Contribution à la sécurisation de la cryptographie post-quantique basée sur les codes correcteurs d'erreurs face aux attaques par canaux auxiliaires.

Soutenance de Thèse

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24 juin 2024

Modern cryptography

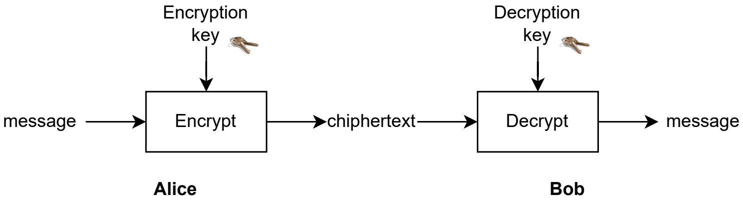

Figure – Overview of a cryptosystem

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)

Figure – IBM Quantum Computer

→ Quantum Computer threat !

Shor's and Grover's Algorithms

Post-Quantum Cryptography (PQC)

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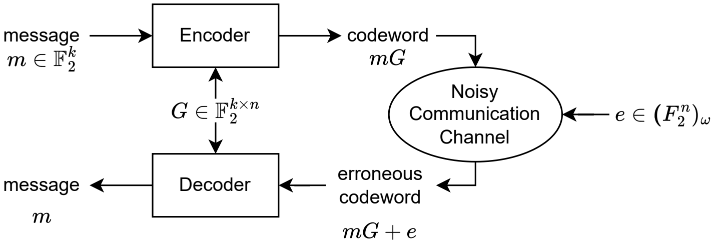
Shor's and Grover's Algorithms Several possibilities (NIST contest) :

- Lattice-based cryptography : Kyber [BDK$^+$18], Dilithium [DKL$^+$18]
- Hash-based cryptography : Sphincs$^+$ [BHK$^+$19]
- **Code-based cryptography** : HQC [AMAB$^+$17], BIKE [ABB$^+$17], ClassicMcEliece [BCL$^+$]
  → 1 or 2 code-based schemes will be standardized !
- Multivariate cryptography, Isogeny-based cryptography, multi-party computation, ...

Error Correcting codes



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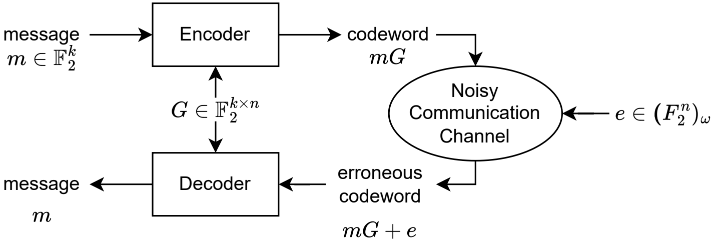

message $m \in \mathbb{F}_2^k$

Encoder

codeword mG

$G \in \mathbb{F}_2^{k \times n}$

Noisy Communication Channel

$e \in (F_2^n)_\omega$

Decoder

erroneous codeword $mG + e$

message m

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]).

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 an attacker needs to pay to recover a secret information**.
And often also **The number of different secret keys**.

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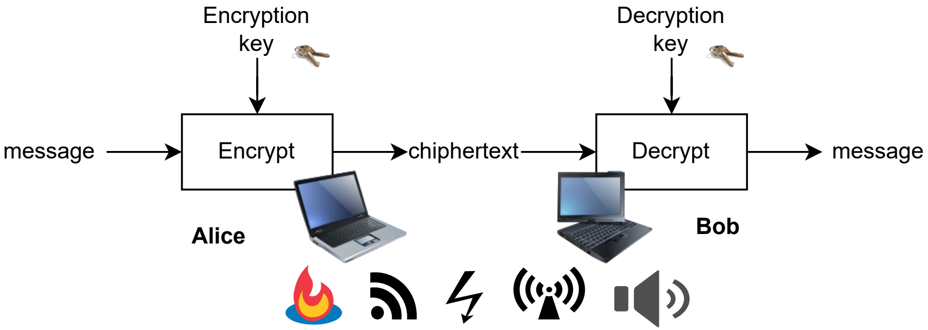
$$2^{256} \approx\approx 10^{80} \leftarrow \text{Number of atoms in the observable universe}$$

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

Side-Channel Attacks



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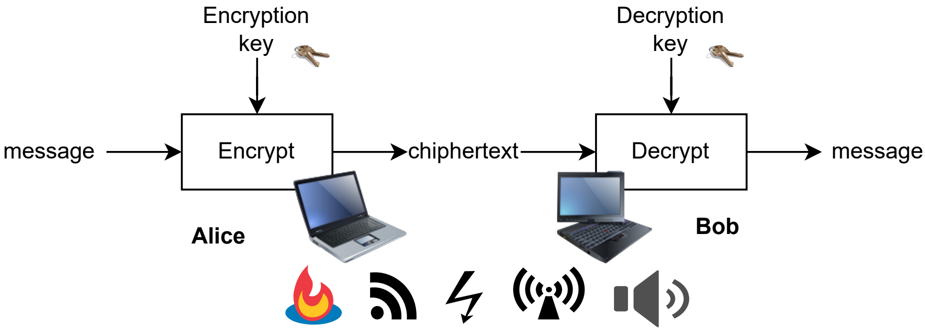
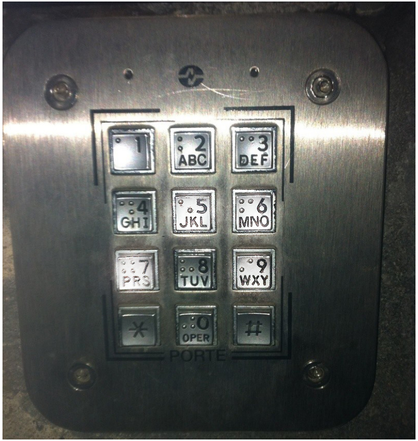


Physical behavior is correlated to manipulated data.
The first side-channel attack was introduced by Paul Kocher in 1996 [Koc96].

