Side-channel Analysis and Countermeasure for Implementation of Lattice-based Signature

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Abstract: Lattice-based cryptography is believed to be a promising candidate for post-quantum cryptography (PQC). The NIST announced that the third-round finalists in the standardization project of PQC (NIST-PQC) and four out of seven finalists are lattice-based cryptography. An implementation is desired that is resistant to side-channel analysis for the widespread use of lattice-based cryptography. This paper studies possible side-channel analysis on the signature scheme MLWRSign, a lattice-based signature scheme. We apply differential power analysis to the implementation of MLWRSign to specify all the sensitive parts. The experimental results show that only Karatsuba and Toom-Cook multiplications can be vulnerable to DPA with the Hamming weight power consumption model. Furthermore, we propose masking countermeasures for multiplication: inter-functional and intra-functional masking. Our lightweight countermeasure is beneficial to further enhance the security of post-quantum cryptography, which is naturally resistant to side-channel attacks.

1 INTRODUCTION

Recently, there has been substantial research on quantum computers that potentially provides the power to break (Shor, 1994; Shor, 1997) current public-key cryptography such as RSA and ECC in a feasible time. The NIST called for proposals to standardize post-quantum cryptography (PQC) and public-key cryptography registrant to quantum computers. There are two categories in the NIST-PQC standardization project: public-key encryption/KEMs and digital signatures.

In addition to quantum computer threats, PQC should protect against side-channel analysis. Cryptographic algorithms are considered mathematically robust; however, their implementation might leak sensitive information through physical leakage. Physical leakage is no more or less than an exhibited physical property, such as power, electromagnetic emanation (EM) (Huang et al., 2019), acoustic vibration, and time computation.

Some attacks against PQC have already been published; thus, designers should also consider these attacks and implement countermeasures. Vulnerabilities against timing attacks and differential power analysis (DPA) should be considered at an early stage of conception by making the execution time constant and the power consumption independent of secret data. A masking scheme is the most studied countermeasure in the state-of-the-art to defeat DPA. The most important PQC algorithms families are lattice-based, code-based, multivariate-based, hash-based, and isogeny-based.

In this paper, we studied possible side-channel analysis on the signature scheme MLWRSign, an LWR variant of CRYSTALS-Dilithium that is one of the finalists in the NIST-PQC competition. We applied DPA to the implementation of MLWRSign to specify all the sensitive parts. We found that only Karatsuba and Toom-Cook multiplications can be vulnerable to DPA with the Hamming weight power consumption model. Furthermore, we proposed masking countermeasures for multiplication: inter-functional and intra-functional masking. Our lightweight countermeasure is beneficial to further enhance the security of post-quantum cryptography, which is naturally resistant to side-channel attacks.

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2 RELATED WORK

Cryptographic implementations can be vulnerable to side-channel attacks. The different attacks studied in the literature, such as DPA and template attacks, can be transposed to the post-quantum implementations. Some publications have already addressed the side-channel threats against post-quantum cryptography. From a side-channel analysis viewpoint, the critical parts are very similar since those algorithms are based on the same specific problems (code-based and lattice-based). The differences in algorithms do not provide more resistance. A cautionary countermeasure should be implemented to protect the critical parts of the algorithm. The private parts, including key generation, signature, and decryption, should implement countermeasures against side-channel attacks.

Timing Attack. The first timing attack, introduced by Kocher, targets RSA implementations (Kocher, 1996). It takes advantage of the non-constant execution timing of modular multiplication. Other timing attacks (Dhem et al., 2000; Schindler, 2000; Schindler, 2002) also take advantage of the non-constant execution timing of the operations.

Cache-timing Attack. A cache is a small memory used to increase performance in modern processors. Bernstein first discovered cache attacks on AES (Bernstein, 2005). Cache attacks are currently an important research subject. Critical vulnerabilities related to cache attacks and, more generally, microarchitectural attacks emerged, such as Spectre or Meltdown (Kocher et al., 2019; Lipp et al., 2018) in 2017 and 2018. The latter is related to the operating system and the CPU. Specter attacks exploit speculative execution, whereas meltdown exploits out-of-order execution. These attacks have several variants.

Simple Power Analysis. Simple power analysis (SPA) is a visual inspection and analysis of the leakage trace. The timing duration and characteristic patterns for each operation can be identified and mapped to the algorithm.

Differential Power Analysis. The attacker makes assumptions on intermediate variables during the execution of the algorithm in classical differential power analysis (DPA). Several traces are acquired and correlated with the intermediate variables.

