Side-Channel Attacks against HQC and Countermeasures

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Modern cryptography

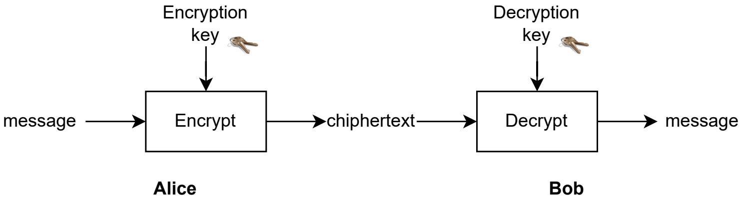

Figure – Overview of a cryptosystem

Hybrid Cryptosystem :

- Symmetric-key cryptography : based on exhaustive key research
- Public-key cryptography : based on a hard problem

→ RSA [RSA78] - Elliptic Curves Cryptography (ECC) [Kob87, Mil85]

Post-Quantum Cryptography (PQC) – NIST Standardization

Figure – IBM Quantum Computer

→ Quantum Computer threat !
Shor's and Grover's Algorithms

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Shor's and Grover's Algorithms

Several possibilities (NIST Standards) :

- Kyber (ML-KEM - FIPS203) [BDK+18]
- Dilithium (ML-DSA - FIPS024) [DKL+18]
- Falcon (not yet published) [PFH+20]
- Sphincs+ (SLH-DSA - FIPS205) [BHK+19]
- HQC (not yet published) [AMAB+17]

Other past code-based candidates :

- BIKE [ABB+17] // ClassicMcEliece [BCL+]

And now ? ! → new round for additionnal signature schemes !
(promizing MPC-in-the-head ? !)

Cryptographic Security

We consider three levels of security : (I) 2^{128}, (III) 2^{192} and (IV) 2^{256}

This represents the **minimal number of operation requiered to recover a secret information**.

And often also **The number of different secret keys**.

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$$2^{128} = \underbrace{2^{33}}_{\substack{\text{8.6 billion}\\ \text{Number of}\\ \text{human beings}\\ \text{on earth}}} \times \underbrace{2^{33}}_{\substack{\text{8.6 GHz}\\ \text{CPU frequency}}} \times \underbrace{2^{62}}$$

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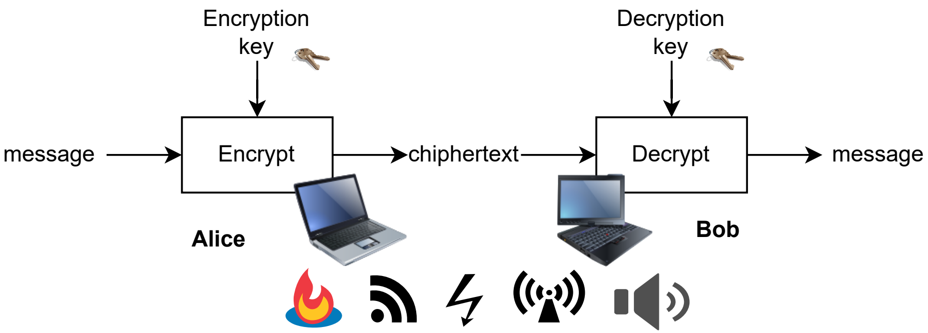
$$2^{256} \approx\approx 10^{80} \leftarrow \text{Number of atoms in the observable universe}$$

Number of worldwide operations for Bitcoin in a year $\approx 2^{95}$.

Side-Channel Attacks



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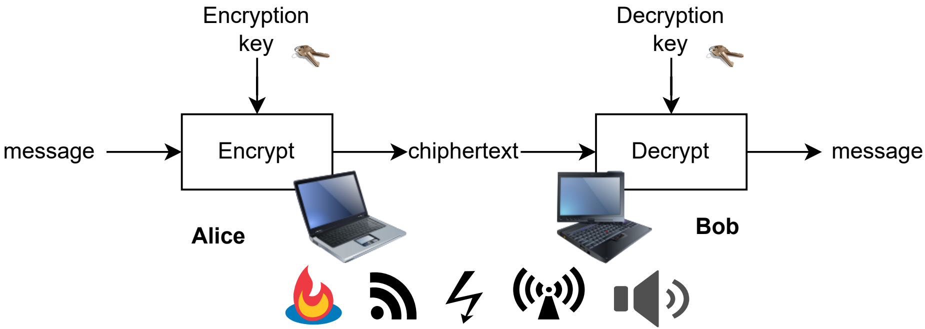

Physical behavior is correlated to manipulated data.
The first side-channel attack was introduced by Paul Kocher in 1996 [Koc96].

Side-channel attacks toy example

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Random Digicode : 10^4 combinations

Side-channel attacks toy example

Random Digicode : 10^4 combinations
Worn Digicode : 24 combinations

- Bypass the security with a physical observation

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Error Correcting Codes

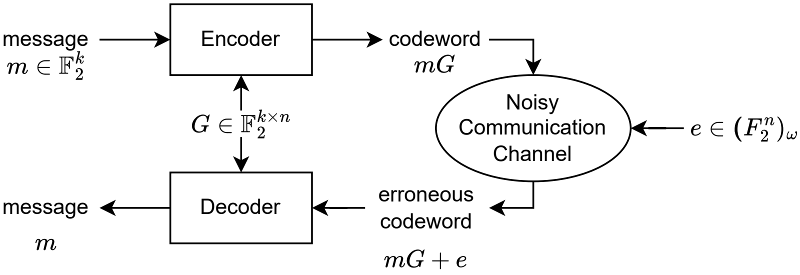

Figure – Overview of an Error Correcting Code.

Code-based cryptography : $G \xleftarrow{\$} \mathbb{F}_2^{k \times n}$, $m \xleftarrow{\$} \mathbb{F}_2^k$ and $e \xleftarrow{\$} (\mathbb{F}_2^n)_\omega$.

Decoding Problem :

Given $(mG + e, G)$, it is hard to recover m (NP-complete [BMVT78]).

