A key-recovery timing attack on post-quantum primitives using the Fujisaki-Okamoto transformation and its application on FrodoKEM

Qian Guo, Thomas Johansson, Alexander Nilsson

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Preliminaries

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This presentation: A general attack against the Fujisaki-Okamoto transformation.

Our contribution

The Fujisaki-Okamoto (FO) transform does not directly handle secret data, yet must be implemented in constant time.

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Maybe others?

We show the attack for FrodoKEM (Lattice/LWE based).

A quick, lightweight, background

Publik Key Encryption Schemes

$\mathtt{sk}, \mathtt{pk} \leftarrow \mathtt{KeyGen}(\cdot)$ $(\mathtt{sk}, \mathtt{pk}) \Leftrightarrow$ (secret key, public key)

$\mathtt{c} \leftarrow \mathtt{PKE.CPA.Encrypt}(\mathtt{pk},\mathtt{m})$ $(\mathtt{m}, \mathtt{c}) \Leftrightarrow$ (plaintext, ciphertext)

$\mathtt{m} \leftarrow \mathtt{PKE.CPA.Decrypt}(\mathtt{sk},\mathtt{c})$

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Key Encapsulation Mechanisms

$\mathrm{sk}, \mathrm{pk} \leftarrow \texttt{KeyGen}(\cdot)$

$\mathrm{c}, \mathrm{ss} \leftarrow \texttt{KEM.CCA.Encaps(pk)}$ $\qquad \mathrm{ss} \Leftrightarrow (\text{shared secret})$

$\mathrm{ss} \leftarrow \texttt{KEM.CCA.Decaps(sk,c)}$

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Security game with access to a decryption oracle.

The Fujisaki-Okamoto (FO) transform can be used to transform a CPA secure PKE-cipher into a CCA secure cipher.

A common property:

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LWE encoding

$c = g(pk, m; r) + e(r)$

Code-based encoding

$c = mG \oplus e$

LWE and Code-based schemes

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Decryption fails if e varies by a larger degree.

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Algorithm 1: $\texttt{KEM.CCA.Encaps}$

Input: $\texttt{pk}$

Output: $(\texttt{c}, \texttt{ss})$

pick a random $\texttt{m}$

$(r, k) \leftarrow H(\texttt{m}, \texttt{pk})$

$c \leftarrow \texttt{PKE.CPA.Encrypt(pk,m;r)}$

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Algorithm 1: `KEM.CCA.Encaps`

Input: `pk`

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pick a random m
(r, k) ← H(m, pk)
c ← PKE.CPA.Encrypt(pk,m;r) /* IND-CPA secure */
ss ← H(c, k)
return (c, ss)
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Algorithm 2: `KEM.CCA.Decaps`

Input: $(\mathtt{sk}, \mathtt{pk}, \mathtt{c})$

Output: $(\mathtt{ss})$

$\mathtt{m}' \leftarrow$ `PKE.CPA.Decrypt(sk,c)`

$(r', k') \leftarrow H(m', \mathtt{pk})$

$\mathtt{c}' \leftarrow$ `PKE.CPA.Encrypt(pk,m';r)`

if $(\mathrm{c}' = \mathrm{c})$ then **return** $ss' \leftarrow H(c, k)$

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The Attack, Generalized

The Vulnerability

c:	FF	EE	DD	CC	BB	AA	99	88	77	66
c':	FF	EE	DD	CC	BB	AA	99	88	77	66

} `memcmp`

Assumptions:

1. Not constant time
2. Tiny modification to c $\rightarrow$ no change to c'
3. Large modification to c $\rightarrow$ total change of c'

Strategy:

- Do modifications at the end of c
- Find the exact threshold between case 2 and 3.
- Time `KEM.CCA.Decaps`, repeat as necessary.
- Extract secrets from the KEM-scheme.

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Algorithm 3: Error.Oracle

Input: m, a ciphertext modification d

Output: b (decryption failure or not)

$(r, k) \leftarrow H_1(m, \mathtt{pk})$

$c \leftarrow$ `PKE.CPA.Encrypt(pk,m;r)`

$c' \leftarrow c + d$

$t \leftarrow$ Measure[`KEM.CCA.Decaps(sk,c')`]

$b \leftarrow F(t)$

return b

where $F(t)$ uses t to determine whether `PKE.CPA.Decrypt` returns $m' = m$ or $m' \neq m$.