- Correlation Power Analysis (CPA) (Brier et al., 2004): The CPA computes a leakage model and correlates with traces vertically for each key hypothesis. The highest peak corresponds to the best key candidate.
- Linear Regression Analysis (LRA) (Lomné et al., 2013): The LRA uses the least square method to minimize the error (between the estimation and the observation) and model the leakage trace with the intermediate value.
- Collision Attack (Moradi et al., 2010): The collision attack builds the leakage model on the traces. A more generic case of the collision attack is the template attack (Rechberger and Oswald, 2005).

Fault Injection Attack. The differential fault attack (DFA) exploits an introduced fault when computing a sensitive operation. The fault can be performed on data and instruction and achieved by laser injection, EM injection, or glitches (on clock or voltage). When the signature is deterministic, the couple (faulted result, correct result) can recover the whole or partial private information.

3 LATTICE-BASED SIGNATURE: MLWRSign

Okada et al. (Okada et al., 2020) proposed a lattice-based digital signature scheme MLWRSign that is a learning with rounding (LWR) variant in CRYSTALS-Dilithium third-round finalists of the standardization project of post-quantum cryptography by NIST (NIST-PQC). The secret key in MLWRSign is approximately 30% smaller than CRYSTALS-Dilithium with the same security level due to the simplicity of the LWR. The running time of MLWRSign is comparable to that of CRYSTALS-Dilithium.

4 SIDE-CHANNEL ANALYSIS ON MLWRSign

The target of evaluation (ToE) is an STM32 Nucleo-64 [9] with 32 MHz max CPU frequency. The STM32 Nucleo-64 board provides an affordable and flexible method for users to try out new concepts and build prototypes by choosing from various performance and power consumption features provided by the STM32 microcontroller. The STM32 Nucleo-64 board does not require any separate probe as it integrates the ST-LINK debugger/programmer. The STM32 Nucleo-64 board comes with the STM32 comprehensive free

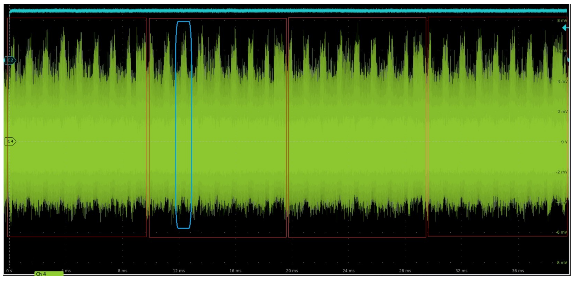


Figure 1: Acquisition of one execution of `polyvecl_mul` function.

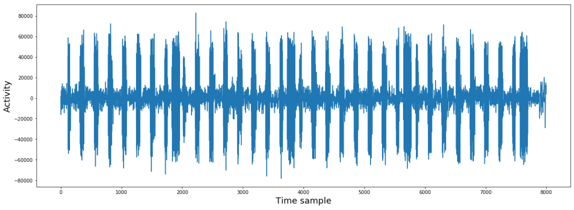


Figure 2: Result of the bandpass filter.

software libraries and examples available with the STM32Cube MCU Package.

4.1 Horizontal Analysis

Figure 1 shows one electromagnetic emanation (EM) acquisition of the `polyvecl_mul` function (in green). The blue curve shows the start and end of the execution. In particular, we have four large blocks that correspond to the `poly_mul` function (red rectangle).

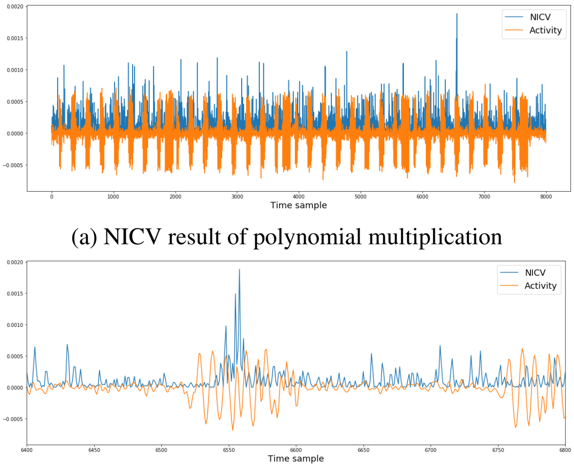
In each block, we can distinguish seven patterns related to the Karatsuba simple four functions (blue rectangle) inside each `poly_mul` function. We can perform some processing of the traces to see these operations more clearly. For this purpose, we first perform an STFT to locate the interesting bound. The scope is configured as follows:

- Sampling Rate: 31.25 MS/s,
- Filter: Low-pass at 20 MHz, and
- Impedance: 50.

