Divide and Surrender:

Exploiting Variable Division Instruction Timing in HQC Key Recovery Attacks

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Main Contributions

- Identified a division timing side-channel vulnerability in HQC KEM

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- New SMT-based exploitation strategy

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- New SMT-based exploitation strategy
- New key-recovery method for HQC
- Evaluation of the attack on an AMD Zen2 CPU
  - Median attack runtime less than 2 minutes

Hamming Quasi-Cyclic (HQC)

NIST Post-Quantum Key Encapsulation Mechanism (KEM) Standardization

Main selected algorithm: Kyber (lattice-based)

Round 4:

- Code Based:
  - Classic McEliece
  - Hamming Quasi-Cyclic (HQC)
  - BIKE
- SIKE (isogeny-based, broken)

HQC KEM

Key Encapsulation Mechanism (KEM) consists of three algorithms:
(KeyGen, Encaps, Decaps)

- $(\mathsf{pk}, \mathsf{sk}) \xleftarrow{\$} \mathsf{KeyGen}()$
- $(k_0, c) \xleftarrow{\$} \mathsf{Encaps}(\mathsf{pk})$
- $k_1 \leftarrow \mathsf{Decaps}(\mathsf{sk}, c)$

HQC KeyGen [Agu+22]

$\mathcal{R} := \mathbb{F}_2[X]/\langle X^n - 1\rangle$

Algorithm 1 KeyGen()

1: $(x, y) \leftarrow\$ \mathcal{R}_w \times \mathcal{R}_w$
2: sk $\leftarrow (x, y)$
3: $h \leftarrow\$ \mathcal{R}$; h corresponds to parity-check matrix $H = (I_n \ \mathrm{rot}(h))$
4: $s = x + h \cdot y$
5: pk $\leftarrow (h, s)$
6: **return** pk, sk

e.g. with parameters $n = 17669$, $w = 66$

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e.g. with parameters $n = 17669$, $w = 66$

HQC PKE: Encryption and Decryption

Algorithm 7 Encrypt(pk, m)

1: $e, r_1, r_2 \xleftarrow{\$} \mathcal{R}_{\omega_e} \times \mathcal{R}_{\omega_r} \times \mathcal{R}_{\omega_r}$
2: $u \leftarrow r_1 + h \cdot r_2$
3: $v \leftarrow \mathcal{C}.\mathsf{Encode}(m) + s \cdot r_2 + e$
4: **return** $c = (u, v)$

Algorithm 8 Decrypt($\mathsf{sk} = (x, y), c = (u, v)$)

1: **return** $\mathcal{C}.\mathsf{Decode}(v - u \cdot y)$

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HQC PKE: Encryption and Decryption

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Algorithm 18 Decrypt(sk $= (x, y)$, $c = (u, v)$)

1: **return** $\mathcal{C}.\mathsf{Decode}(v - u \cdot y)$

Decryption Failures

Decoding is successful when $v - u \cdot y$ has $\leq \delta$ errors:

$$
\begin{aligned}
& v - u \cdot y \\
=& \mathcal{C}.\mathsf{Encode}(m) + s \cdot r_2 + e - (r_1 + h \cdot r_2) \cdot y \\
=& \mathcal{C}.\mathsf{Encode}(m) + (x + h \cdot y) \cdot r_2 + e - (r_1 + h \cdot r_2) \cdot y \\
=& \mathcal{C}.\mathsf{Encode}(m) + \underbrace{x \cdot r_2 + e - r_1 \cdot y}_{\text{sparse}}
\end{aligned}
$$

HQC KEM: Encaps and Decaps

Algorithm 19 KEM.Encaps

Input: pk

Output: K, $c = (u, v)$, salt

1: $m \leftarrow\$ \mathbb{F}_2^k$
2: $\text{salt} \leftarrow\$ \mathbb{F}_2^{128}$
3: $\theta \leftarrow \mathcal{G}(m \| \text{pk} \| \text{salt})$
4: $c \leftarrow$PKE.Encrypt(pk, m, θ)
5: $K \leftarrow \mathcal{K}(m, c)$

