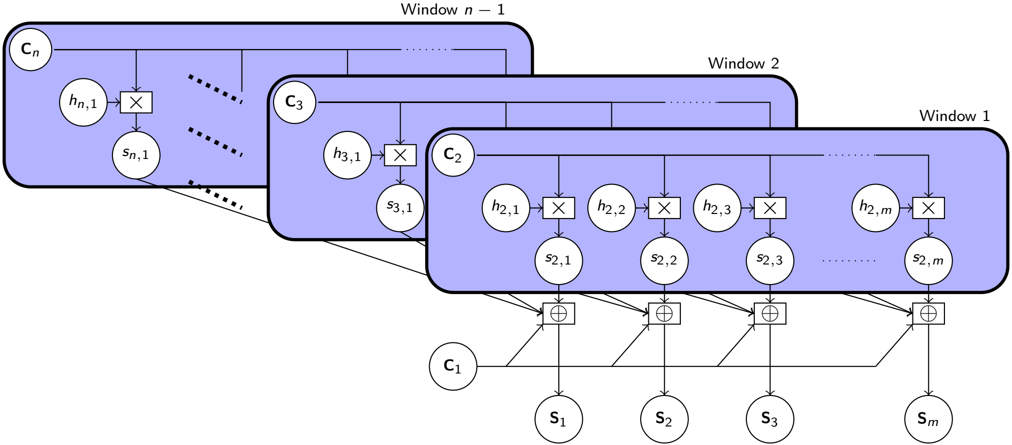
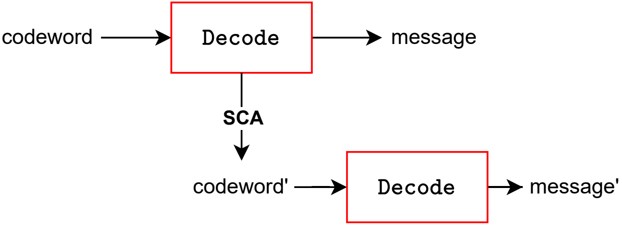


Figure – Graphical representation of the RS syndrome computation from HQC

Re-decoding Strategy



Security level	HQC parameters			List decoder
λ	k_1	n_1	t	τ_{GS}
HQC-128	16	46	15	19
HQC-192	24	56	16	19
HQC-256	32	90	29	36

Table – Reed-Solomon error correction capability of the RS decoder for each HQC set of parameters, given for a classical decoder and the Guruswami-Sudan list decoder.

Attack Accuracy in Simulation

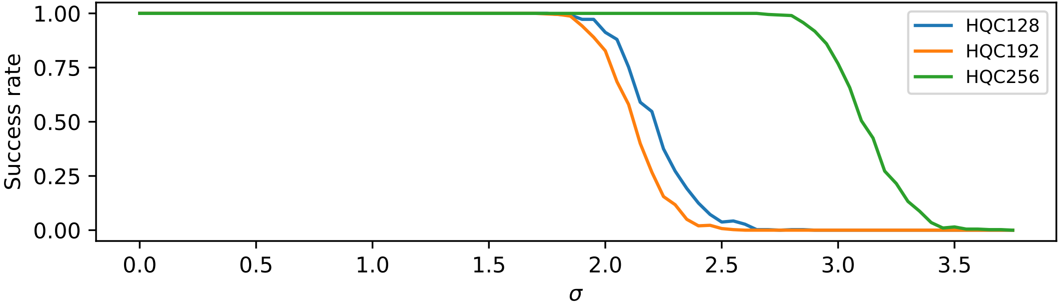
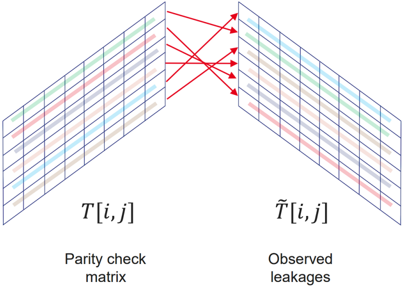


Figure – Simulated success rate of SASCA on the decoder, with re-decoding strategy, depending on the selected security level of HQC

Breaking shuffling countermeasures

- Fine Shuffling (Adapted from a Kyber countermeasure)
  $\rightarrow$ Randomly choose $a \times b$ or $b \times a$.
- Coarse shuffling (Adapted from a Kyber countermeasure)
  $\rightarrow$ Randomly shuffle columns of the parity check matrix
- Window Shuffling (Novelty)
  $\rightarrow$ Randomly shuffle lines of the parity check matrix



$$D[i,i'] = \sum_{j=1}^{256} \mathrm{d}\left(\tilde{T}[i,j], T[i',j]\right)$$

Instance of the assignment Problem.
$\rightarrow$ Solver : Hungarian algorithm.