Building Code-based cryptography

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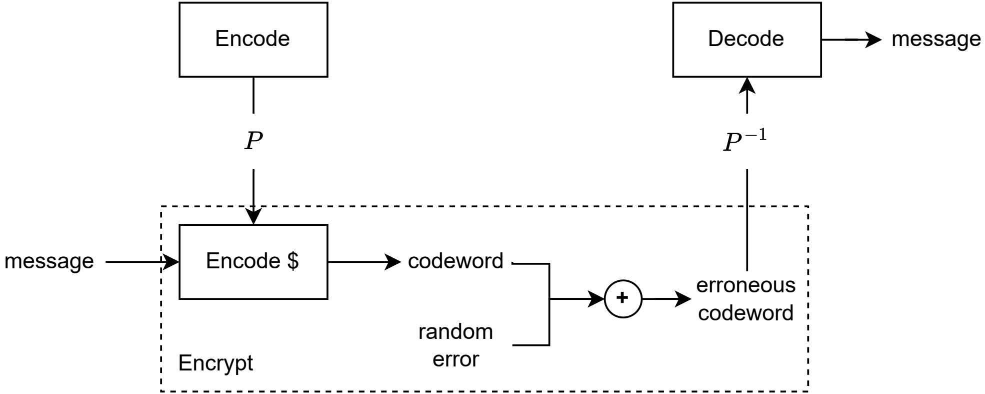

Figure – Masking error correcting code structure to build cryptography

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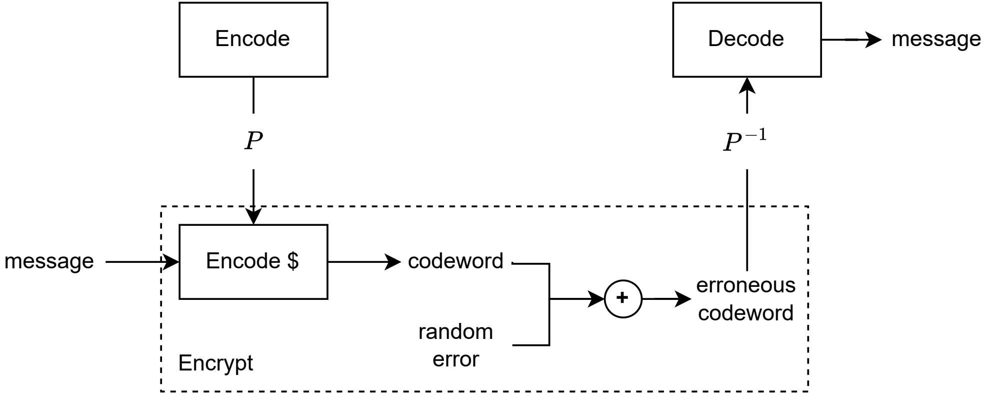


Figure – Masking error correcting code structure to build cryptography

Hamming Quasi-Cyclic (HQC)

$$\mathcal{R} = \mathbb{F}_2[X]/(X^n - 1)$$

Alice		Bob
$\mathbf{h} \xleftarrow{\$} \mathcal{R}$ $\quad \mathbf{x}, \mathbf{y} \xleftarrow{\$} \mathcal{R}_\omega^2$ $\mathbf{s} = \mathbf{x} + \mathbf{h}\mathbf{y}$	$\xrightarrow{\mathbf{s}, \mathbf{h}}$	message m $\mathbf{e} \xleftarrow{\$} \mathcal{R}_{\omega_r}$ $\quad \mathbf{r}_1, \mathbf{r}_2 \xleftarrow{\$} \mathcal{R}_{\omega_e}^2$ $\mathbf{u} = \mathbf{r}_1 + \mathbf{h}\mathbf{r}_2$
$\mathbf{m}' = \mathcal{C}.\mathtt{Decode}(\mathbf{v} - \mathbf{u}\mathbf{y})$	$\xleftarrow{\mathbf{u}, \mathbf{v}}$	$\mathbf{v} = \mathcal{C}.\mathtt{Encode}(\mathbf{m}) + \mathbf{s}\mathbf{r}_2 + \mathbf{e}$

Figure – HQC Public Key Encryption Scheme

- No Code structure masking

2 codes for HQC :

- $\mathbf{h}$ is a random code to protect the secret key and perform the encryption.
- $\mathcal{C}$ is a public and efficient code to perform decryption. Any code can be selected.

Hamming Quasi-Cyclic (HQC) 2

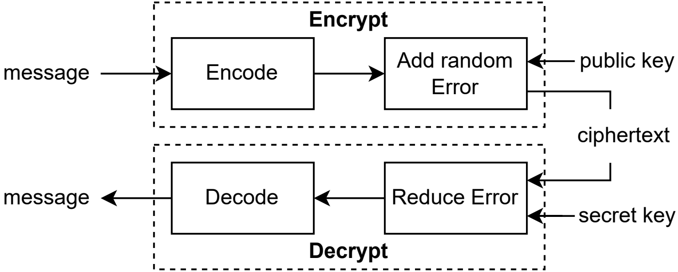
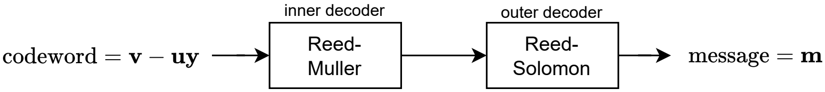


Figure – Hamming Quasi-Cyclic Overview

Concatenated Code structure

- Before 2019 → Concatenated BCH and repetition codes.
- After 2019 → Concatenated Reed-Muller and Reed-Solomon codes.



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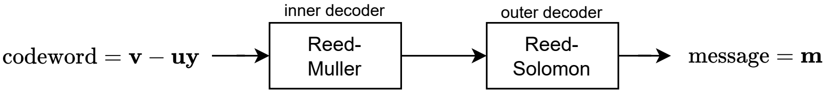

Figure – HQC Concatenated codes structure

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

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

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Attack Scenario I

→ Chosen Ciphertext attack to recover the secret key $\mathbf{y}$.

$$\mathcal{C}.\texttt{Decode}(\mathbf{v} - \mathbf{uy})$$

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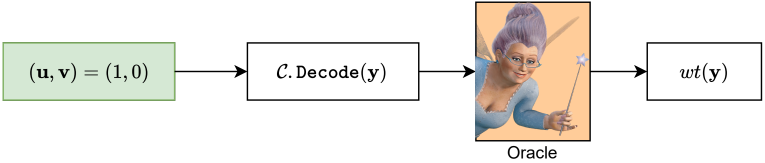

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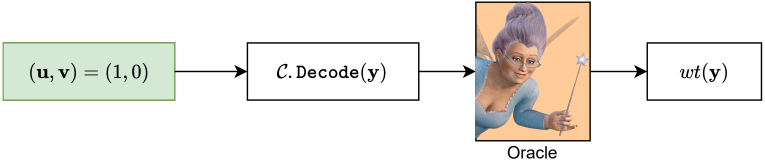
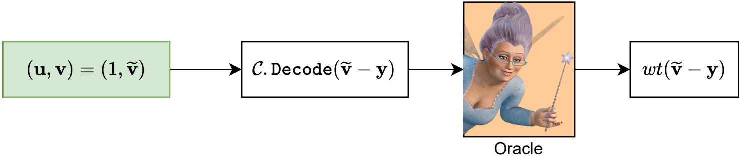
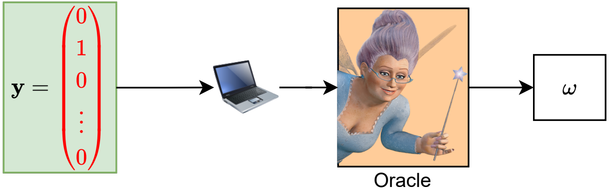




Attack Scenario II



ω is known public parameter of HQC.

