A Side Channel Attack on Masked ML-DSA

Find the Weakest Spot

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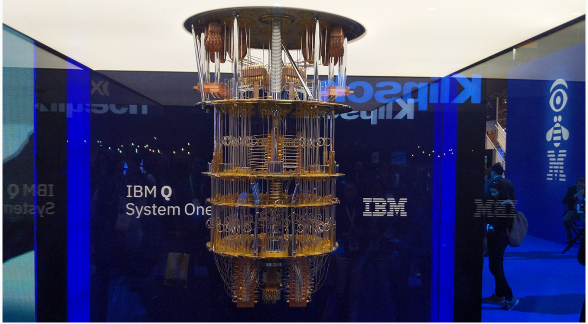
Intro

Post-quantum Cryptography



- Breaks asymmetric cryptography
- Long term PKI

https://www.extremetech.com/extreme/283427-quantum-computing-goes-commercial-with-ibms-q-system-one

Intro
Dilithium/ML-DSA


FIPS 204

Federal Information Processing Standards Publication

Module-Lattice-Based Digital Signature Standard

Category: Computer Security   Subcategory: Cryptography

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U.S. Department of Commerce
Gina M. Raimondo, Secretary

National Institute of Standards and Technology
Laurie E. Locascio, NIST Director and Under Secretary of Commerce for Standards and Technology

- Module-Lattice-based Digital Signature
- Standardized in 2024
- Dilithium: original proposal
- Fiat-Shamir with aborts

https://nvlpubs.nist.gov/nistpubs/FIPS/NIST.FIPS.204.pdf

Intro

Dilithium/ML-DSA Signing

Algorithm 1 Simplified Signing Algorithm

procedure SIGN(secret s_1, public A, message m)
  while no valid signature **do**
    $y \leftarrow$ random sample
    $c \leftarrow$ hash of m and part of Ay
    $z \leftarrow y + cs_1$
    Try again if z leaks sensitive info
  end while
  return signature $\leftarrow (z, c)$
end procedure

- No SCA assessment on masked ML-DSA!
- Many attacks do not tolerate noise well

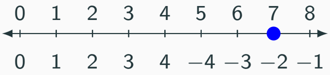
- SASCA on seed of PRNG [KPP20]
- Distinguish zero coefficients in y [Uli+24]
- CPA on cs_1 in NTT domain
  - Software [Che+21]
  - Hardware (FPGA) [Ste+23]
- Find noise-free equations $cs_1 = x + \delta$ [Qia+24]
- SASCA framework on cs_1 [Bro+24]

Boolean and Arithmetic Masking

- Boolean
  - Xor'ing shares
  - $0101_2 \oplus 0111_2 = 0010_2$
- Arithmetic over modulus q
  - Sum of shares mod q
  - $5 + 7 \bmod 9 = 3$
- Masking order
  - Memory and cycle overhead
  - In practice small

Signed and Unsigned Representation

- To represent 7 mod 9:

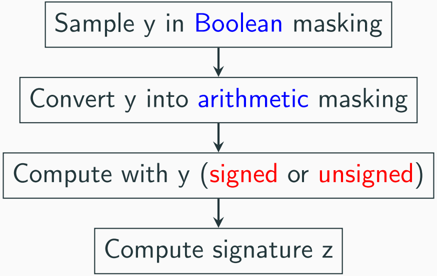


- Unsigned: canonical
- Signed: centered

Signed representation usually leaks more [TMS24]

Intro
Masked Dilithium/ML-DSA

Figure 1: Simplified Masked ML-DSA



State of the art:

- 2023: Closed source masked Dilithium [Azo+23]
- 2023: Gadgets for Dilithium [Cor+23]
- 2024: Extended for ML-DSA [Cor+24]

Can we still target y? If so, how?

- Boolean or Arithmetic?
- Signed or Unsigned?

Information Theoretic Analysis
Methodology

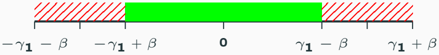
Setup:

- First-order masking
- Hamming weight (HW) leakage model
- Noise-free and noisy (Gaussian)

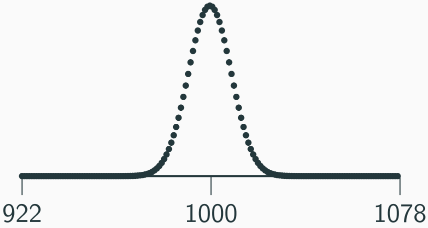
- Leaked Info: mutual info between random variables
- Our case:
  - $x = cs_1$
  - Defined by leakage function L on shares m
- How to compute $I(x; L(\mathrm{m}) \mid z)$?