Algorithm 20 KEM.Decaps

Input: $\text{sk} = (x, y)$, $c = (u, v)$, salt

Output: K

1: $m' \leftarrow$ PKE.Decrypt(sk, c)
2: $\theta' \leftarrow \mathcal{G}(m' \| \text{pk} \| \text{salt})$
3: $c' \leftarrow$ PKE.Encrypt(pk, m', θ')[a]
4: **if** $m' = \perp \ \vee \ c \neq c'$ **then**
5: $\quad K \leftarrow \mathcal{K}(\sigma, c)$
6: **else**
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HQC KEM: Encaps and Decaps

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Input: pk

Output: K, $c = (u, v)$, salt

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2: $\text{salt} \leftarrow\$ \mathbb{F}_2^{128}$
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Algorithm 26 KEM.Decaps

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Algorithm 28 KEM.Decaps

Input: $\text{sk} = (x, y)$, $c = (u, v)$, salt

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Output: K

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Algorithm 34 KEM.Decaps

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HQC KEM: Encaps and Decaps

Algorithm 35 KEM.Encaps

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[a] [Guo+22]

HQC KEM: Encaps and Decaps

Algorithm 37 KEM.Encaps

Input: pk

Output: K, $c = (u, v)$, salt

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Algorithm 38 KEM.Decaps

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[a] [Guo+22]

Vulnerability & Side-Channel

Timing Vulnerability

Fix for rejection-sampling timing-attack [Guo+22]:

Constant-time algorithm [Sen21].

But: uses modulo-reductions.

```
for (size_t i = 0; i < weight; ++i) {
    tmp[i] = i + rand_u32[i] % (PARAM_N - i);
}
```

Figure 1: Vulnerable code snippet generating division (`div`) instructions.

Numerator Dependent Division Throughput

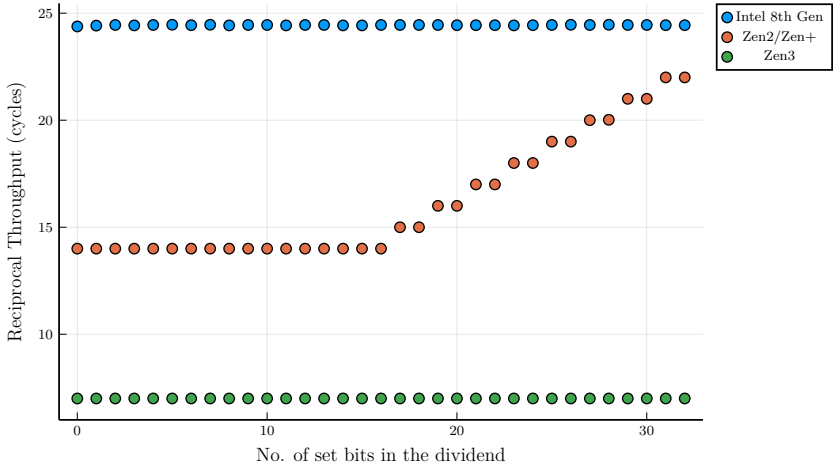
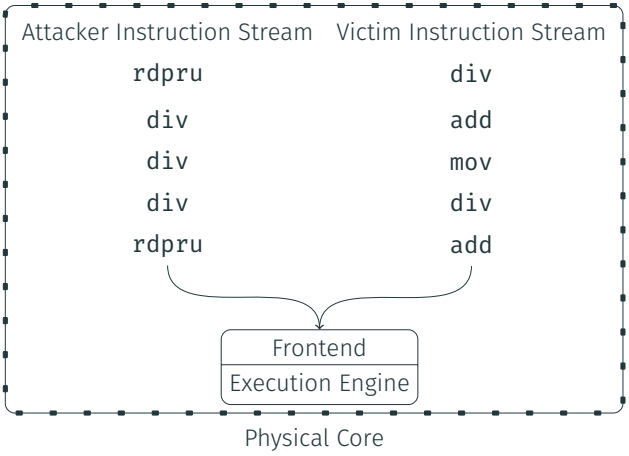
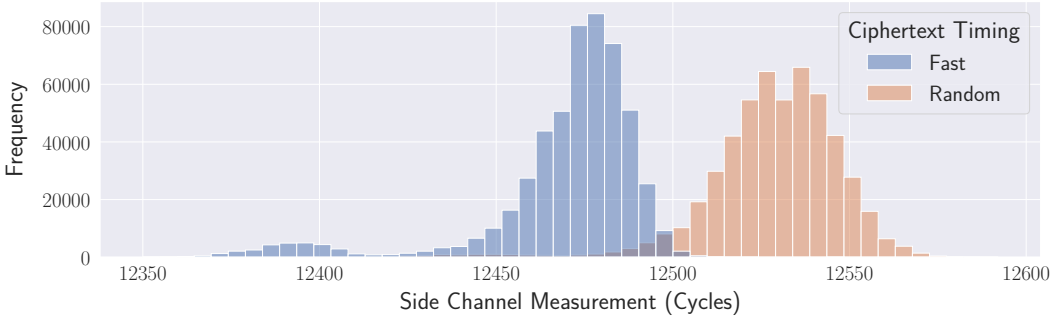