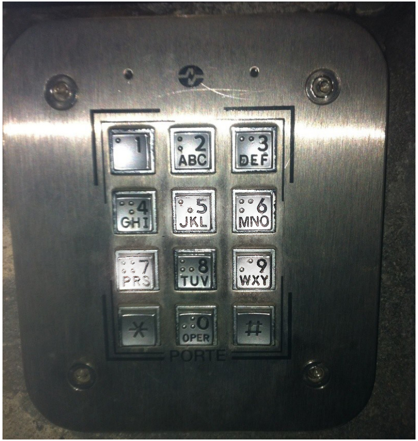
Side-channel attacks toy example



Side-channel attacks toy example

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

Side-channel attacks challenges

	Algebraic Attack	Side-Channel Attacks
Target	Mathematical Structure	Implementation
Protection	Change parameters	Change implementation

Goal : Find a secure implementation with good performances

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Goal : Find a secure implementation with good performances

Side-Channel evaluation :

- Key or message recovery
- Physical access
- Number of required physical measurement
- Execution time

→ Side-channel attacks mainly target embedded cryptography.

Context and Questions

Context :

- Need for secure Post-Quantum cryptography (NIST contest)
- Code-based cryptography is a promising family of PQC
- Side-channel attacks threat

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- Need for secure Post-Quantum cryptography (NIST contest)
- Code-based cryptography is a promising family of PQC
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Question :

- Is code-based cryptography secure against side-channel attacks ?
- How to secure code-based cryptography against side-channel attacks ?

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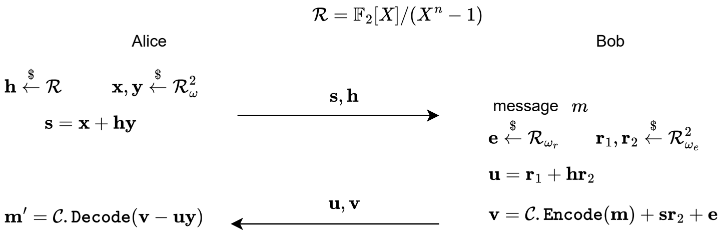
Hamming Quasi-Cyclic (HQC)



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

Alice

$\mathbf{h} \overset{\$}{\leftarrow} \mathcal{R}$ $\quad \mathbf{x}, \mathbf{y} \overset{\$}{\leftarrow} \mathcal{R}_\omega^2$

$\mathbf{s} = \mathbf{x} + \mathbf{h}\mathbf{y}$

$\xrightarrow{\mathbf{s}, \mathbf{h}}$

Bob

message m

$\mathbf{e} \overset{\$}{\leftarrow} \mathcal{R}_{\omega_r}$ $\quad \mathbf{r}_1, \mathbf{r}_2 \overset{\$}{\leftarrow} \mathcal{R}_{\omega_e}^2$

$\mathbf{u} = \mathbf{r}_1 + \mathbf{h}\mathbf{r}_2$

$\mathbf{v} = \mathcal{C}.\mathtt{Encode}(\mathbf{m}) + \mathbf{s}\mathbf{r}_2 + \mathbf{e}$

$\xleftarrow{\mathbf{u}, \mathbf{v}}$

$\mathbf{m}' = \mathcal{C}.\mathtt{Decode}(\mathbf{v} - \mathbf{u}\mathbf{y})$

Figure – HQC Public Key Encryption Scheme

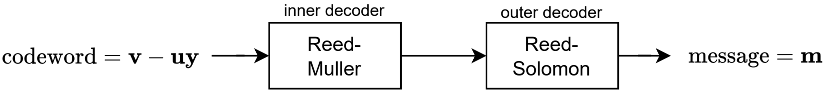
- No Code structure masking

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.

Concatenated Code structure

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



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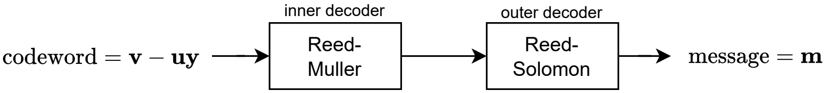

Figure – HQC Concatenated codes structure

(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 $\mathbf{y}$.

$$\mathcal{C}.\mathtt{Decode}(\mathbf{v} - \mathbf{u}\mathbf{y})$$

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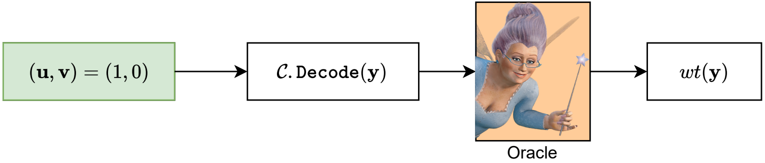
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Oracle
$wt(\mathbf{y})$