Information Theoretic Analysis
Computing MI

- $y : [-\gamma_1 + 1, \gamma_1]$, $x : [-\beta, \beta], \gamma_1 = 2^{17}, \beta = 78$
- $z = y + x$



Distribution of y conditioned on z



Information Theoretic Analysis
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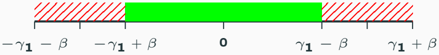
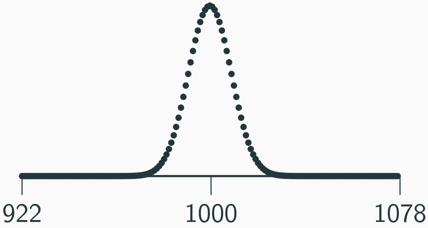


- Fixing $z \to$ small range of y
  - x has $2\beta + 1 = 157$ possible values
  - y is uniquely determined by x

Distribution of y conditioned on z



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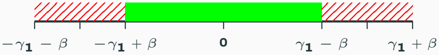
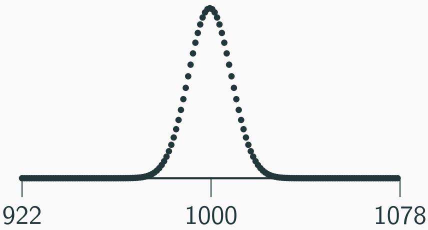


- Fixing $z \rightarrow$ small range of y
  - x has $2\beta + 1 = 157$ possible values
  - y is uniquely determined by x
  - Boolean: $m_0 \in [0, 2^{18} - 1], m_1 = y \oplus m_0$
  - Arithmetic: $m_0 \in [0, q - 1], m_1 = y - m_0 \mod q$

Distribution of y conditioned on z



Information Theoretic Analysis
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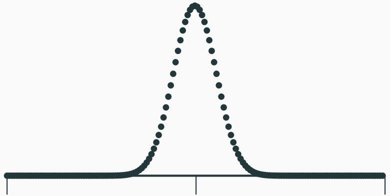
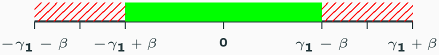
- $I(x; L(\mathrm{m}) \mid z) = \frac{1}{2(\gamma_1 - \beta)} \sum_{z=z'} I(x; L(\mathrm{m}) \mid z = z')$

Distribution of y conditioned on z



Information Theoretic Analysis
Computing MI

- $y : [-\gamma_1 + 1, \gamma_1]$, $x : [-\beta, \beta], \gamma_1 = 2^{17}, \beta = 78$
- $z = y + x$



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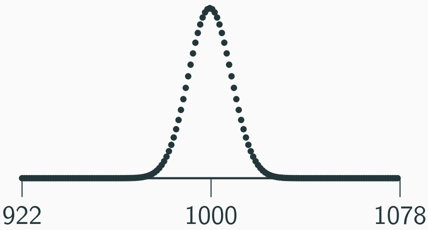
- $I(x; L(\mathrm{m}) \mid z) = \frac{1}{2(\gamma_1 - \beta)} \sum_{z=z'} I(x; L(\mathrm{m}) \mid z = z')$
- $L(\mathrm{m})$ depends on signed/unsigned representation

Distribution of y conditioned on z



Information Theoretic Analysis
Noise-free

Figure 2: Boolean

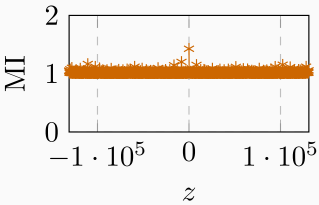


Figure 3: Arithmetic

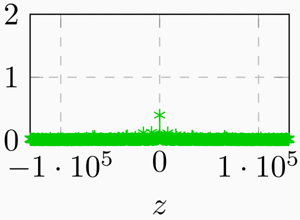


Table 1: $I(x; L(\mathrm{m}) \mid z)$.

Variant	MI
Arith. cen. ($t = 2$)	0.01363
Arith. can. ($t = 2$)	0.01317
Boolean ($t = 2$)	1.01949
Boolean ($t = 1$)	2.16538
Arith. cen. ($t = 1$)	0.17219
Arith. can. ($t = 1$)	0.16708

Not much difference b/w signed and unsigned

- z provides info on y already
- Signed representation leaks slightly more

Accidental leakage for arithmetic masking:

- $y = \mathrm{m}_0 + \mathrm{m}_1 \bmod q$
- $\mathrm{HW}(\mathrm{m}_0 \oplus \mathrm{m}_1) \neq \mathrm{HW}(y)$