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Secret Key Recovery

Algorithm 4: Secret Key Recovery

Input: n_1

Output: $\texttt{sk}$

```
for i ← 0;  i < n_1;  i ← i + 1  do
    begin find (m_i, d_i) such that
        Error.Oracle(m_i, d_i) = 0 and
        Error.Oracle(m_i, d_i + 1) = 1
    end
end
Use set {((m_i, d_i), 0 ≤ i < n)} to extract the secret key
return sk
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The case of FrodoKEM

Simplified:

$$(r_1, r2, \text{seed}_A, s) \leftarrow \text{uniform random seeds.}$$

$$E \leftarrow \text{Frodo.SampleMatrix}(r_2)$$

Secret Key (S, s)

$$S \leftarrow \text{Frodo.SampleMatrix}(r_1)$$

Public Key $(\textbf{seed}_A, B)$

$$A \leftarrow \text{Frodo.Gen}(\text{seed}_A)$$

$$B \leftarrow AS + E \tag{1}$$

FrodoKEM KeyGen

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FrodoKEM Encaps

Algorithm 5: FrodoKEM.Encaps (simplified)

Input: $\mathtt{pk}$

Output: $\mathtt{ss}$, $\mathtt{c}$

$m \leftarrow$ uniform random plaintext

$(r_1, r_2, r_3, k) \leftarrow H(H(\mathtt{pk})||m)$

$(S', E', E'') \leftarrow$ **for** $i \in \{1, 2, 3\}$ **do** Frodo.SampleMatrix(r_i) **end**

$B' \leftarrow S'A + E'$

$C \leftarrow S'B + E'' + \mathit{Frodo.Encode}(m)$

$\mathtt{c} \leftarrow$ Frodo.Pack$(B'||C)$

return $(H(\mathtt{c}||k), \mathtt{c})$

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FrodoKEM Decaps

Algorithm 6: FrodoKEM.Decaps (simplified)

Input: `c`, `sk`

Output: `ss`

$(B', C) \Leftarrow \text{Frodo.Unpack}(c)$

$m' \leftarrow \text{Frodo.Decode}(C - B'S)$

$(r_1, r_2, r_3, k') \leftarrow H(H(\mathtt{pk})||m')$

$(S', E', E'') \leftarrow$ **for** $i \in \{1, 2, 3\}$ **do** $\text{Frodo.SampleMatrix}(r_i)$ **end**

$B'' \leftarrow S'A + E'$

$C' \leftarrow S'B + E'' + Frodo.Encode(m')$

if $B'||C = B''||C'$ **then**

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if $B'||C = B''||C'$ **then**

  return $H(c||k')$

else

  return $H(c||s)$ /* where s is part of secret key */

end

The combined noise matrix E'''