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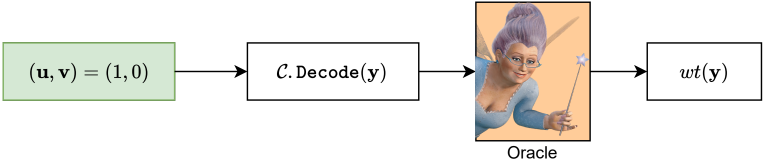
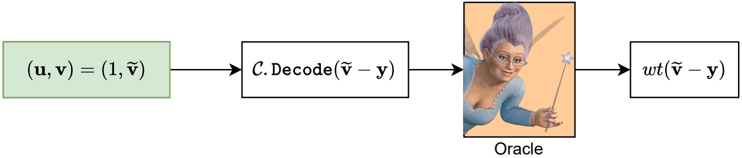
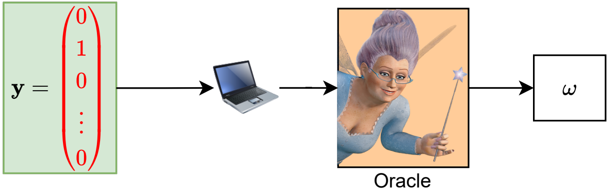


$(\mathbf{u}, \mathbf{v}) = (1, 0)$ → $\mathcal{C}.\texttt{Decode}(\mathbf{y})$ → Oracle → $wt(\mathbf{y})$



$(\mathbf{u}, \mathbf{v}) = (1, \tilde{\mathbf{v}})$ → $\mathcal{C}.\texttt{Decode}(\tilde{\mathbf{v}} - \mathbf{y})$ → Oracle → $wt(\tilde{\mathbf{v}} - \mathbf{y})$

Attack Scenario II



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

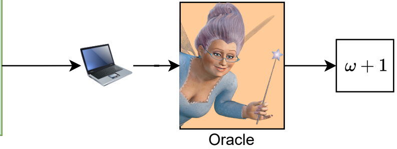
Oracle

ω

Attack Scenario III

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

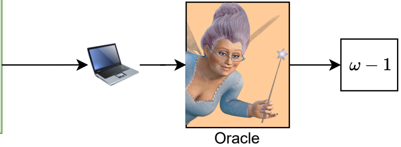
$$\widetilde{\mathbf{v}} - \mathbf{y} = \begin{pmatrix}1\\0\\0\\\vdots\\0\end{pmatrix} - \begin{pmatrix}0\\1\\0\\\vdots\\0\end{pmatrix} = \begin{pmatrix}1\\1\\0\\\vdots\\0\end{pmatrix}$$



Oracle

$\omega + 1$

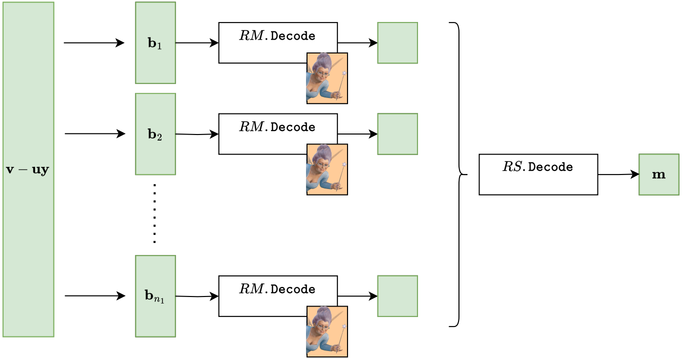
$$\widetilde{\mathbf{v}} - \mathbf{y} = \begin{pmatrix}0\\1\\0\\\vdots\\0\end{pmatrix} - \begin{pmatrix}0\\1\\0\\\vdots\\0\end{pmatrix} = \begin{pmatrix}0\\0\\0\\\vdots\\0\end{pmatrix}$$



Oracle

$\omega - 1$

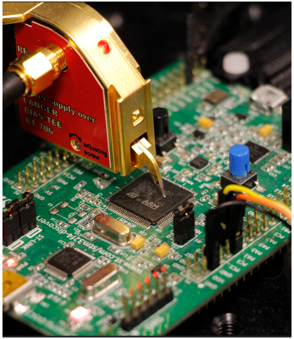
Divide and Conquer



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

How to build the Oracle ?

$$\text{Class } i = \left\{ EM(RM.\texttt{Decode}(\mathbf{x})) \mid \mathbf{x} \xleftarrow{\$} \mathbb{F}_2^{n_2}, \texttt{HW}(\mathbf{x}) = i \right\}$$



→ Set-Up :

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

Leakage Assessment

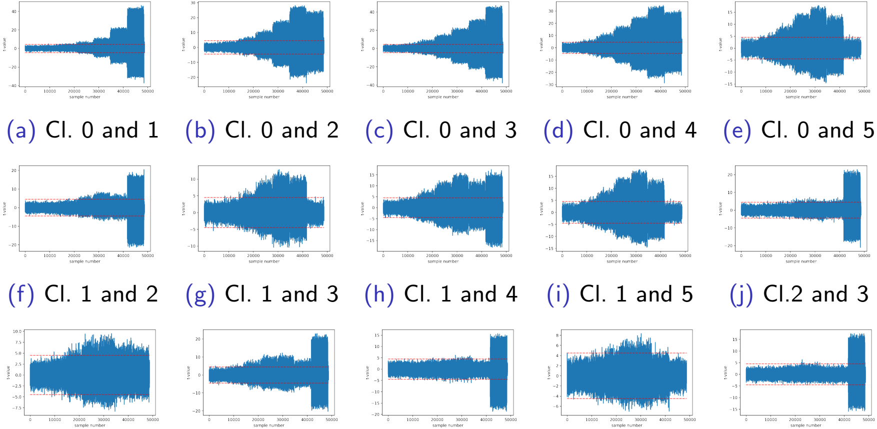
For two sets S_0 and S_1 with cardinality n_0 and n_1, means μ_0 and μ_1 and variances σ_0 and σ_1.