Figure 4: Boolean

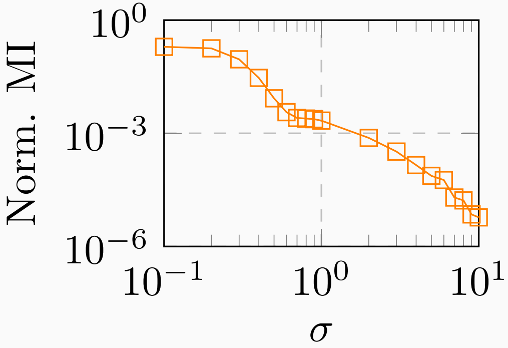
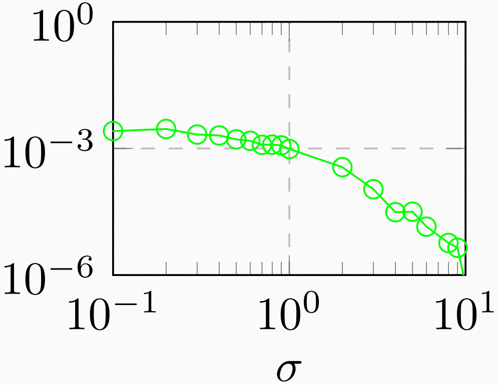


Figure 5: Arithmetic



Not much difference b/w signed and unsigned

What is belief propagation?

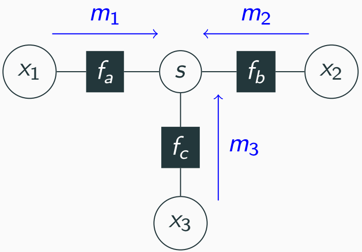
- "Gossiping neighbors"
- Pass distributions

Generic framework for LWE [Her+25]:

- Uses belief propagation
- Instantiated for ML-KEM as an example
- Open source

Example:

$$f(s, x_1, x_1, x_3) = f_a(x_1, s) f_b(x_2, s) f_c(x_3, s)$$



SASCA
Filtering

Drop equations with the highest entropy

- Numerical instability
- Efficiency

Figure 6: Less uniform

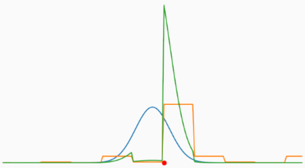


Figure 7: More uniform

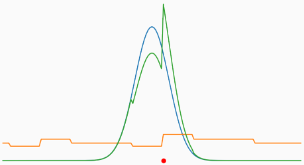
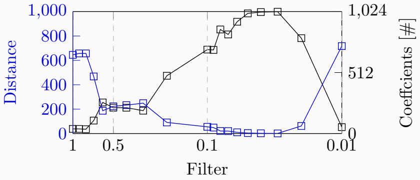


Figure 8: Effect of Filtering



Overview of simulated attacks:

- Signed and unsigned
- 1st order: HW(y), HW(y) + HW(x), LSBs of y
- 2nd order: HW(m), Boolean and Arithmetic

Figure 9: Boolean

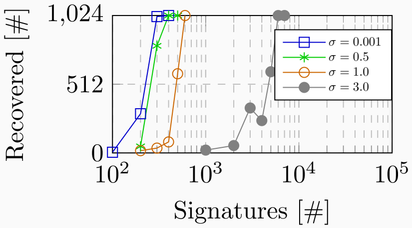
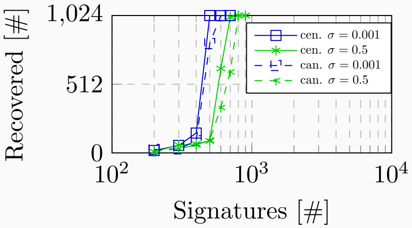


Figure 10: Arithmetic



Setup:

- Ported implementation from [Cor+24]
- Cortex-M3 and M4
- Target Boolean shares of y

Overview of physical attacks:

- 1^{st} order: HW(y), LSBs of y
- 2^{nd} order: HW(m)