Figure 2: Division throughput for varying numerands and a fixed divisor (17669).

DIV-SMT: Simultaneous Multithreading/Hyperthreading to the rescue



Timing Difference



Exploitation

Recall: HQC encryption/decryption

Algorithm 39 Decrypt($\mathsf{sk} = (x, y), c = (u, v)$)

1: **return** $\mathcal{C}.\mathsf{Decode}(\underbrace{v - u \cdot y}_{=\mathcal{C}.\mathsf{Encode}(m)+x\cdot r_2+e-r_1\cdot y})$

Set r_1 to $\mathbf{1}$ and r_2 and e to 0: the error becomes secret key!

Recover the error of the ciphertext to recover the secret key.

Recall: HQC encryption/decryption

Algorithm 40 Decrypt($\mathsf{sk} = (x, y), c = (u, v)$)

1: **return** $\mathcal{C}.\mathsf{Decode}(\underbrace{v - u \cdot y}_{=\mathcal{C}.\mathsf{Encode}(m)+y})$

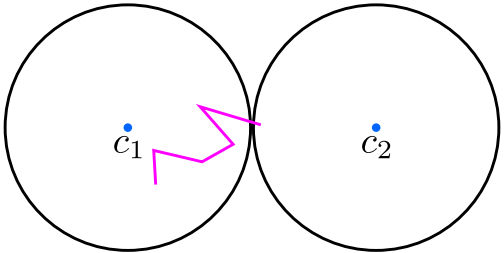
Set r_1 to $\mathbf{1}$ and r_2 and e to 0: the error becomes secret key!

Recover the error of the ciphertext to recover the secret key.

Reaction Attack [HGS99]

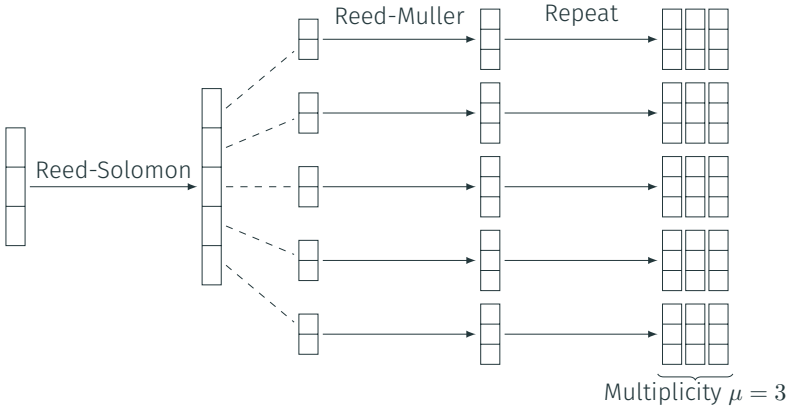
Offline: find “fast” message

Then recover the error y:

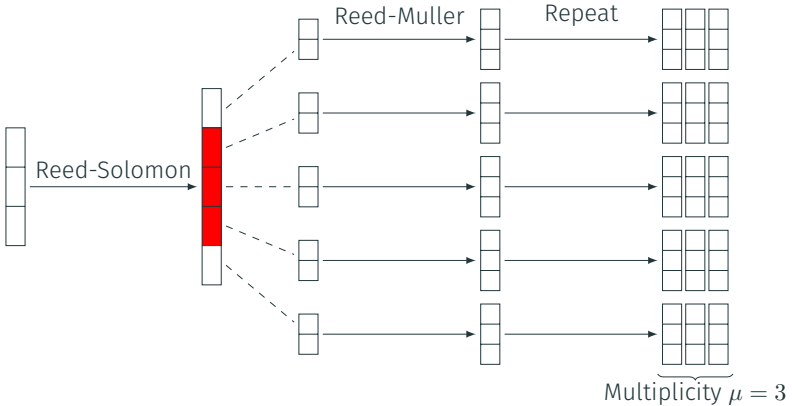


Attack Optimization

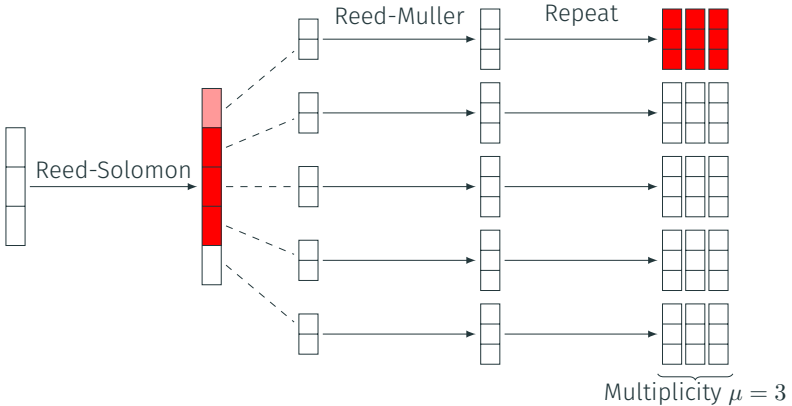
Concatenated Code



Concatenated Code



Concatenated Code



Zero Tester + Shifting

- Test if a block of 384 consecutive bits contains only zero-bits
  - Add errors that “almost” reach the decoding boundary

Zero Tester + Shifting

- Test if a block of 384 consecutive bits contains only zero-bits
  - Add errors that “almost” reach the decoding boundary
- Shift secret-key to zero-test arbitrary 384-bit blocks

Recovering Zero Bits

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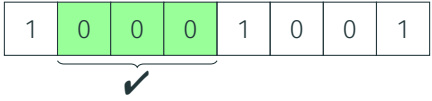
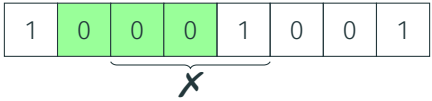
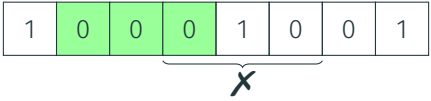


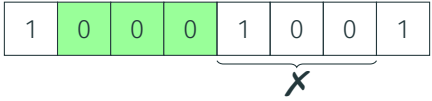
Recovering Zero Bits



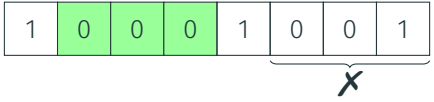
Recovering Zero Bits



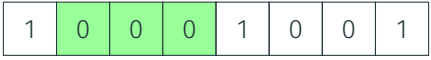
Recovering Zero Bits



Recovering Zero Bits

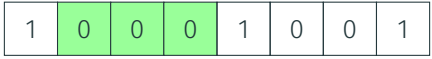


Recovering Zero Bits



How to choose good shifts?

Recovering Zero Bits



How to get entire secret key?

Recovering the Full Key

$$x + h \cdot y = s \tag{1}$$

Recover $\approx n$ out of $2n$ zero-bits with zero-tests

Recover the remaining bits using linear-algebra, integrating public-key information

Simulation Results

Work	Oracle Calls
GHJLNS22 [Guo+22]	866 143
SHRWS22 [Sch+22]	>50 000
HSCGJ23 [Hua+23]	>50 000
SCA-LDPC[Guo+23]	10 000
OurWork	1 142