line 2: $m' \leftarrow$ **Frodo.Decode**$(C - B'S)$

$$C - B'S = \text{Frodo.Encode}(m') + \underbrace{S'E - E'S + E''}_{E'''}$$

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Since S', E' and E'' are known and Equation (1) $\Rightarrow E = B - AS$:

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line 2: $m' \leftarrow$ **Frodo.Decode**$(C - B'S)$

$$C - B'S = \text{Frodo.Encode}(m') + \underbrace{S'E - E'S + E''}_{E'''}$$

Since S', E' and E'' are known and Equation (1) $\Rightarrow E = B - AS$:

We get linear equations for the values in S, if we know E'''.

Figuring out E'''

Paraphrasing lemma 2.18 from [Nae+18]:

For successfull decryption:

$-2^{D-B_p-1} \leq E'''_{i,j} < 2^{D-B_p-1}$ for all entries i, j in matrix E'''.

Where $B_p \leq D$ and $B_p, D \in \mathbb{Z}$ are FrodoKEM paramters.

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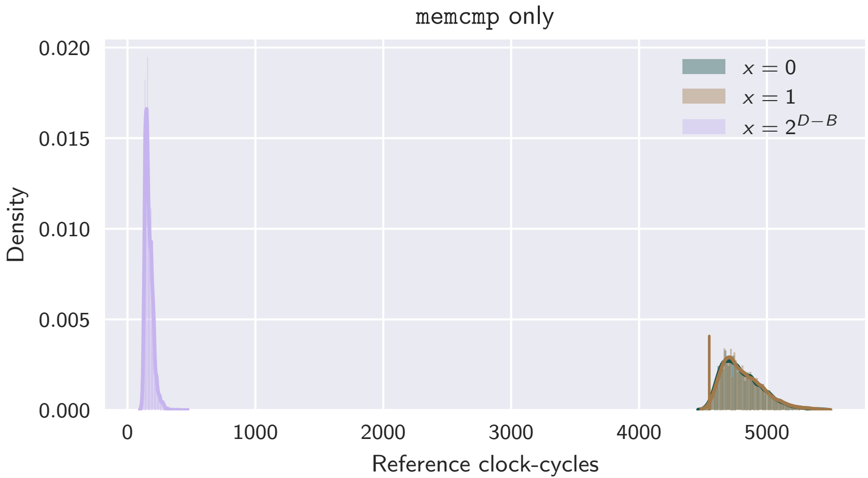
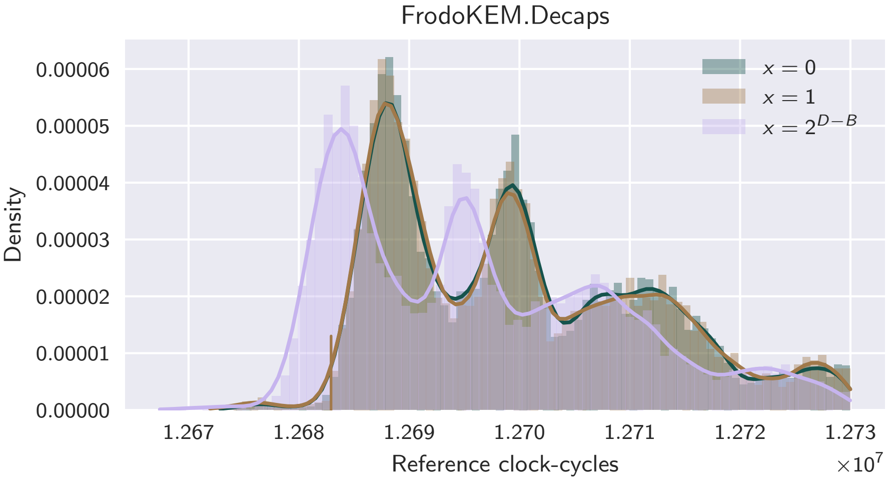
Thus $E'''_{i,j} = 2^{D-B_p-1} - x_0$
if Error.Oracle$(m_i, x_0) = 1$
and Error.Oracle$(m_i, x_0 - 1) = 0$.

Graphs, numbers and such

Results


memcmp only
0.020
0.015
0.010
0.005
0.000
Density
$x = 0$
$x = 1$
$x = 2^{D-B}$
0
1000
2000
3000
4000
5000
Reference clock-cycles

Results II


FrodoKEM.Decaps
Density
0.00006
0.00005
0.00004
0.00003
0.00002
0.00001
0.00000
1.267
1.268
1.269
1.270
1.271
1.272
1.273
Reference clock-cycles
$\times 10^7$
$x = 0$
$x = 1$
$x = 2^{D-B}$

Results III

Tiny differences

$$\frac{4800}{12700000} \approx 0.04\%$$

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Binary search

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Complete Key Recovery

$97000 \times 1344 \times 8 \approx 2^{30}$ queries for FrodoKEM-1344-AES on a Intel i5-4200U CPU running at 1.6GHz.

Summary

Conclusions

“All our implementations avoid the use of secret address accesses and secret branches and, hence, are protected against timing and cache attacks.”
— FrodoKEM Specification.

Very good, but still not enough

Thank you!

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