The duration of each `polyvec_mul` is approximately 40 ms. Figure 2 shows the result of the bandpass filter 1–4 MHz applied to the short-time Fourier transform (STFT) of the leakage traces in Fig. 1. The Karatsuba multiplications are distinguishable inside each polynomial multiplication (`poly_mul`).

4.2 Vertical Analysis

The target of evaluation is run with different input data. Each time, the power consumption or the electromagnetic radiation is acquired. Statistical analysis is performed on the different traces to deduce the manipulated values, hence the secret scalar. We can cite the different methods as DPA, CPA, or LRA. The real acquisitions are noisier than the simulated acquisitions. As explained previously, many sensitive operations (that depend on s1) can be targeted. Hereafter we perform our evaluation on the polynomial multiplication (`polyvecl_mul`) function.



(a) NICV result of polynomial multiplication

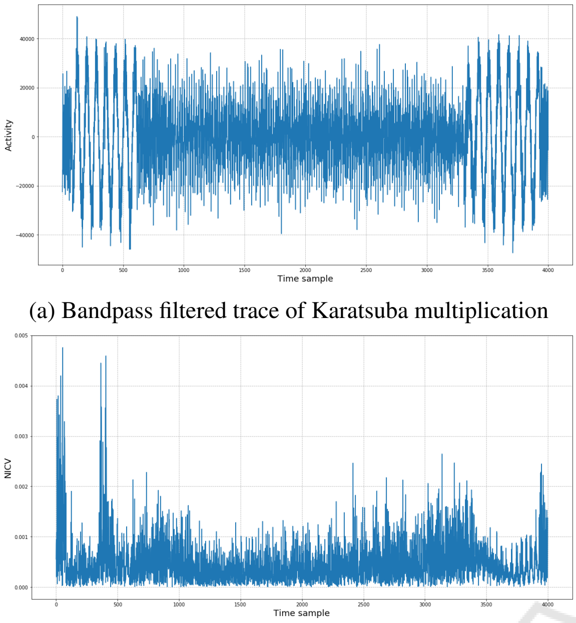
(b) Zoom on the leakage peak in Karatsuba multiplication

Figure 3: NICV result based on 10,000 filtered traces.

The key generation procedure and the signature procedure have similar polynomial multiplications: $\boldsymbol{A} \cdot \boldsymbol{s}_1$ and $\boldsymbol{A} \cdot \boldsymbol{y}$, respectively. The variable A is a public parameter; thus, it is known by an attacker. We acquired 10,000 traces with random $s1$ and fixed A to see how much this operation is leaking. Each trace has 500,000 samples. We located the operations that manipulate a subpart (nibble by nibble or byte by byte) of this secret by performing NICV (Bhasin et al., 2014) using the parameter s_1. As the traces were relatively noisy, we applied a bandpass frequency filter (Fig. 2). We then compute the NICV on the filtered traces.

Figure 3a shows the raw trace (orange line) and the NICV results (blue line) based on the 10,000 filtered traces of the polynomical multiplication (`polyvecl_mul` function). A significant leakage can be seen at one Karatsuba multiplication. Figure 3b focuses on the peak that shows that the leakage is in the Karatsuba multiplication. More significant leakage can be obtained with more traces.

Note that the traces are long, and the analysis can be complex. The accuracy of the measurements is also a compromise about the number of samples to be acquired. We thus focused on smaller functions, i.e., Karatsuba, to overcome these limits.



(a) Bandpass filtered trace of Karatsuba multiplication

(b) NICV result of Karatsuba multiplication

Figure 4: Leakage trace of Karatsusba multiplication.

4.3 Analysis of Karatsuba Multiplication

Most operations in the power traces are linked to Karatsuba multiplication. We thus focused our analysis on this part of the algorithm. We select a single Karatsuba multiplication to eliminate potential sources of desynchronization.

The bandpass filtered trace and NICV results of Karatuba multiplication are shown in Fig. 4, and the NICV result shows a significant peak (Fig. 4b). However, this step is relative to the local copy of the inputs (a_0 and b_0), and no leakage is identified in the computation step.