	$\mathcal{O}_{HQC}^{perfect}$	$\mathcal{O}_{HQC}^{iedal}$	$\mathcal{O}_{HQC}^{0.995}$	$\mathcal{O}_{HQC}^{0.95}$	$\mathcal{O}_{HQC}^{0.9}$	$\mathcal{O}_{HQC}^{0.515}$
SCA-LDPC[Guo+23]	9 000	10 000	18 000	35 250	59 500	n/a
Our Work	1 094	1 142	2 246	4 922	6 951	5 728 728
Success Rate	78.00%	77.30%	76.90%	77.10%	76.60%	77.13%

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Countermeasures

- Manually implement Barrett reduction
- Use a different method to map to the required range
  In BIKE: $i + \frac{(n-i)s_i}{2^{32}}$

Divide and Surrender:

Exploiting Variable Division Instruction Timing in HQC Key Recovery Attacks

Robin Leander Schröder[1,2], Stefan Gast[3] and Qian Guo[4]

August 16, 2024

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2. Fraunhofer Austria, Vienna, Austria
3. Graz University of Technology, Austria
4. Lund University, Sweden

Main Contributions

- Identified a division timing side-channel vulnerability in HQC KEM
- New SMT-based exploitation strategy
- New key-recovery method for HQC
- Evaluation of the attack on an AMD Zen2 CPU
  - Median attack runtime less than 2 minutes

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Data Flow and Relevance

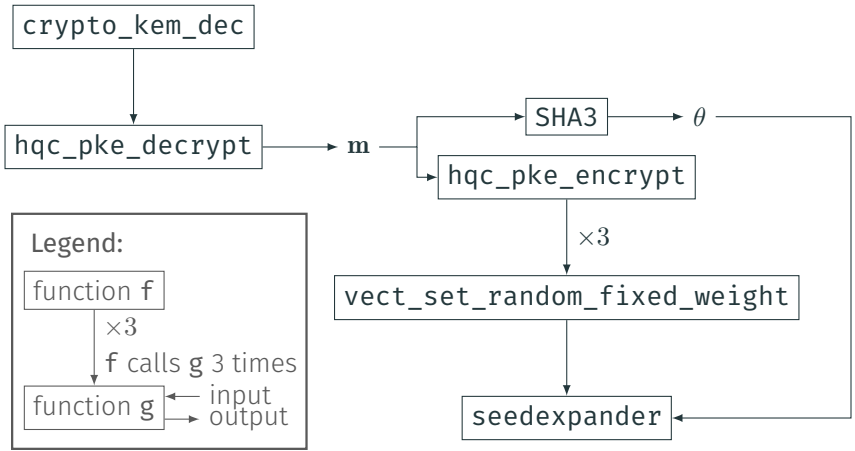

Figure 3: Data flow in Hamming Quasi-Cyclic (HQC).

HQC Decapsulation

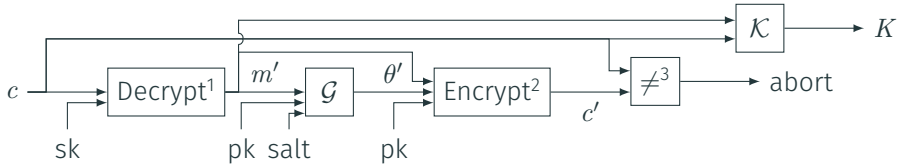

Figure 4: Decapsulation function

[1] WT+19; PT19.
[2] Guo+22.
[3] GJN20.

HQC Decapsulation

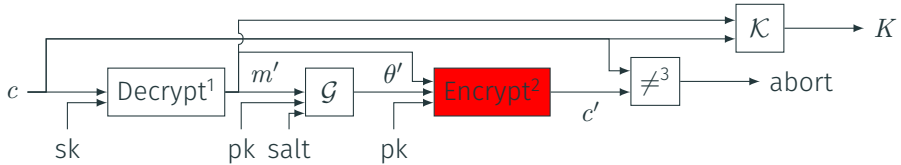

Figure 4: Decapsulation function

[1] WT+19; PT19.
[2] Guo+22.
[3] GJN20.

Disclosure

- February 2023: Disclosed the issue to the HQC design team.
- March 2023: Disclosed to PQClean
- 2024-02-21: We submitted our paper to ePrint Archive
- 2024-02-23: HQC team released a fixed optimized reference implementation, manually implementing the Barrett reductions.