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

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



(a) Cl. 0 and 1 (b) Cl. 0 and 2 (c) Cl. 0 and 3 (d) Cl. 0 and 4 (e) Cl. 0 and 5

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Success rate of the Oracle classification and Attack Summary

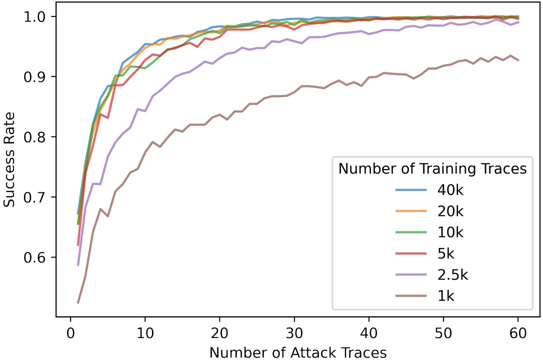

Figure – Single bit success rate recovery depending on the number of attack traces and the number of training traces per class.

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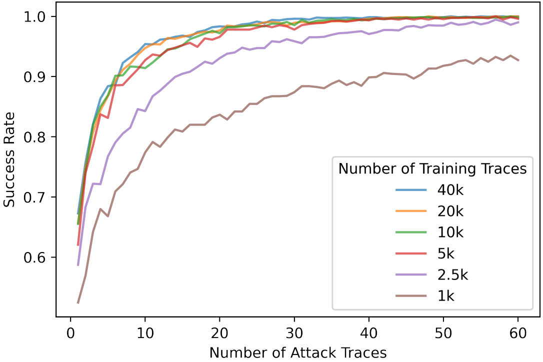

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Attack Summary :

- 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

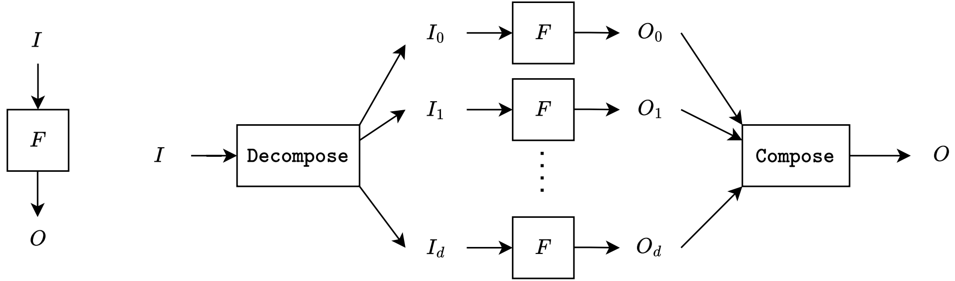

Figure – d order Masking of a linear operation F

We can apply this strategy to the Reed-Muller Decoder

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

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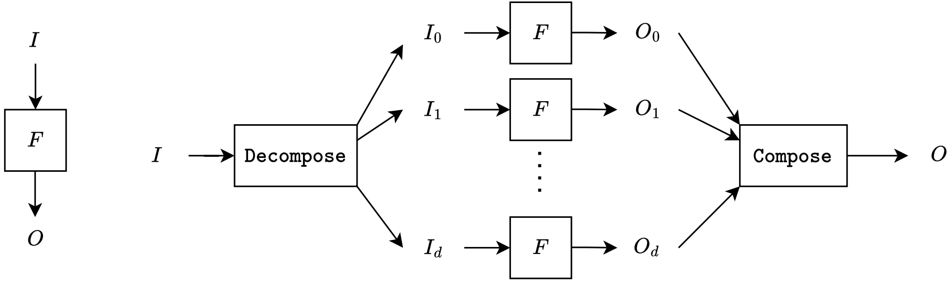
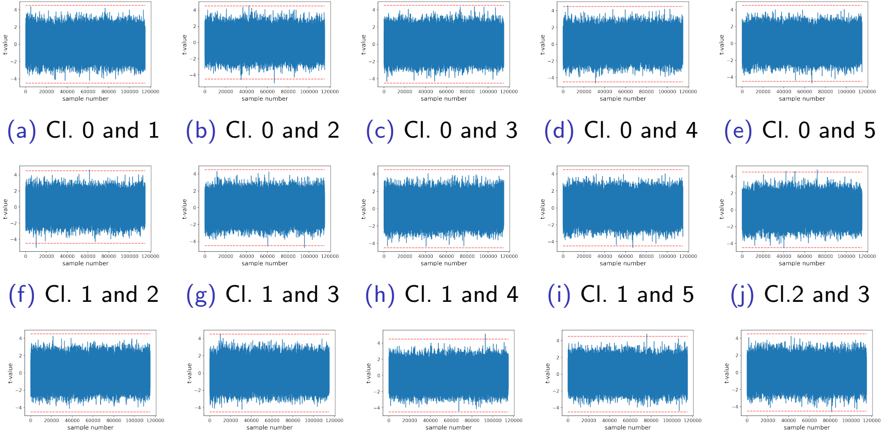


