Side-Channel Analysis of Post-Quantum Schemes

Julius Hermelink

April 1, 2025

Who am I?

Short CV:

- Postdoc at MPI-SP in Bochum.
- PhD from UniBw in Munich in 2024.
- Master's in Mathematics from LMU in 2020.

Research interests:

- Implementation attacks on post-quantum schemes.
- Soft-analytic side-channel attacks.
- Cryptanalysis (under side information).
- Information theory.
- Formal models for side-channel security.

The Quantum Threat

Quantum computers threaten currently used asymmetric cryptography.

We have to assume that:

- Large-scale quantum computer break commonly used asymmetric schemes.
- Adversaries: harvest now, decrypt later.

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- Adversaries: harvest now, decrypt later.

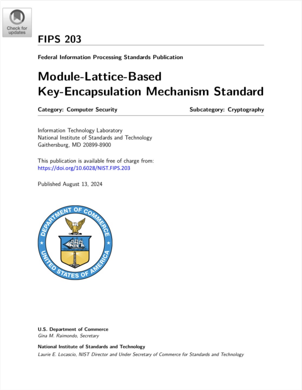
Therefore, we need:

- Post-quantum asymmetric cryptography.
- Most pressingly key exchanges.

IBM Research, https://www.flickr.com/photos/ibm_research_zurich/51248690716/, unmodified, license: CC BY 2.0

The NIST Standardization Process

NIST is in the process of standardizing post-quantum cryptography.



Check for updates

FIPS 203

Federal Information Processing Standards Publication

Module-Lattice-Based Key-Encapsulation Mechanism Standard

Category: Computer Security — Subcategory: Cryptography

Information Technology Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8900

This publication is available free of charge from:
https://doi.org/10.6028/NIST.FIPS.203

Published August 13, 2024

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- Five candidates already selected.
- Three are lattice-based.
- ML-KEM and ML-DSA standardized.

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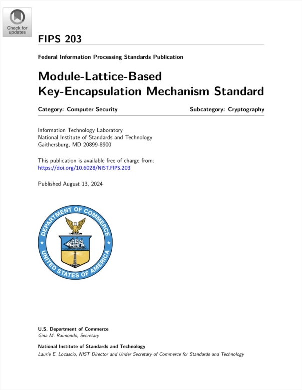

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ML-KEM used in Signal, Chrome, iMessage, ...

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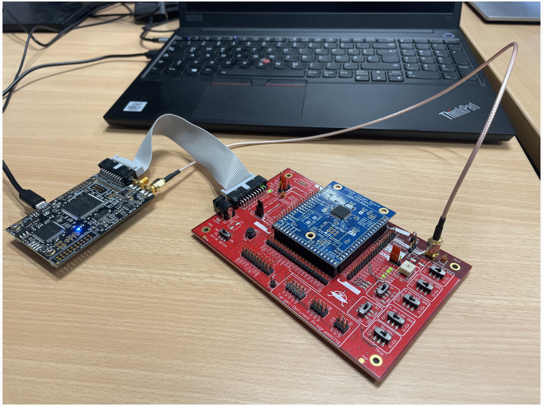
Attacks on Embedded Devices

Embedded devices may be particularly vulnerable to side-channel and fault attacks.



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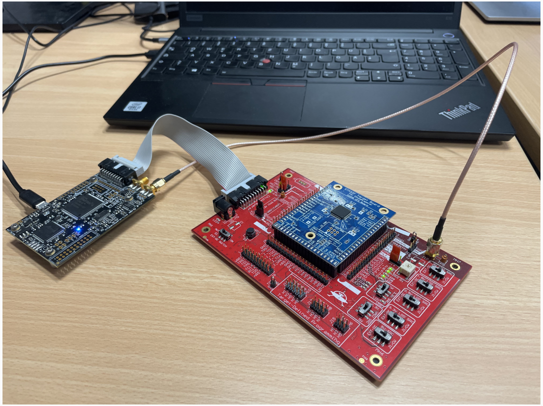
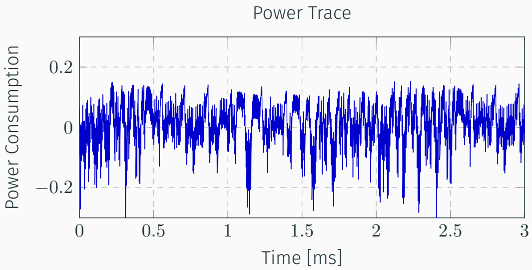