Attack Scenario III

If $\tilde{\mathbf{v}}$ has an Hamming weight of 1, they are two possibilities :

$$\tilde{\mathbf{v}} - \mathbf{y} = \begin{pmatrix}0\\1\\0\\\vdots\\0\end{pmatrix} - \begin{pmatrix}0\\1\\0\\\vdots\\0\end{pmatrix} = \begin{pmatrix}0\\0\\0\\\vdots\\0\end{pmatrix}$$

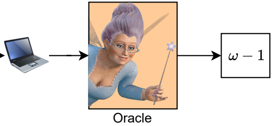


Figure – Collision Case

$$\tilde{\mathbf{v}} - \mathbf{y} = \begin{pmatrix}1\\0\\0\\\vdots\\0\end{pmatrix} - \begin{pmatrix}0\\1\\0\\\vdots\\0\end{pmatrix} = \begin{pmatrix}1\\1\\0\\\vdots\\0\end{pmatrix}$$

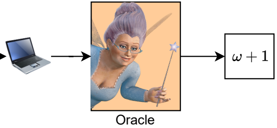
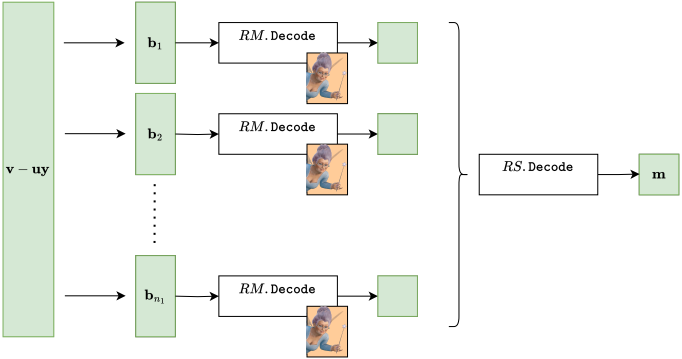


Figure – No-collision Case

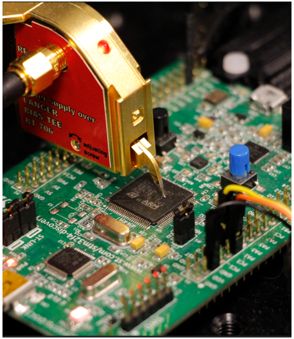
Divide and Conquer



- Each decoder manipulates a codeword of small Hamming weight (≤ 5 with probability $\geq 98\%$)

How to build the Oracle ?

$$\text{Class } i = \left\{ \mathbf{x} \xleftarrow{\$} \mathbb{F}_2^{n_2}, \mathtt{HW}(\mathbf{x}) = i \right\}$$



→ Set-Up :

- STM32F407
- Langer Near Field Probe
- Rhode-Schwarz RTO2024
- 50000 electromagnetic measurement per class.

Leakage Assessment

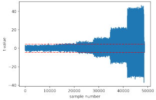
For two sets S_0 and S_1 with cardinality n_0 and n_1, means μ_0 and μ_1 and variances σ_0 and σ_1.

$$t = \frac{\mu_0 - \mu_1}{\sqrt{\left(\frac{\sigma_0^2}{n_0} + \frac{\sigma_1^2}{n_1}\right)}} \tag{1}$$

We look for absolute t-values greater than 4.5.

- If $|t| \geq 4.5$, it means that they exists a statistical difference with confidence 99.9999% that may be exploit with SCA.
- Otherwise, they are no first order distinguability to exploit.

t-test Results



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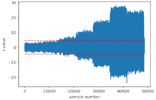
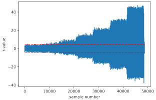


(b) Cl. 0 and 2



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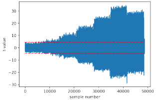
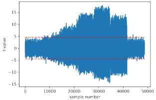


(d) Cl. 0 and 4



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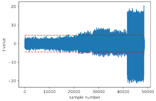

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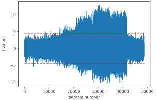

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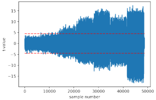

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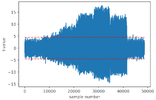

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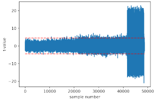

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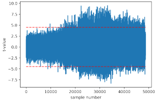

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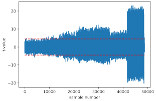

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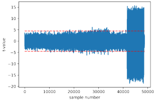
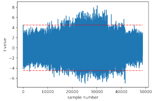


(m) Cl. 3 and 4



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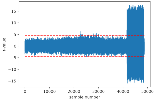

(o) Cl. 4 and 5

Success rate of the Oracle classification and Attack Summary

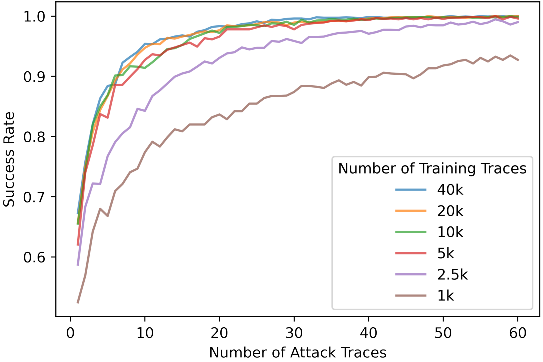

Figure – Single bit success rate recovery depending on the number of attack traces and the number of training traces per class.

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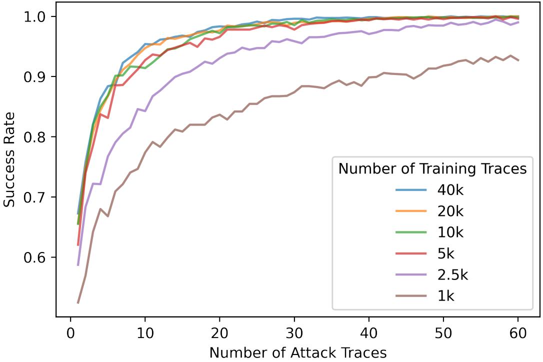

Figure – Single bit success rate recovery depending on the number of attack traces and the number of training traces per class.