The traces were not perfectly aligned; thus, we added an operation to output a trigger signal to an internal loop in Karatusba multiplication to address the desynchronization issue. Figure 5 shows that the leakage is significant without any post-processing (filtering) of the traces. We confirmed that Karatsuba multiplication can be sensitive to side-channel analysis.

5 COUNTERMEASURE

We first propose inter-functional masking as a primary countermeasure. The secret key generated in the key generation algorithm is multiplied by random values. The masked secret key used in the signing algorithm changes randomly, making it challenging to apply side-channel analysis.

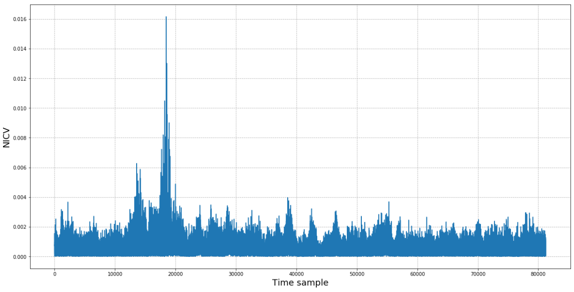


Figure 5: Leakage peak in NICV of internally syncronized Karatsuba multiplication.

We then proposed intra-functional masking as a more sophisticated countermeasure. The intermediates values in the multiplication function are changed by random masks and protect against side-channel analyses.

5.1 Interfunctional Masking

We apply multiplicative masking to the secret key of MLWRSign. The idea of multiplicative masking is to write s as $r^{-1} \times (r \times s)$. The masking value r is chosen as a random number in $\mathbb{Z}_q^*$ or a random polynomial in $\mathbb{Z}_q[x]$. Our countermeasure uses an odd random integer r and q that is a power of 2 so that r is invertible in $\mathbb{Z}_q$. A brute force attack can be used to find random numbers, and template attacks are applicable to reveal the secret parameter s. We can use a random polynomial to increase the possible polynomial choices to prevent template attacks.

The parameter s of the secret key is not stored as the plain form at the end of the key generation after applying multiplicative masking. The secret parameter s is stored randomized as described in Algorithm 1. A random mask r is selected uniformly in $\mathbb{Z}_q^*$ The masked secret rs computed as $rs = r \times s$. The unmasking variable r_inv is computed as $r\_inv r^{-1}$ mod q. The secret parameter s is stored after the key generation as (r_inv, rs).

The multiplication $c \times s$ is performed as $c \times s = (r\_inv \times c) \times rs$. The total overhead is two multiplications in $\mathbb{Z}_q$. Algorithm 2 describes multiplicative masking for the sign algorithm.

The secret key (rs, r_inv) can be refreshed to (rs', r'_inv) with the property $rs' \times r'\_inv = rs \times r\_inv = s$. A new random integer r' is selected from $\mathbb{Z}_q^*$ and the new masked secret rs' is computed as $\mathrm{rs}' = (r\_inv \times r') \times rs$ to maintain the property. r_{inv} is computed as the inverse of r' in $\mathbb{Z}_q^*$. The refresh overhead is two multiplications in $\mathbb{Z}_q$ and an inversion in $\mathbb{Z}_q^*$. Algorithm 3 describes refresh or multiplicative masking.

Algorithm 1: Multiplicative masking in key generation.

```
Input  : $s$
Output: $(rs, r\_inv)$
repeat
    $r \leftarrow\$ \mathbb{Z}_q^*$;
until $r'$ is odd;
$rs \leftarrow r \times s \mod q$;
$r\_\mathrm{inv} \leftarrow r^{-1} \mod q$;
return $(rs, r\_\mathrm{inv})$;
```

Algorithm 2: Multiplication in sign.

```
Input  : $c$, $(rs, r\_\mathrm{inv})$
Output: $c \times s$
cs $\leftarrow (r\_\mathrm{inv} \times c) \times rs \mod q$;
return cs;
```

Algorithm 3: Refresh.

```
Input  : $(rs, r\_\mathrm{inv})$
Output: $(rs', r'\_\mathrm{inv})$
repeat
    $r' \leftarrow\$ \mathbb{Z}_q^*$;
until $r'$ is odd;
$rs'_1 \leftarrow (r\_\mathrm{inv} \times r') \times rs$;
$r'\_\mathrm{inv} \leftarrow r'^{-1} \mod q$;
return $(rs', r'\_\mathrm{inv})$;
```

5.2 Intrafunctional Masking

We can apply additive masking to immediate values in the multiplication functions to achieve advanced protection against side-channel analyses. MLWRSign used Karatsuba and Toom-Cook multiplications. No masking implementations for Toom-Cook multiplication have been proposed, while masked Karatsuba multiplication is available (Rebeiro and Mukhopadhyay, 2008). We thus propose additive masking for Toom-Cook multiplication, where additive masking is applied to points of polynomials, and pointwise multiplication is executed on masked values.