Figure – d order Masking of a linear operation F

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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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]

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

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→ Allows a message recovering within a few minutes

Decryption Failure Rate (DFR)

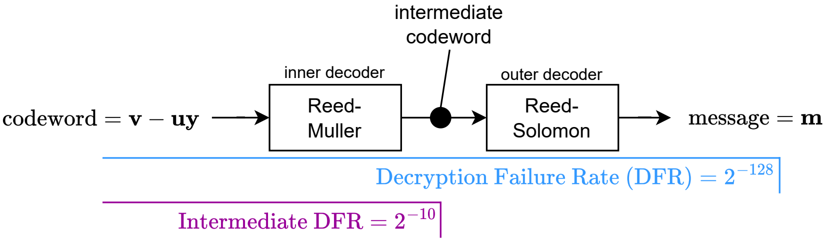
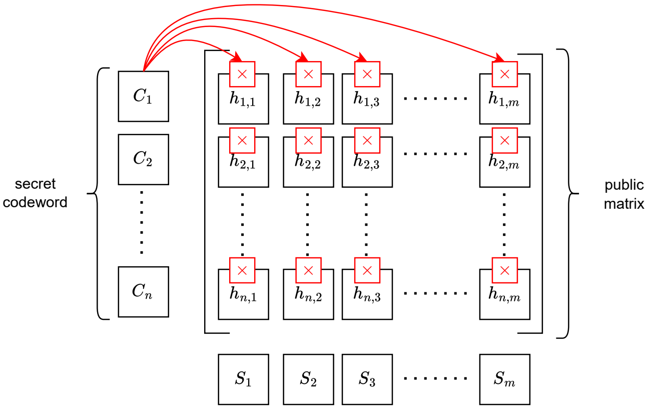

intermediate codeword
inner decoder
Reed-Muller
outer decoder
Reed-Solomon
codeword = $\mathbf{v} - \mathbf{u}\mathbf{y}$
message = $\mathbf{m}$
Decryption Failure Rate (DFR) = 2^{-128}
Intermediate DFR = 2^{-10}

Figure – Decryption Failure Rate of HQC

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

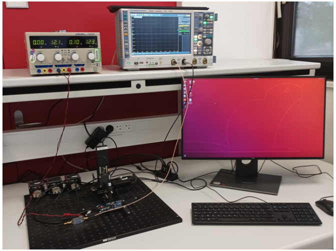
Attack Scenario

- 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)



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Templates on the Galois field multiplication operands

- Galois field multiplication based on FFT strategy [BGTZ08]

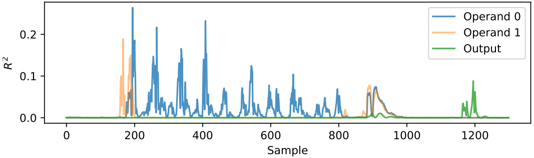

Figure – Leakage Assesment on Galois field multiplication

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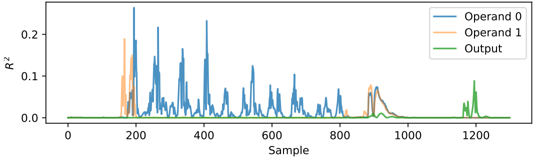


Figure – Leakage Assesment on Galois field multiplication

	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.

Reed-Solomon syndrome computation graphical representation

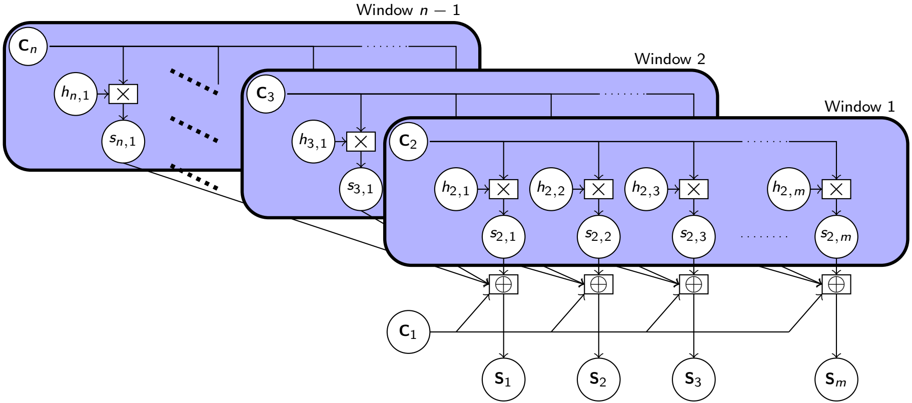


Figure – Graphical representation of the RS syndrome computation from HQC

How to combine that much leakage ? → Belief Propagation.