Attack Summary :

- 50 attack traces are enough to obtain 100% accuracy
- Reed-Muller decoding independence
- Finally, $50 \times 384 = 19200$ traces are enough to target HQC-128.

Masking Countermeasure

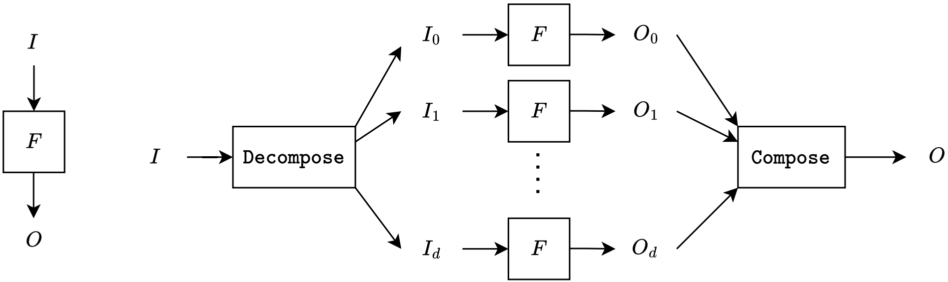

Figure – d order Masking of a linear operation F

We can apply this strategy to the Reed-Muller Decoder

- Reduce the success probability from p to p^{d+1}

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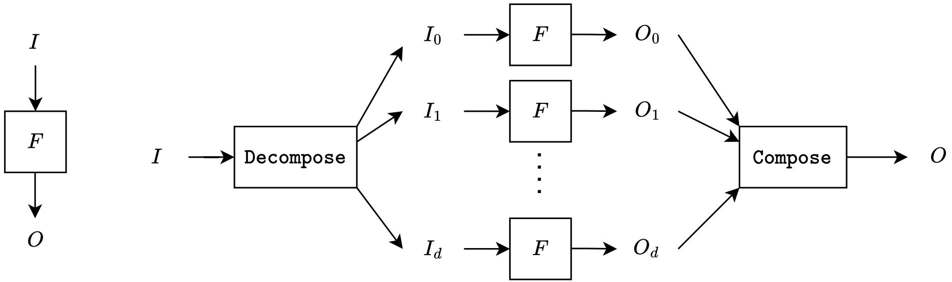
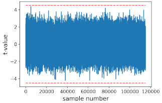


Figure – d order Masking of a linear operation F

We can apply this strategy to the Reed-Muller Decoder

- Reduce the success probability from p to p^{d+1}
- Change the distribution of the inputs.

t-test Results



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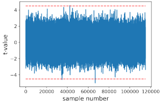

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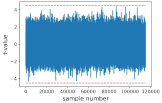

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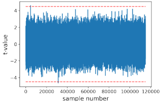

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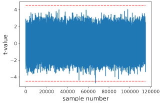

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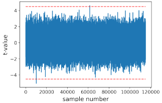

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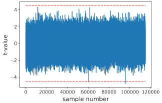

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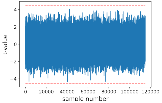

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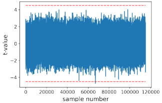

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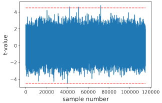

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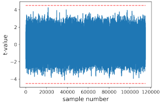
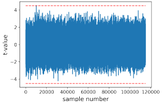


(k) Cl. 2 and 4



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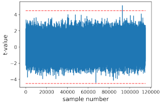
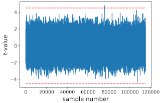


(m) Cl. 3 and 4



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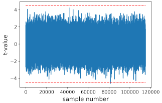

(o) Cl. 4 and 5

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Decryption Failure Rate (DFR)

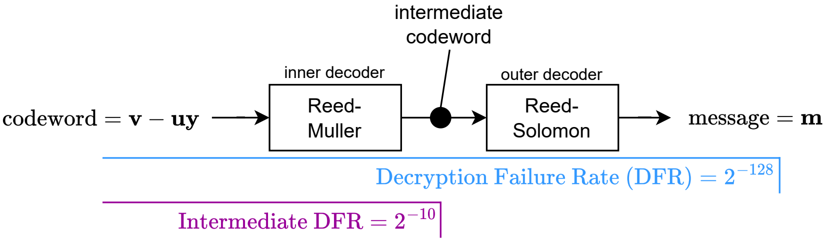
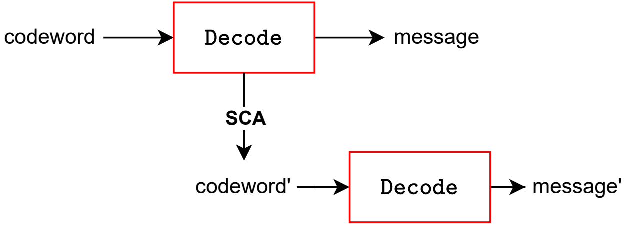


Figure – Decryption Failure Rate of HQC

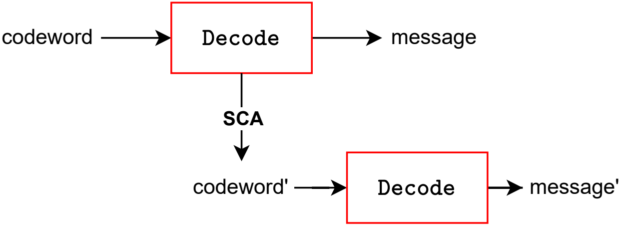
- Reed-Solomon code manipulates an error-free intermediate codeword.

Re-decoding Strategy



→ Side-channel errors correction with Error correcting codes structure !

Re-decoding Strategy



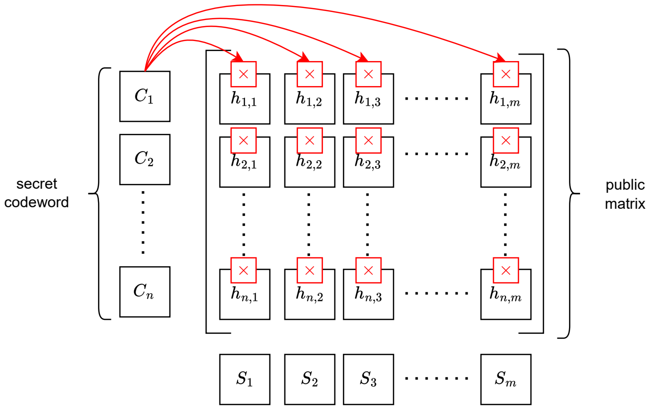
$\rightarrow$ Side-channel errors correction with Error correcting codes structure !

