The Challenge of Side-Channel Countermeasures on Post-Quantum Crypto

Rina Zeitoun - rina.zeitoun@idemia.com
IDEMIA - Crypto & Security Labs

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Outline

Context

IDEMIA: The leader in identity technologies

- Identity (3B ID docs, 5M biometric terminals).
- Payment (800M payment products - 2021).
- Telecoms (900M SIM cards - 2021).

Into the wild

- Our products are deployed in hostile environments.
- Attackers have physical access to the device.
- Must be resistant to side-channel/fault attacks.

☞ Security against side-channel attacks is **mandatory**.

Side-Channel Attacks

Main Powerful Attacks

- Timing Attacks, Simple Power Analysis, Differential/Correlation Power/Electromagnetic Analysis, Template Attacks, Fault Attacks, etc.

Into Specifications of Selected NIST PQC Algorithms

- Resistance to Timing Attacks is always addressed.
- All other attacks are mainly **left for research**.

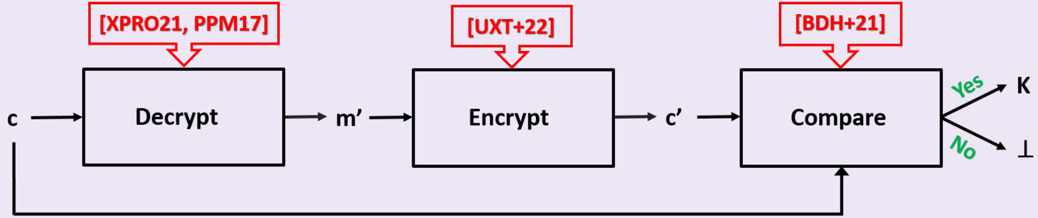
Smartcards: In real life

- Timing attacks are indeed important to consider.
- But **all** other classical side-channel attacks are definitely **real threats**!
- Main powerful attacks should **systematically** be studied in NIST submissions.

Outline

Side-channel Attacks on Lattice-based KEM

Power/EM Attacks on Decapsulation based on FO Transform



☞ **Whole Decapsulation needs to be masked**

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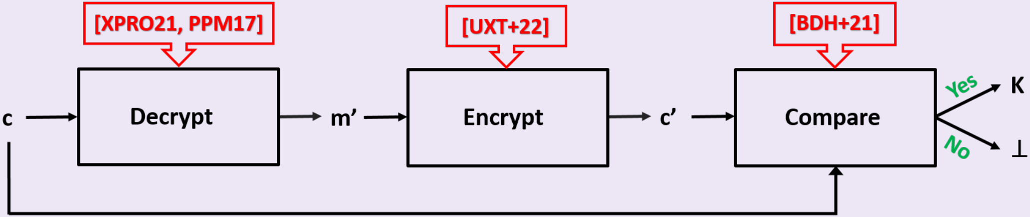

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Template Attacks on Key Generation

- Template attacks require detailed knowledge of target but can be a real threat!
- Investigated in security certifications (Common Criteria and EMVco).

Outline

Masking Countermeasure

High-Order Masking Countermeasure

- Each sensitive variable x is shared into n variables: $x = x_1 \oplus x_2 \oplus \cdots \oplus x_n$
- Manipulate $x_1, x_2, \ldots, x_n$ independently

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Computing with Boolean Masking

Given $x = x_1 \oplus \cdots \oplus x_n$ and $y = y_1 \oplus \cdots \oplus y_n$, how can we compute $x \oplus y$?

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Arithmetic Masking Countermeasure

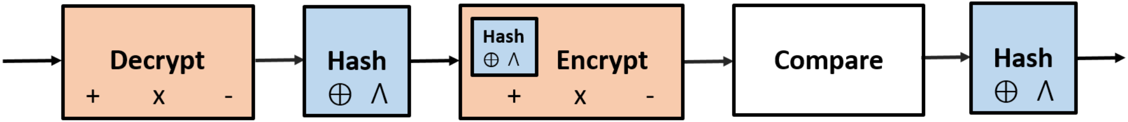
Generate arithmetic sharings s.t. $x = x_1 + \cdots + x_n \mod 2^k$ and $y = y_1 + \cdots + y_n \mod 2^k$

- Compute $x_1 + y_1 \mod 2^k, \cdots, x_n + y_n \mod 2^k$

Arithmetic and Boolean Masking

Masks Conversions

- Need to convert between arithmetic and Boolean masking.
- Efficient classical masks conversions exist ([Gou01],[CGV14],[CGTV15],[BCZ18], etc.)



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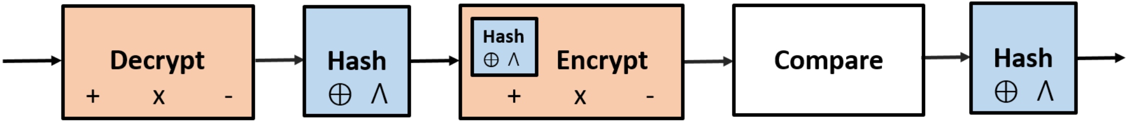

Difference with previous schemes

- **Symmetric schemes:** k-bit Boolean $\Leftrightarrow$ arithmetic modulo 2^k; usually $k = 32$
- **Post-Quantum schemes:** k-bit Boolean $\Leftrightarrow$ arithmetic modulo q; **arbitrary** k, q

New Problematics with Post-Quantum Crypto

Arbitrary Masks Conversions

- Generic conversions suitable for PQ schemes exist ([BBE+18]: generalization of [CGTV15])
- Downside: Can be too costly in practice

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Other Problematics

- Secure polynomials comparison (Kyber, Dilithium)
- Secure computation of compression: $\lceil (2^d/q) \cdot x \rfloor \bmod 2^d$ (Kyber)
- Secure generation of a random in a given interval (Dilithium)
- Secure Euclidean division (NTRU, Dilithium)
- etc.