The Insecurity of Masked Comparisons

Julius Hermelink, Kai-Chun Ning, Richard Petri, and Emanuele Strieder. "The Insecurity of Masked Comparisons: SCAs on ML-KEM's FO-Transform". In: *ACM CCS 2024*. Ed. by Bo Luo, Xiaojing Liao, Jun Xu, Engin Kirda, and David Lie. ACM Press, Oct. 2024, pp. 2430–2444

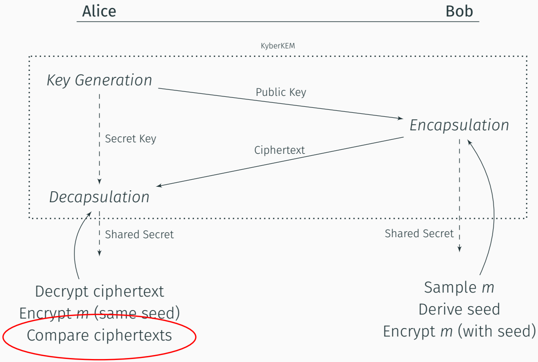
Fujisaki-Okamoto Transform Comparisons

In ML-KEM:

- Comparison $\texttt{ct}' == \texttt{ct}$.
- Checks if honestly generated.
- Comparison is sensitive operation.

Adversary observes comparison:

- Enables chosen-ciphertext attack.
- Gives inequalities in the secret key.
- Solving using our prior work.



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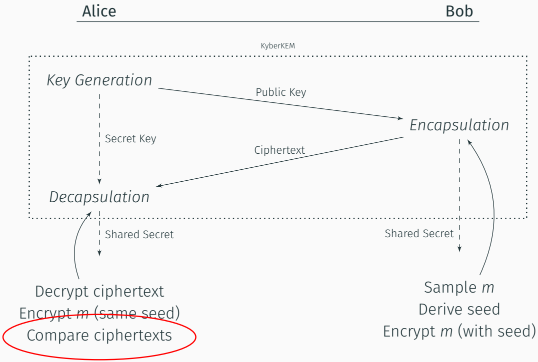
$$(-1)^{\texttt{obs}}(\mathbf{r}^\top \mathbf{e} - \mathbf{s}^\top(\mathbf{e}_1 + \Delta\mathbf{u}) + e_2 + \Delta v) \leq 0$$

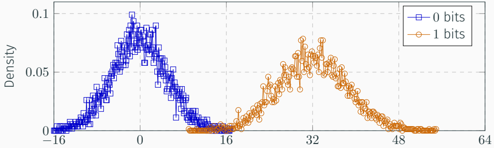


Leakage Model

Recent masked t-probing secure proposal: We suspected signal amplification.

Masking countermeasures share information over multiple variables, e.g., $s = s_0 \oplus s_1$.

Our model (simulation for $\sigma = 5$):



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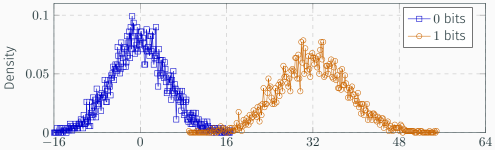
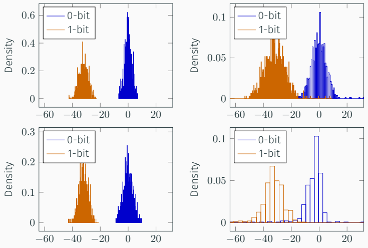


Power consumption of processing a single shared bit.

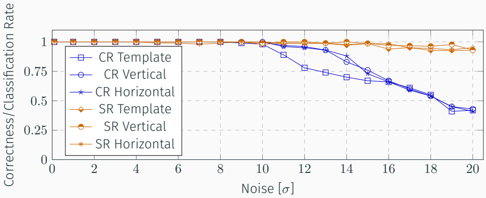
Actual leakage confirms our model:



Results

Carried out in practice and simulated for different noise levels.

Simulated results with 4 shares:



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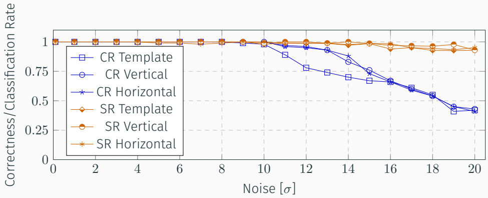

Why do these attacks work so well?