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 – More powerful decoder for Reed-Solomon codes [VG99]

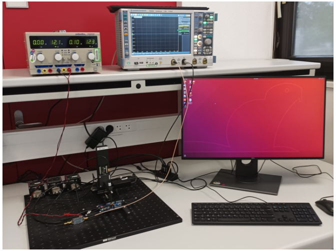
Attack Scenario – Reed-Solomon Decoder

- Target the Reed-Solomon Syndrome computation $\mathbf{Hc}^T$ to recover the codeword $\mathbf{c}$.



Attacker Model

In theory	In practice
Access to a clone device	Both training and attack on the same device
One target function only	Target the Galois field multiplication
No control on the SNR	No trace averaging (true single trace attack)



→ Set-Up :

- STM32F407
- Langer Probe
- Rhode-Schwarz RTO2024

Templates on the Galois field multiplication operands

- Galois field multiplication based on FFT strategy [BGTZ08]

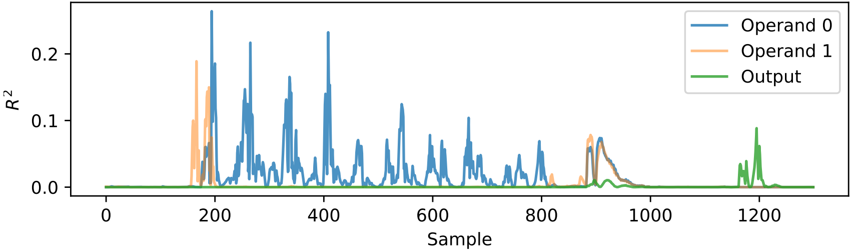


Figure – Leakage Assesment on Galois field multiplication

	Value template accuracy	Hamming weight template accuracy
Operand 0	**0.9389**	0.5929
Operand 1	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.

- Use the 93.89% accuracy to build a straightforward attack !

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- (we keep this swapp until the end of this presentation)
- We then exploit the $51,78\%$ accuracy on the Hamming weight of the output.

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How to efficiently exploit this "low accuracy" leakage ? → Belief Propagation.

Attack Description

- Message recovery attack with a single trace !
- First used of **Belief Propagation** [Mac03, KFL01] against code-based cryptography.

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
- Attack against hash function Keccak [KPP20] in 2020
- First BP attack against code-based cryptography [GMGL23]

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$\rightarrow$ Allows a message recovering within a few minutes

Belief Propagation – Overview

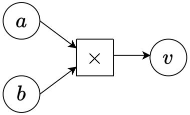

Figure – Graphical representation of a Multiplication

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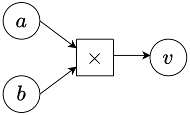

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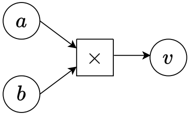

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The Marginal Probability Distributions

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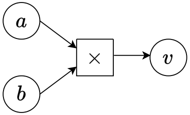

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The Marginal Probability Distributions

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

$\rightarrow$ Propagate and Combine knowledge

Reed-Solomon syndrome computation graphical representation

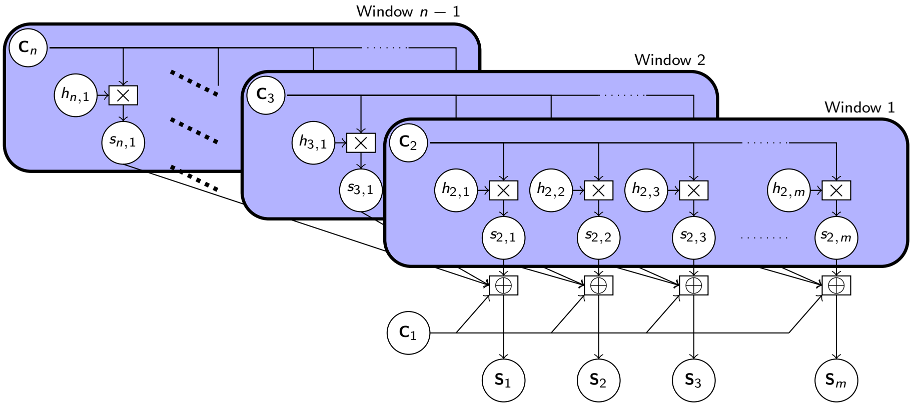

Figure – Graphical representation of the RS syndrome computation from HQC

Belief Propagation – Properties

What is proven ?

- Proof of convergence for tree like graphes
- `graph_depth` iterations are requiered to converge

Belief Propagation – Properties

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- `graph_depth` iterations are requiered to converge

What is not proven ?

- No proof of convergence for Cyclic graphes (oscillation phenomenon)

→ solution : Loopy Belief Propagation

Attack Accuracy in Simulation

→ Leakage on outputs of Galois field multiplication + Run BP :

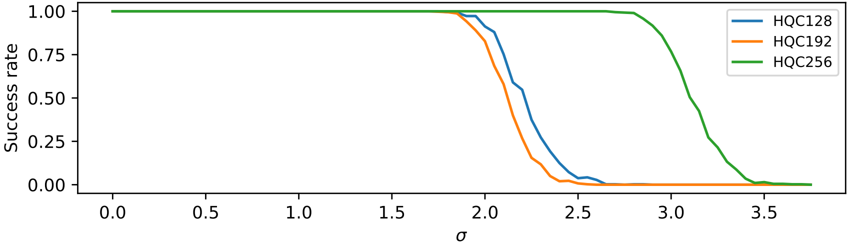


Figure – Simulated success rate of SASCA on the decoder, with re-decoding strategy, depending on the selected security level of HQC

- Attack works at high noise levels
- Attack strength increases with security level

Countermeasure ? – Codeword Masking (High Level Masking) Broken !