Breaking Codeword Masking (High Level Masking)

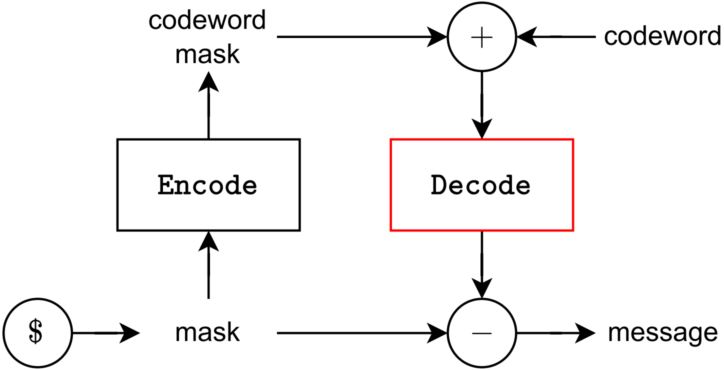


Figure – High level Masking of a decoder (Codeword Masking) [MSS13]

Encoder Attack Accuracy in Simulation

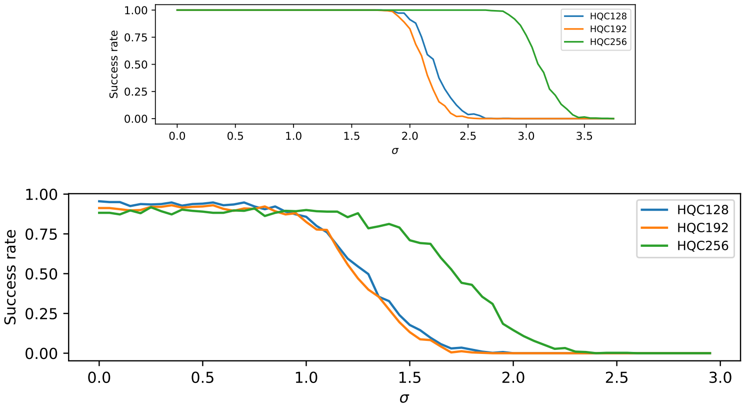


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Table of Contents

re-encryption step from HHK transform

- HQC-KEM is based on HHK transform [HHK17]
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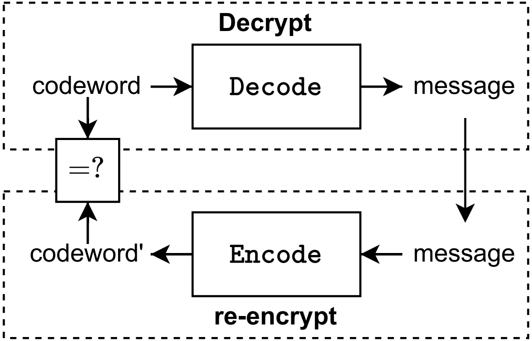

Figure – HQC Structure with HHK transform

FO Attack Accuracy in Simulation

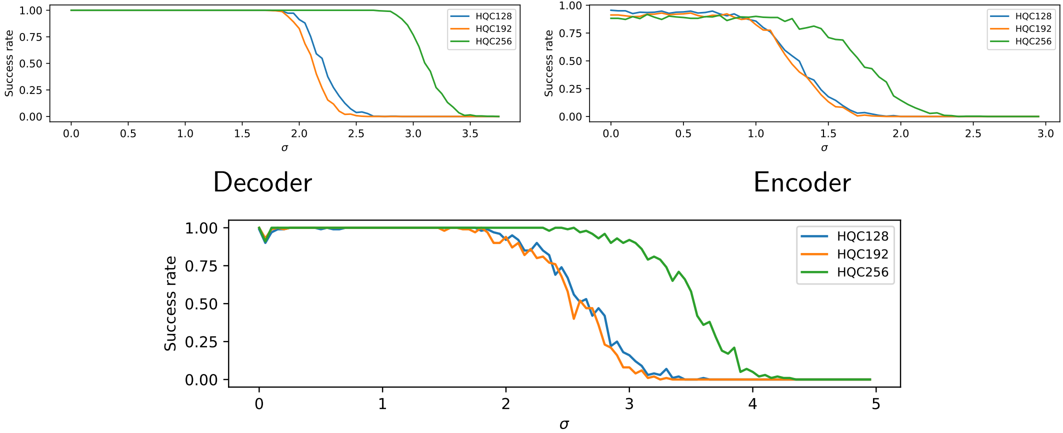

Figure – Simulated success rate of SASCA on the decoder and encoder exploiting re-encryption

Table of Contents

Full Shuffling Countermeasure

- The idea is to shuffle the entire matrix, instead of only rows or columns, during the matrix vector multiplication.
  → Even if an attacker exactly recover the shuffled matrix, there exists 2^{504}, 2^{614} and 2^{1030} different permutations for the three security levels respectively.

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  - → Even if an attacker exactly recover the shuffled matrix, there exists 2^{504}, 2^{614} and 2^{1030} different permutations for the three security levels respectively.
- The encoder could be change to a classical multiplication with a generator matrix to benefit from the same countermeasure.

Table of Contents

Conclusion and Perspectives

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- Efficient countermeasure against these attacks are required.

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Future Works

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Thank you for your attention !

Any questions ?

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