Belief Propagation – Overview

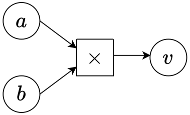


Figure – Graphical representation of a Multiplication

Belief Propagation – Overview

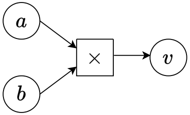


Figure – Graphical representation of a Multiplication

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

Belief Propagation – Overview

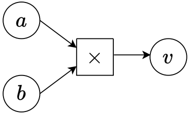


Figure – Graphical representation of a Multiplication

The Goal is to compute : $\mathbb{P}\left(a \mid b, v\right), \mathbb{P}\left(b \mid a, v\right), \mathbb{P}\left(v \mid a, b\right)$
The Marginal Probability Distributions

Belief Propagation – Overview

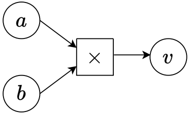


Figure – Graphical representation of a Multiplication

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

The Marginal Probability Distributions

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

→ Propagate and Combine knowledge

Belief Propagation – Properties

What is proven ?

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

Belief Propagation – Properties

What is proven ?

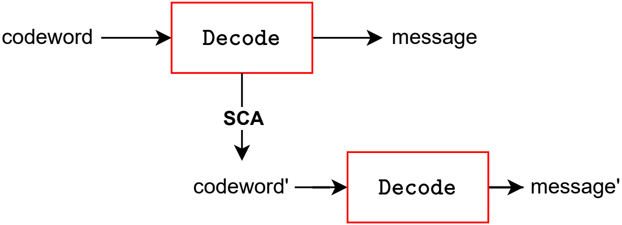
- Proof of convergence for tree like graphes
- `graph_depth` iterations are requiered to converge

What is not proven ?

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

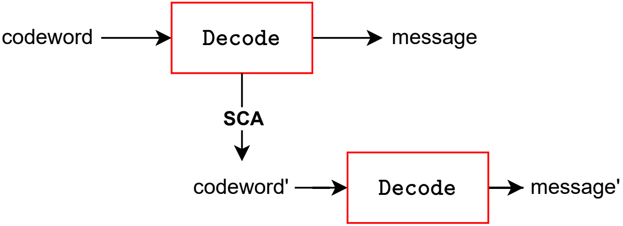
→ solution : Loopy Belief Propagation

Re-decoding Strategy



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

Re-decoding Strategy



→ 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 Accuracy in Simulation

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

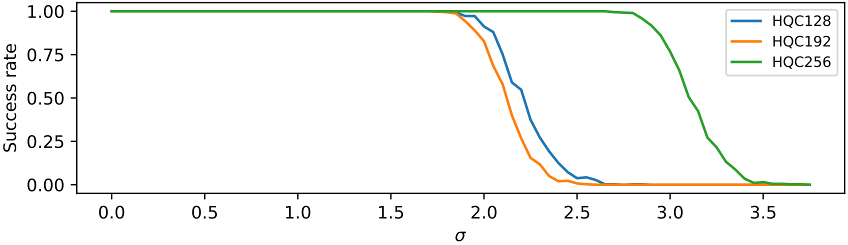


Figure – Simulated success rate of SASCA on the decoder, with re-decoding strategy, depending on the selected security level of HQC

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

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

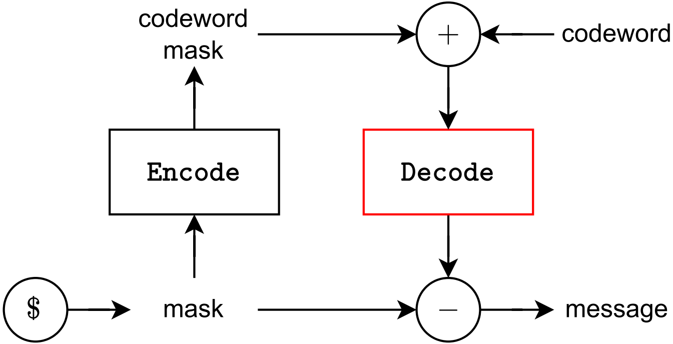


Figure – Codeword Masking [MSS13]

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

Encoder Attack Accuracy in Simulation

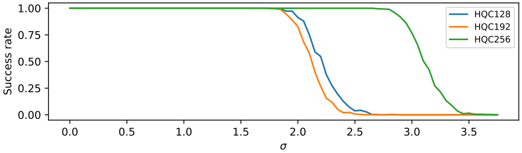


Figure – Simulated Success rate of the attack against the decoder

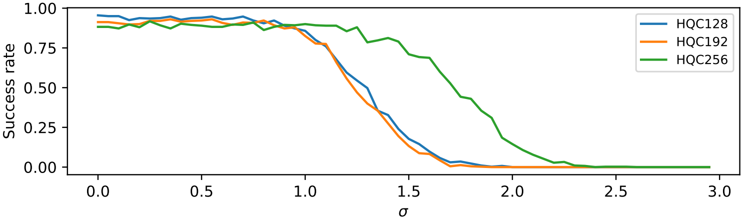


Figure – Simulated success rate of the attack against the encoder

→ Several cycles in the Encoder graph :