- Slight advantage enough.
- Amplified leakage.

→ High noise requirements.

Noise/masking order necessary to prevent attacks extraordinarily high.

A Generic Framework for Side-Channel Attacks against LWE

Julius Hermelink, Silvan Streit, Erik Mårtensson, and Richard Petri. "A Generic Framework for Side-Channel Attacks against LWE-based Cryptosystems". In: *To appear in Eurocrypt*. LNCS. Springer, 2025. URL: https://eprint.iacr.org/2024/1211

Julius Hermelink, Kai-Chun Ning, and Richard Petri. *Finding and Protecting the Weakest Link: On Side-Channel Attacks on Masked ML-DSA*. Cryptology ePrint Archive, Report 2025/276. 2025. URL: https://eprint.iacr.org/2025/276

Distribution Hints

The secret often has to be recovered from side information.

Adversary may learn, e.g.,:

- $\langle \mathbf{v}, \mathbf{x} \rangle = l$
- $\langle \mathbf{v}, \mathbf{x} \rangle \equiv l \mod p$
- $\langle \mathbf{v}, \mathbf{x} \rangle = l + \mathcal{N}(0, \sigma)$
- $\langle \mathbf{v}, \mathbf{x} \rangle \leq l$
- $\mathrm{HW}(\langle \mathbf{v}, \mathbf{x} \rangle) = h + \mathcal{N}(0, \sigma)$
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Distribution Hints:

$$\langle \mathbf{v}, \mathbf{x} \rangle \sim \mathcal{D}$$

for known vector $\mathbf{v}$, distribution $\mathcal{D}$, and secret $\mathbf{x}$.

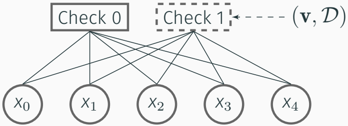
The definition:

- Generalizes all but one previous hints.
- Complements lattice-based frameworks.

Solver for Distribution Hints

We present two solvers working on distribution hints.

Belief propagation-based solver:



Represent unknown key coefficients

Update for $x_j = x_j'$ where $s_j = \sum_{i \neq j} v_i x_i$:

$$P(x_j = x_j') = \sum_{a \in \operatorname{supp} \mathcal{D}} P_{\mathcal{D}}(a) P(s_j = a - v_j x_j')$$

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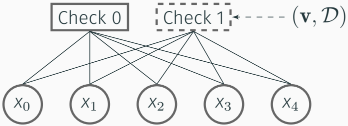

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Greedy solver:

Compute change scores for coefficients j:

$$s_j(c) = \sum_{a \in \operatorname{supp} \mathcal{D}} P_{\mathcal{D}}(a) |\mathbf{v}^\top \mathbf{x}' + v_j c - a|,$$

and perform k best updates on guess $\mathbf{x}'$.

$P(s_j = a - v_j x_j')$ replaced by $|\mathbf{v}^\top \mathbf{x}' + v_j c - a|$.

A more conceptual approach to side-channel attacks.

Masked ML-DSA:

- Different types of masking.
- Choice of signed and unsigned integers.
- Several attacks on unmasked ML-DSA.

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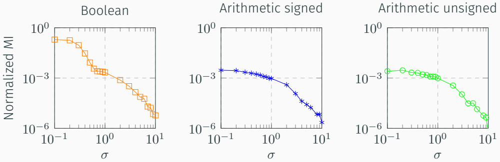

Side-Channel Attacks on Masked ML-DSA

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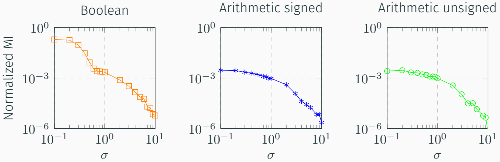

Our framework can be applied with hint-filtering technique.

Future Directions

Real-world security largely an open question.

- Improved cryptanalysis under side-information.
- Non-standard side-channel.
- Impacts of leakage on protocol level.
- Conceptual information-theoretic approaches to (previous) attacks.
- Formal models/verification.
- Other PQC schemes.
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- **David Oswald**: embedded security and side-channel analysis.
- **Christophe Petit**: cryptanalysis and isogeny-based cryptography.
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Thank you for your attention!