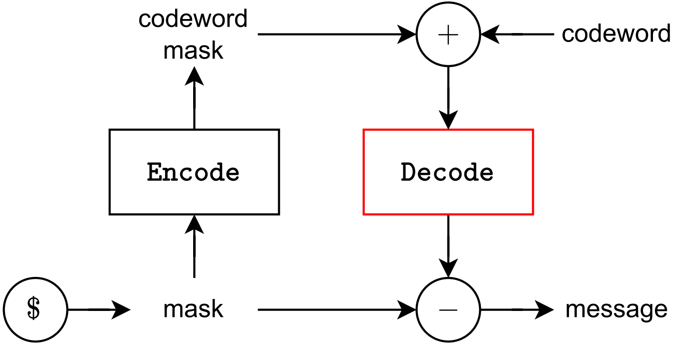


Figure – Codeword Masking [MSS13]

- Attack against the decoder which manipulates Galois field multiplications → Inefficient countermeasure

Encoder Attack Accuracy in Simulation

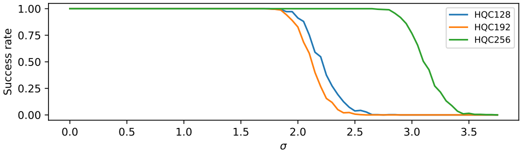


Figure – Simulated Success rate of the attack against the decoder

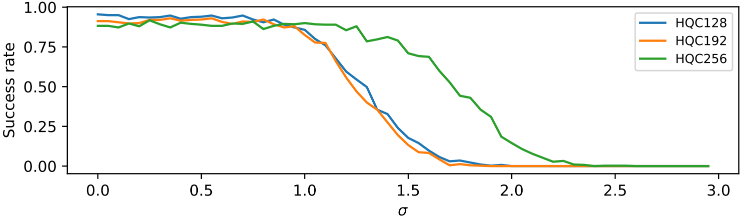


Figure – Simulated success rate of the attack against the encoder

→ Several cycles in the Encoder graph :

- Oscillation phenomenons.
- Attack less accurate at higher noise levels.

re-encryption step from HHK transform

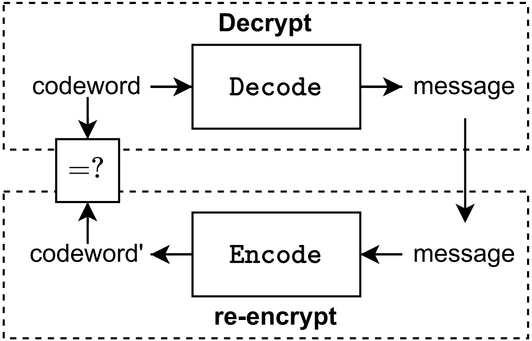
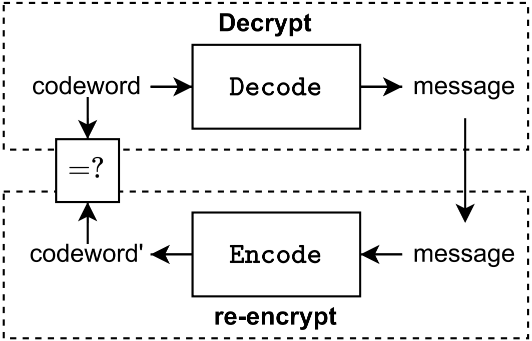


Figure – HQC Structure with HHK transform

- HQC-KEM is based on HHK transform [HHK17]
- This transform introduces a re-encryption step.

re-encryption step from HHK transform



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- Enable to concatenate graphs
- First attack exploiting both encryption and re-encryption

Re-encryption Attack Accuracy in Simulation

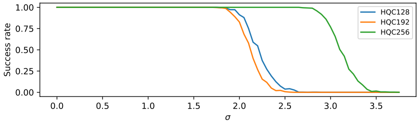


Figure – Simulated Success rate against the decoder

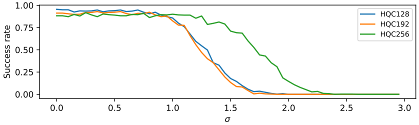


Figure – Simulated Success rate against the encoder

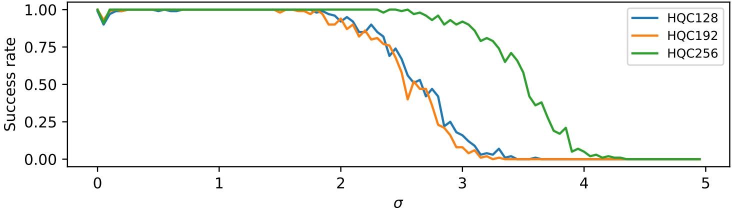
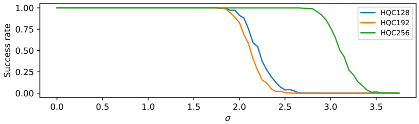


Figure – Simulated Success rate against the concatenated decoder and encoder graph

- Concatenated graph increases the strength of the attack !
- Observation of oscillation phenomenon (encoder cycles)

Re-encryption Attack Accuracy in Simulation



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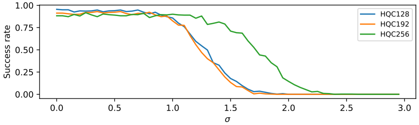

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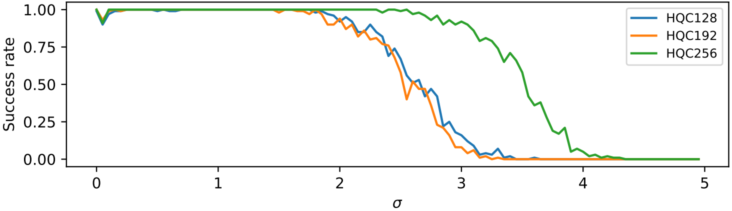

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$\rightarrow$ Efficient shuffling countermeasure to protect the Encoder and the Decoder !

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- An adversary can choose a set of t wires in the circuit
- We simulate it by a perfect knowledge of the values carried by the chosen wires.
- A gadget is t-probing secure if the output of any t-probing adversary is indenpedent of sensitive data.

- An adversary can choose a set of t wires in the circuit
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- A gadget is t-probing secure if the output of any t-probing adversary is indenpedent of sensitive data.

How to build a gadget ? $\rightarrow$ We will use a low level **masking**.

- Boolean : $a = \bigoplus_{i=0}^{t} a_i$
- Artihmetic : $a = \sum_{i=0}^{t} a_i \mod q$

Gadget properties

- t-Non-Interference (t-NI)
  - $\rightarrow$ Every set of t internal probes can be simulated with at most t shares of each input.
- t-Strong Non-Interference (t-SNI)
  - $\rightarrow$ Every set I of t_1 internal probes and every set O of t_2 output probes such that $t_1 + t_2 \leq t$, the set of probes $I \cup O$ can be simulated with t_1 shares of each input.
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Interferences and probes propagations can be prevented by refreshing the shares.