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

re-encryption step from HHK transform

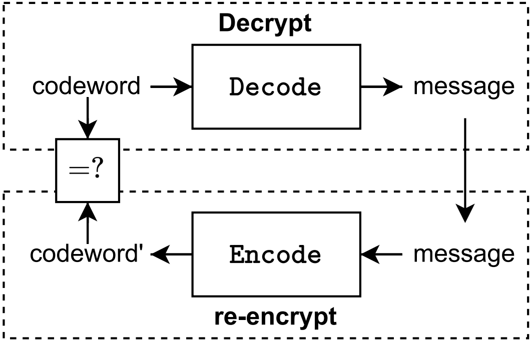


Figure – HQC Structure with HHK transform

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

re-encryption step from HHK transform

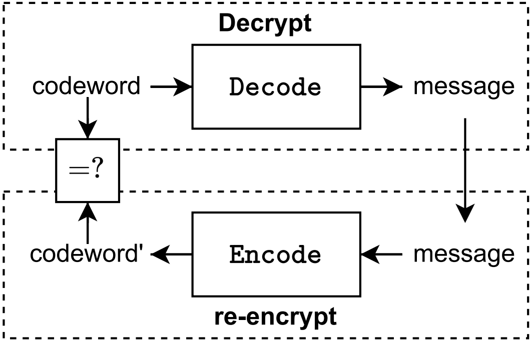


Figure – HQC Structure with HHK transform

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

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

Re-encryption Attack Accuracy in Simulation

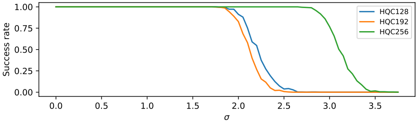


Figure – Simulated Success rate against the decoder

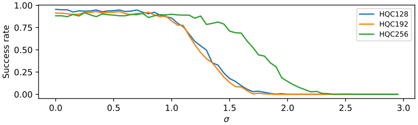


Figure – Simulated Success rate against the encoder

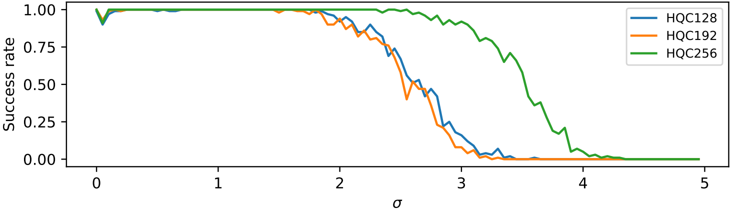


Figure – Simulated Success rate against the concatenated decoder and encoder graph

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

Re-encryption Attack Accuracy in Simulation

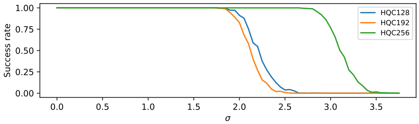


Figure – Simulated Success rate against the decoder

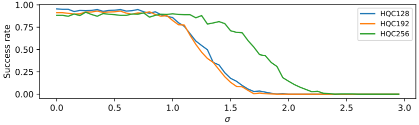


Figure – Simulated Success rate against the encoder

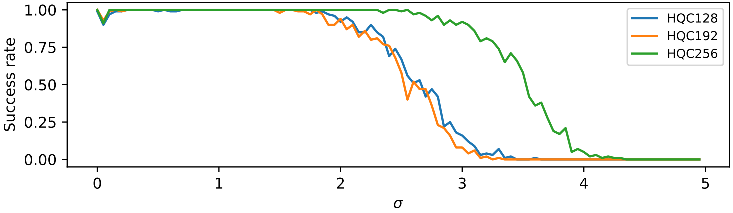


Figure – Simulated Success rate against the concatenated decoder and encoder graph

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

→ Efficient shuffling countermeasure to protect the Encoder and the Decoder !

Table of Contents

1. Hamming Quasi-Cyclic
   - Overview
2. HQC Key recovery attack
   - A chosen ciphertext attack
   - Building the Oracle
   - Countermeasure
3. HQC message recovery attacks
   - Attack Description
   - Soft Analytical Side-Channel Attacks
   - Breaking some countermeasures
   - Exploiting re-encryption step
4. Conclusion and Perspectives

Contributions

1 A new key recovery side-channel attack on HQC with chosen ciphertext
G Goy, A Loiseau, P Gaborit
International Conference on Post-Quantum Cryptography (PQcrypto 2022)

2 Estimating the strength of horizontal correlation attacks in the hamming weight leakage model :
A side-channel analysis on HQC KEM
G Goy, A Loiseau, P Gaborit
The Twelfth International Workshop on Coding and Cryptography (WCC 2022)

3 Single trace HQC shared key recovery with SASCA
G Goy, J Maillard, P Gaborit, A Loiseau
IACR Transactions on Cryptographic Hardware and Embedded Systems 2024 (2) (CHES 2024)

4 Secret and Shared Keys Recovery on Hamming Quasi-Cyclic with SASCA
C Baïsse, A Moran, G Goy, J Maillard, N Aragon, P Gaborit, M Lecomte, A Loiseau
(preprint)

Conclusion and Perspectives

What we did ?

- We introduced several side-channel attacks against HQC (key and message recovery).
- We showed that Soft analytical side-channel attacks are a threat for (code-based) cryptography.
- Proposed several countermeasures against these attacks.

Conclusion and Perspectives

What we did ?

- We introduced several side-channel attacks against HQC (key and message recovery).
- We showed that Soft analytical side-channel attacks are a threat for (code-based) cryptography.
- Proposed several countermeasures against these attacks.

Future Works

- Target other code-based schemes (BIKE, ClassicMcEliece) with Belief Propagation Algorithms.
- Secure HQC against side-channel attacks in the theoretical t-probing model. → promising security properties but high impact on performances

Conclusion

Thank you for your attention !