We show an example for the multiplication of $a_1Q + a_0$ and $b_1Q + b_0$ where Q is modulo. The polynomial expressions of the two integers are $a(x) = a_1x + a_0$ and $b(x) = b_1x + b_0$. The sample points can be calculated as

$$a(-1) = -a_1 + a_0, \quad a(0) = a_0, \quad a(1) = a_1 + a_0,$$
$$b(-1) = -b_1 + b_0, \quad b(0) = b_0, \quad b(1) = b_1 + b_0.$$

for $x = -1, 0, 1$. We generate additive masks $m_{a(-1)}$, $m_{a(0)}, m_{a(1)}, m_{b(-1)}, m_{b(0)}, m_{b(1)}$ for six sample points and obtain masked values $a(-1) + m_{a(-1)}$, $a(0) + m_{a(0)}$, $a(1) + m_{a(1)}$, $b(-1) + m_{b(-1)}$, $b(0) + m_{b(0)}$, and $b(1) + m_{b(1)}$.

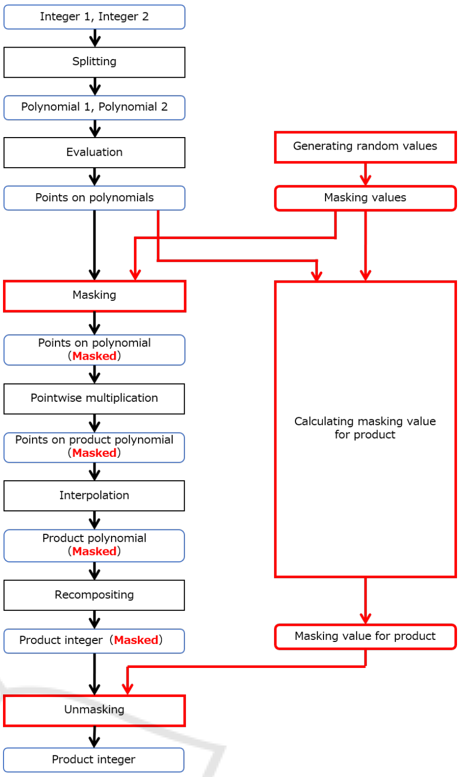


Figure 6: Masked Toom-Cook multiplication.

The masked product is computed from masked sampled points based on the procedure of the original Toom-Cook multiplication. The masking value for the product is computed from the original sample points, and masking values for sampling values are:

$$M = \frac{M(-1) - 2M(0) + M(1)}{2} Q^2 + \frac{M(1) - M(-1)}{2} Q + M(0),$$

where $M(x) = m_{a(x)}m_{b(x)} + m_{a(x)}b(x) + m_{b(x)}a(x)$ for $x = -1, 0, 1$.

We can recover the original product $(a_1Q + a_0) \times (b_1Q + b_0)$ by subtracting the masking value for the product M from the masked product that is the result of Toom-Cook multiplication. Figure 6 shows the masked Toom-Cook multiplication where the newly added data, procedure, and data flow are highlighted in red. The overhead of the intra-functional masking is three multiplications and 13 additions in $\mathbb{Z}_q$

6 CONCLUSION

This paper studied possible side-channel analysis on signature scheme MLWRSign, an LWR variant of

CRYSTALS-Dilithium that is one of the finalists in the NIST-PQC. We applied differential power analysis (DPA) to the implementation of MLWRSign to specify all the sensitive parts. We have encountered a desynchronization issue in the side-channel analysis against post-quantum cryptography. One of the causes is long leakage traces due to larger keys in post-quantum cryptography. Another cause is the complicated power consumption behavior of the microarchitecture of the target device. We insert an operation that outputs synchronization triggers to candidate functions to avoid statistical synchronization to address the difficulty. We found that only Karatsuba and Toom-Cook multiplications can be vulnerable to DPA with the Hamming weight power consumption model. Nevertheless, we can distinguish only some candidates from all possible keys. Furthermore, we proposed masking countermeasures for multiplication: inter-functional and intra-functional masking. Our lightweight countermeasure is beneficial to enhance further the security of post-quantum cryptography, which is naturally resistant to side-channel attacks.

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