Mask Refresh

```c
/**
 * @brief Refresh 8b additives shares with n number of shares
 *
 * @param[out] x masked value. overwritten.
  * @param[in] n Number of shares
 */
void arith_8b_refresh(uint8_t *x, int n)
{
    for(size_t i = 0; i < n; ++i)
    {
        for(size_t j = i+1; j < n; ++j)
        {
            uint8_t r = next_8();
            x[0] += r;
            x[j] -= r;
        }
    }
}
```

Figure – Refresh algorithm

- Complexity of $\mathcal{O}(d^2)$.
- Requiered to prevent Interferences !

Low level masking

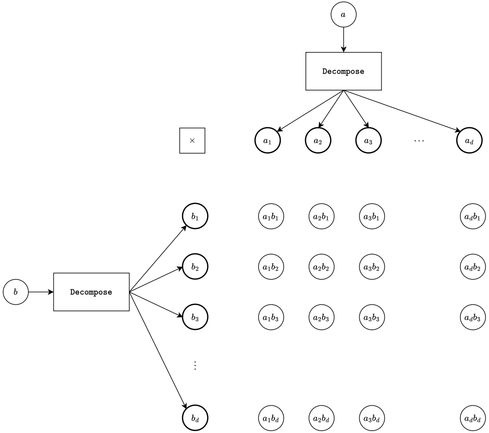


Figure – Low level Masking of a multiplication $\times$ with d shares

Low level masking 2

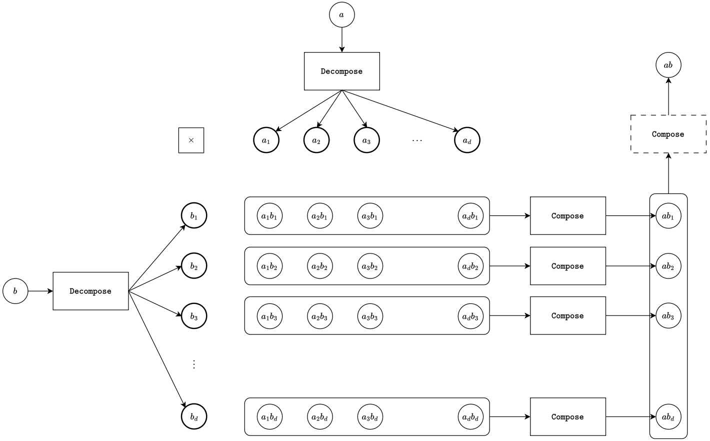
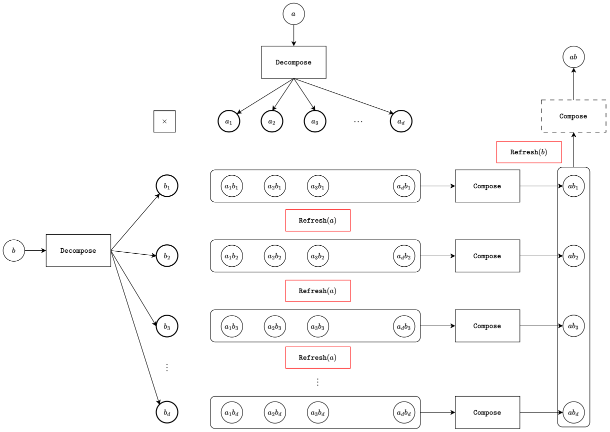


Figure – Low level Masking of a multiplication $\times$ with d shares

Low level masking 3



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Masked Reed-Solomon Encoder

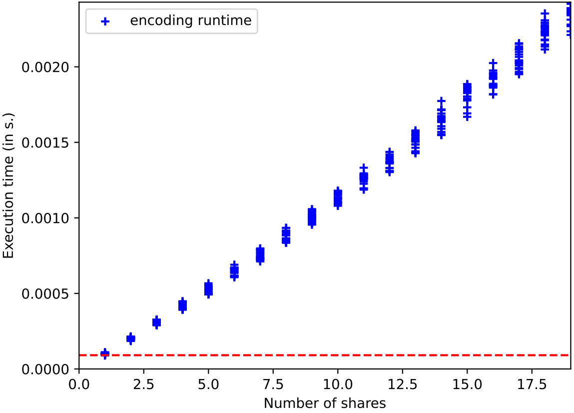

Figure – Average running time of HQC RS encoder

Masked Reed-Solomon Decoder

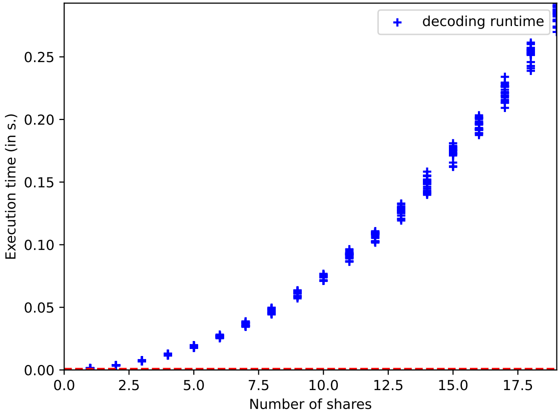

Figure – Average running time of HQC RS decoder

HQC RS running times

Number of shares	$\emptyset$	1	2	4	8	16
HQC RS Encoder	1	1.096	2.227	4.569	9.767	20.962
HQC RS Decoder	1	15.586	41.074	135.080	520.424	2148.040

Table – Reed-Solomon Encoder and decoder running times with reference implementation as refrence [AMAB+23]

- Cost of masking is at least a factor d, with d number of shares.
- But refresh cost $\mathcal{O}(d^2)$.
- The structure of gadgets can dramatically lower the performance.

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Conclusions and Persecpectives

- Side-Channel Attacks represents a threat for (PQ) cryptography
- Error Correcting Codes Structure can be exploit for Side-Channel purposes

Work In Progress

- Secure HQC against side-channel attacks [ABC+22, DR24]

Future Works

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Thank you for your attention !
Any questions ?

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Detecting Collisions

If $\mathbf{v}$ has an Hamming weight of 1, they are two possibilities :

1. $\mathrm{Supp}(\mathbf{y}) \cap \mathrm{Supp}(\mathbf{v}) = \mathrm{Supp}(\mathbf{v})$. Then $\mathtt{HW}(\mathbf{v} - \mathbf{y}) = \mathtt{HW}(\mathbf{y}) - 1$, the decoder will correct one error less than the reference decoding of $\mathbf{y}$.

$$\mathcal{O}_b^{\mathrm{RM}}(\mathbf{v} - \mathbf{y}) = O_b^{\mathrm{RM}}(\mathbf{y}) - 1$$

2. $\mathrm{Supp}(\mathbf{y}) \cap \mathrm{Supp}(\mathbf{v}) = \varnothing$. Then $\mathtt{HW}(\mathbf{v} - \mathbf{y}) = \mathtt{HW}(\mathbf{y}) + 1$, the decoder will correct one error more than the reference decoding of $\mathbf{y}$.

$$\mathcal{O}_b^{\mathrm{RM}}(\mathbf{v} - \mathbf{y}) = O_b^{\mathrm{RM}}(\mathbf{y}) + 1$$

- **Strategy** Remember locations where Oracle outputs 1 less than the reference value.