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Detecting Collisions

If **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 **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 **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

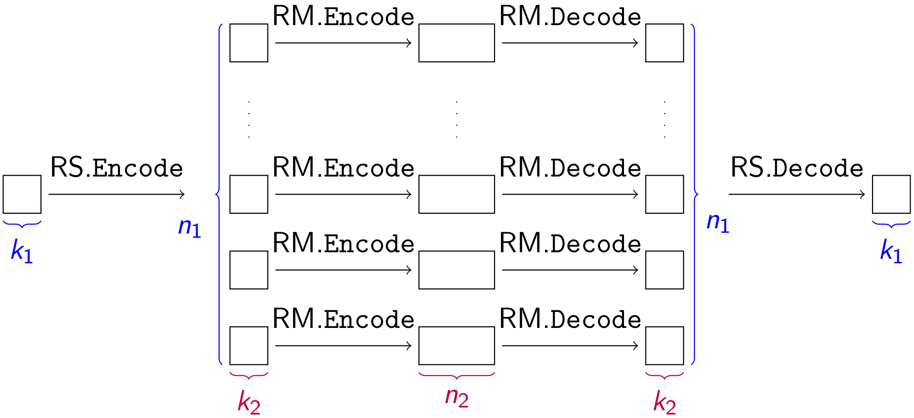


Figure – Simplified HQC Concatenated RMRS Codes Framework

Breaking shuffling countermeasures

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

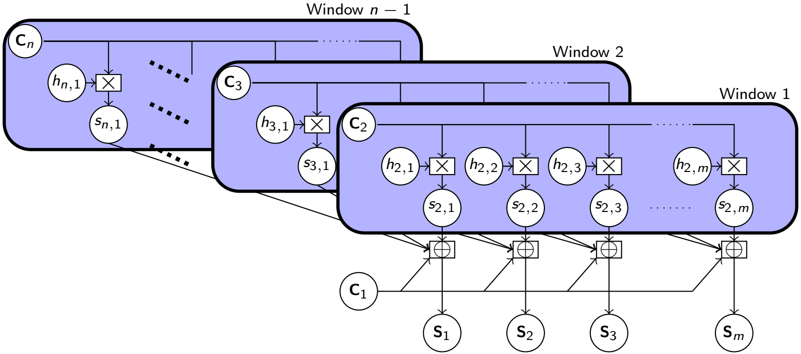
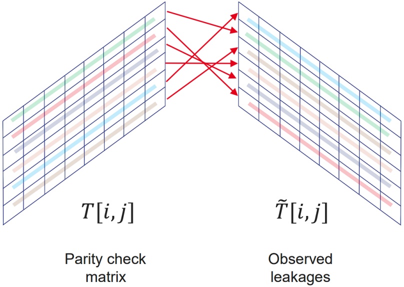


Figure – Graphical representation of the RS syndrome computation from HQC

Breaking shuffling countermeasures 2

- Window Shuffling (Novelty)

  → 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.

→ Solver : Hungarian algorithm.

Full Shuffling Countermeasure

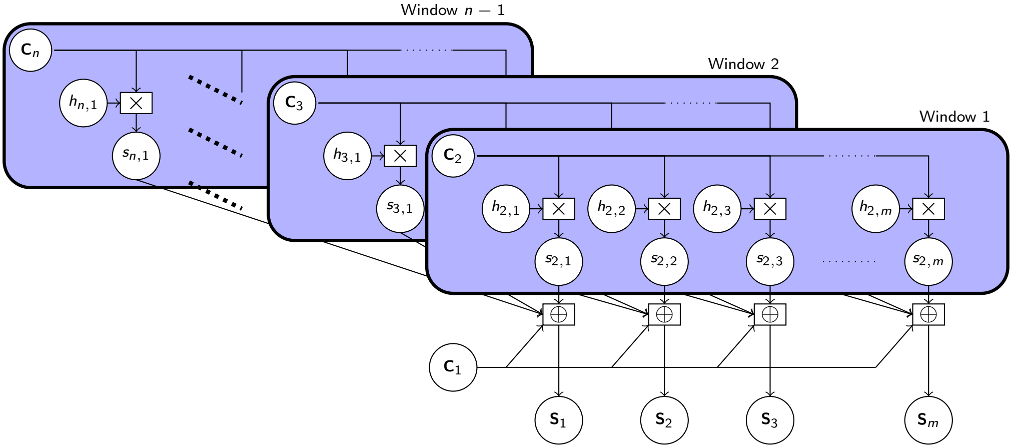
- Lines Shuffling → Not enough !
- Columns Shuffling → Not enough !

↪ 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



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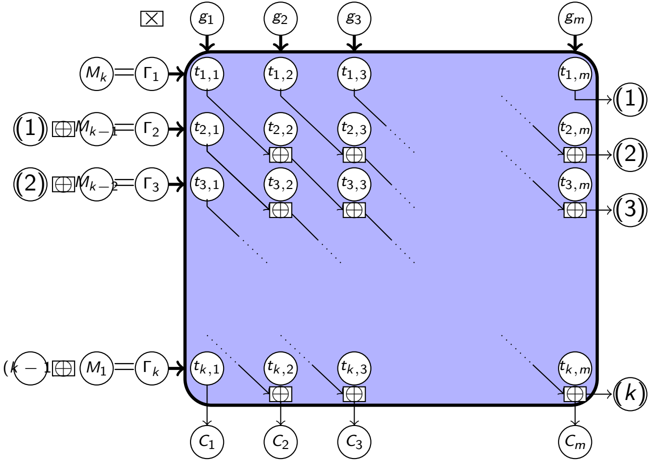
Reed-Solomon Encoder graphical representation



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