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☞ **Need specific solution for each problem**

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Kyber Encryption

Encryption Problematic: Securely compute $\lfloor q/2 \rceil \cdot m$ (prime $q = 3329$)

- We have $m = m_1 \oplus \cdots \oplus m_n$ where m_i are 1-bit long.
- Compute $y_1 + \cdots + y_n \bmod q = 1665 \cdot (m_1 \oplus \cdots \oplus m_n)$.

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Encryption Solution

Convert 1-bit Boolean sharing $m_1, \cdots, m_n$ into arithmetic modulo q

- Use [BBE+18] with complexity $\mathcal{O}(n^2 \cdot \log \log q)$.
- Use [SPOG19] or [CGMZ21a] with complexity $\mathcal{O}(n^2)$.

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Centered Binomial Distribution (CBD)

- Similar problematic and solution to securely compute $e = HW(x) - HW(y)$ in CBD.

Kyber Decryption

Decryption Problematic: Securely compute $m = \lceil (2/q) \cdot x \rfloor \bmod 2$

- We have $x = x_1 + \cdots + x_n \bmod q$.
- Compute $m_1 \oplus \cdots \oplus m_n = \lceil (2/q) \cdot (x_1 + \cdots + x_n) \rfloor \bmod 2$.

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Decryption Solution

- [BGR+21]: Convert A mod $q \hookrightarrow$ B (BBE+18) + 4 secure AND. Complexity $\mathcal{O}(n^2 \cdot \log q)$.
- [CGMZ21a]: Switch A mod $q \hookrightarrow$ A mod 2^k; convert A mod $2^k \hookrightarrow$ B. Complexity $\mathcal{O}(n^2 \cdot \log n)$.

Kyber other problematics: Compress & Compare

$\text{Compress}_{q,d}(x)$ Problematic: Securely compute $\lceil (2^d/q) \cdot x \rfloor \bmod 2^d$

- We have $x = x_1 + \cdots + x_n \bmod q$ and $d = 4, 5, 10$ or 11.
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Comparison Problematic

- We are given ℓ coefficients $x^{(\ell)} = x_1^{(\ell)} \oplus \cdots \oplus x_n^{(\ell)}$ and $y^{(\ell)}$.
- Compare $x_1^{(\ell)} \oplus \cdots \oplus x_n^{(\ell)}$ and $y^{(\ell)}$ without revealing which coefficients fail.

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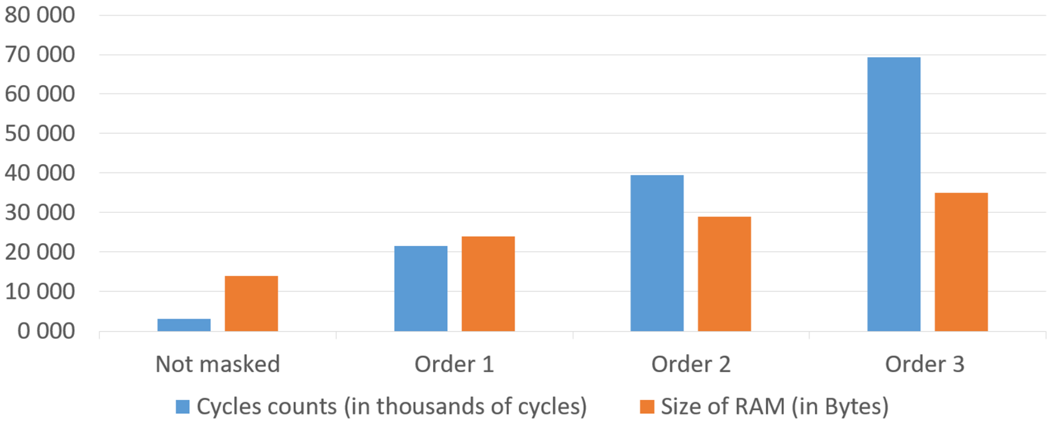
Solutions

- [FBR+21]: First order only; compare $H(x_1^{(\ell)} \oplus y^{(\ell)})$ with $H(x_2^{(\ell)})$.
- [BGR+21]: Do not compress: compare uncompressed coefficients with public ones.
- [CGMZ21b]: Hybrid approach with new compression and comparison methods.

Fully masked implementation of Kyber [CGMZ21a/b]

Kyber768 Decapsulation on ARM Cortex-M3 for given security order:



- For security order $t > 3$, required RAM too large for ARM Cortex-M3 target device.

Outline

Conclusion

Smartcards:

- Real need to secure implementations against all SCA.

Standard specifications:

- Resistance against timing attacks studied in standardized PQ algorithms.
- Other Side-Channel Attacks (Power/EM DPA, templates, fault) mainly left for research.

Attacks in practice:

- Many practical Side-Channel Attacks published.

Countermeasures:

- New challenges for PQ crypto countermeasures.
- Not trivial and imply large overhead (can be unacceptable for many products).

Going Forward:

- Encourage designers to study classical SCA at an early stage ("Masking friendly" PQ crypto).

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Thank you for your attention!

rina.zeitoun@idemia.com

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