Divide and Conquer

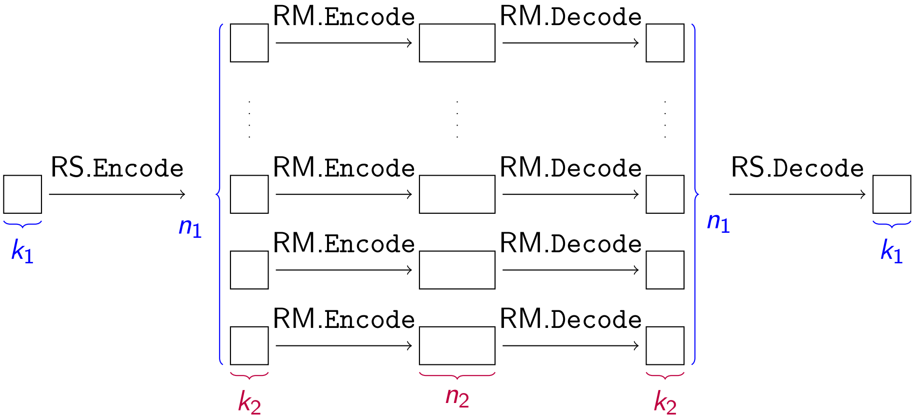


Figure – Simplified HQC Concatenated RMRS Codes Framework

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

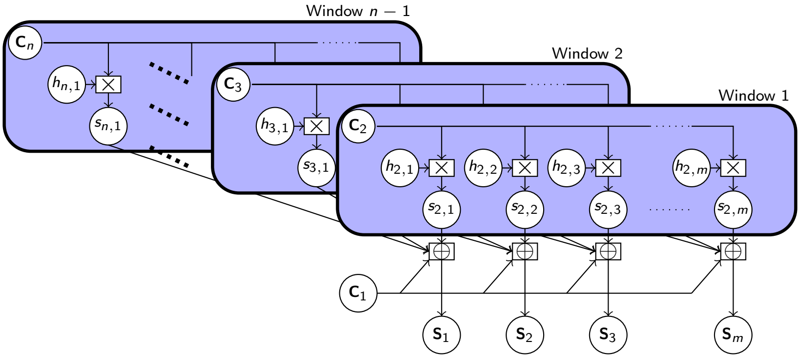
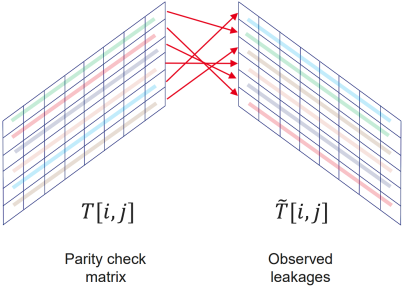


Figure – Graphical representation of the RS syndrome computation from HQC

Breaking shuffling countermeasures 2

- Window Shuffling (Novelty)

  $\rightarrow$ Randomly shuffle lines of the parity check matrix



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

Instance of the assignment Problem.

$\rightarrow$ Solver : Hungarian algorithm.

Full Shuffling Countermeasure

- Lines Shuffling $\rightarrow$ Not enough !
- Columns Shuffling $\rightarrow$ Not enough !

$\hookrightarrow$ Entire Matrix Shuffling !

$$2^{504}, \quad 2^{614}, \quad \text{and } 2^{1030}$$

- We can change the encoder to apply the same countermeasure

Reed-Solomon syndrome computation graphical representation

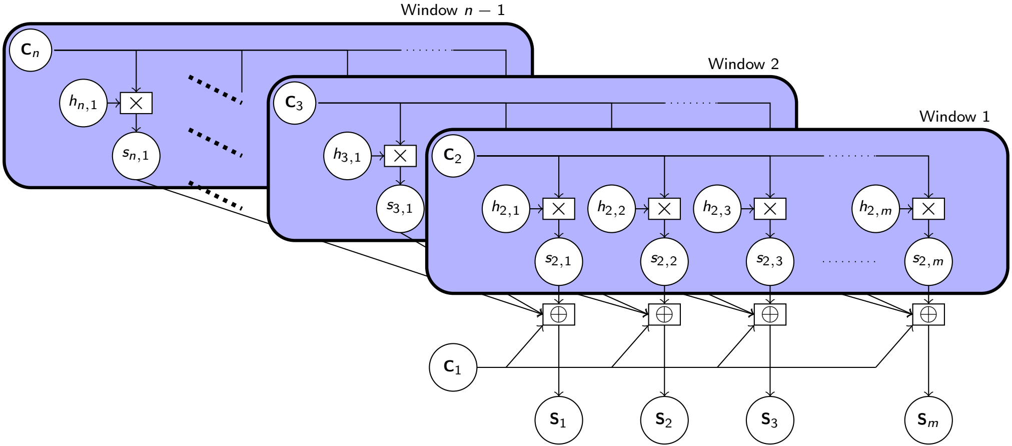


Figure – Graphical representation of the RS syndrome computation from HQC

Reed-Solomon Encoder graphical representation

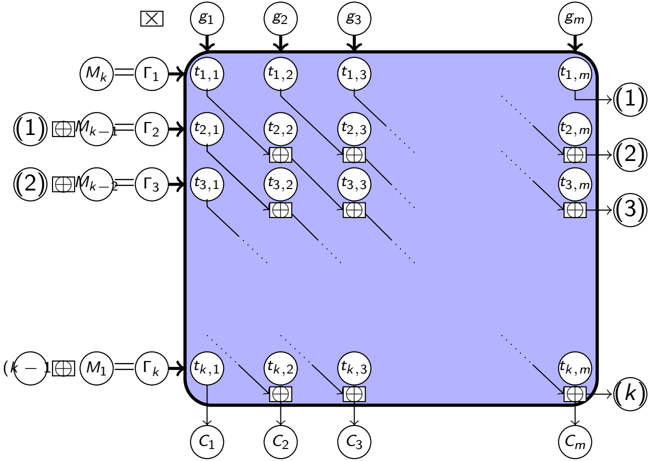


Figure – Graphical representation of the RS encoder from HQC