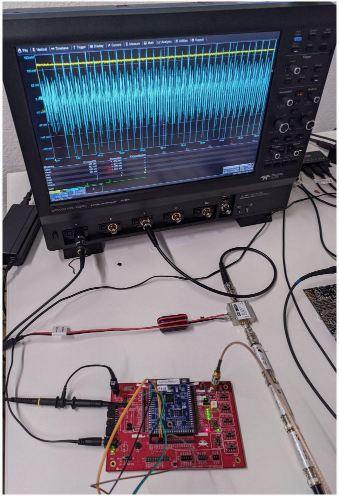


Figure 11: LSBs of y, 1st order

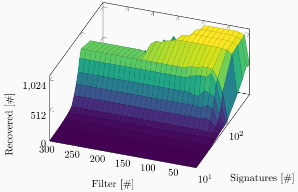


Figure 13: HW(m), 2nd order

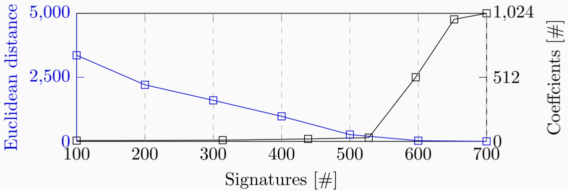


Figure 12: HW(m), 2nd order, simulated

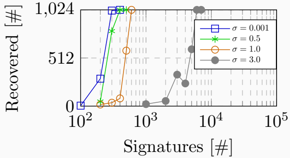


Table 2: Summary of Physical Attacks

Leakage function	Order	σ	Signatures
LSBs of y	1	12	250
HW(y)	1	4.74	300
HW(m)	2	1.47, 1.65	700

Takeaways

- Signed vs Unsigned: not much diff. in this case
- Boolean masking:
  - More likely to have strong accidental leakage
  - Leaks more for all orders
- Noise tolerant 2^{nd} order attacks
- Filters matter: drop dist. with high entropy

Our paper: `https://eprint.iacr.org/2025/276`

Table 3: Summary of Our Attacks

Order	Type	HW(y)	HW(y) + HW(x)	LSBs of y
1	Simulated	✓	✓	✓
	Physical	✓	✗	✓
		HW(m), Boolean	HW(m), Arithmetic	
2	Simulated	✓	✓	
	Physical	✓	✗	

Thank you for your attention!

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Extra

Dilithium/ML-DSA Key Generation

Algorithm 2 Simplified Key Generation

procedure KEYGEN
    $A \leftarrow$ random sample
    $(s_1, s_2) \leftarrow$ random short samples
    $t \leftarrow As_1 + s_2$
    $(t_1, t_0) \leftarrow$ split t into t_1 and t_0
    return pk $\leftarrow (A, t_1)$, sk $\leftarrow (t_0, s_1, s_2)$
end procedure

- SASCA on ML-KEM key in NTT domain [PP19; PPM17]; *Maybe* s_1?
- SASCA on seed of PRNG [KPP20]
- Target s_1 in normal domain with neural network [Han+21]

Due to compiler optimization, unexpected microarchitectural effects

Figure 14: HW(y)

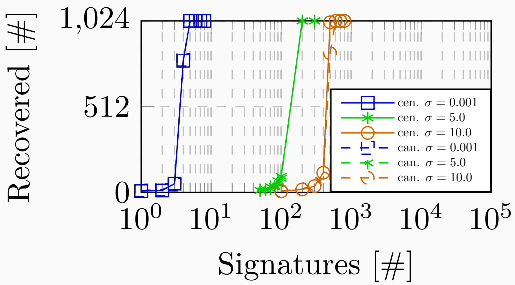
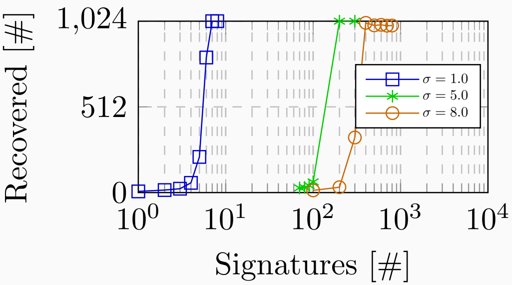


Figure 15: 8 LSBs of y



Extra
Naïve Template Attack

20 PoIs in 1 million gadget calls ($\sim$ 1000 traces)

- Cortex-M3 ($\sigma = 2.5$): 9% advantage per bit
- Cortex-M4 ($\sigma = 12$) : 5% advantage per bit

Table 4: Accuracy targeting individual bits of y.

Bit Index	0	1	2	3	4	5	6	7
Cortex-M4								
σ	38.79	11.72	11.89	11.65	12.84	13.40	12.78	13.06
SNR_{max}	0.000166	0.001818	0.001767	0.001839	0.001514	0.001390	0.001528	0.001465
Accuracy (%)	49.98	50.64	53.80	54.73	54.21	54.39	54.97	54.19
Cortex-M3								
σ	2.37	2.84	2.66	2.46	2.51	2.47	2.52	2.40
SNR_{max}	0.044281	0.030956	0.035102	0.041014	0.039497	0.040864	0.039298	0.043089
Accuracy (%)	59.10	57.62	58.05	58.84	58.34	58.21	58.12	58.61

Table 5: Overhead of Our Countermeasure (in cycles)

	Total signing	masked_sample_y	seed_y
Original	39118662.27	5488094 (14.02%)	175083 (0.44%)
With Countermeasure	52031577.69	17779727 (34.17%)	701690 (1.35%)