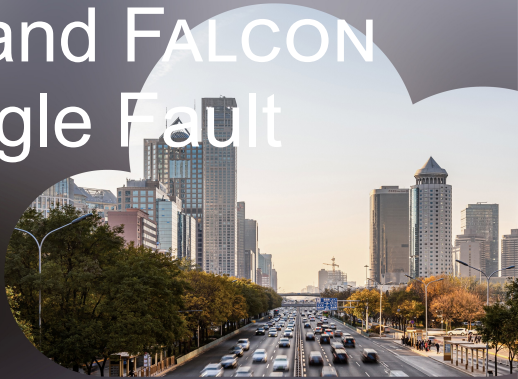
Forging DILITHIUM and FALCON Signatures with Single Fault Injection

Sven Bauer and Fabrizio De Santis



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Reasons for attacking signature verification

Embedded devices verify signatures to

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Embedded devices verify signatures to

- ensure integrity of data, e.g. software updates, before processing
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Hence, bypassing signature verification can allow an attacker to

- install arbitrary software on a device
- access confidential data

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How to attack signature verification

How to force unintended behaviour: Fault injection!

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The obvious place:

- Signature verification ends with a 1-bit result (“valid” or “invalid”).
- So, attacking near the end seems most promising.
- Implementers know this and will protect this critical section.

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How to force unintended behaviour: Fault injection!

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What about other places in the code? Perhaps overlooked by implementers?

- Example: Attack by Muir and Seifert against RSA signature verification (Reminder: Flip bits of public modulus until it is easy to factor; inject fault to achieve same bit flips during verification)
- We are moving into the post-quantum world.
- Similar attacks against verification of post-quantum signatures?

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DILITHIUM signature verification: quick recap

Notation: $R = \mathbb{Z}[X]/(X^n + 1)$, $R_q = \mathbb{Z}_q[X]/(X^n + 1)$, $n = 256$, $q = 8380417$

Require: A message m, a signature $\mathtt{sig} = (\tilde{\mathbf{c}}, \mathbf{z}, \mathbf{h})$, a public key $\mathtt{pk} = (\rho, \mathbf{t}_1)$.

Ensure: Accept or reject

1: $\mathbf{A} \leftarrow \mathtt{ExpandA}(\rho)$ $\quad \triangleright\ \mathbf{A} \in R_q^{k \times \ell}$

2: $\mu \leftarrow \mathtt{SHAKE256}(\mathtt{SHAKE256}(\rho \| \mathbf{t}_1, 256) \| m, 512)$

3: $c \leftarrow \mathtt{SampleInBall}(\tilde{c})$ $\quad \triangleright\ c \in B_\tau \subset R$

4: $\mathbf{w}'_1 \leftarrow \mathtt{UseHint}(\mathbf{h}, \mathbf{Az} - c\mathbf{t}_1 \cdot 2^d, 2\gamma_2)$ $\quad \triangleright\ \mathbf{w}'_1 \in R_q^k$

5: **if** $\|\mathbf{z}\|_\infty < \gamma_1 - \beta$ and $\tilde{c} = \mathtt{SHAKE256}(\mu \| \mathbf{w}'_1, 256)$ and the number of 1s in $\mathbf{h}$ is $\leq \omega$ **then**

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In code (example from `pqm4` project, `crypto_sign/dilithium2/m4f/sign.c`)

```
...
poly_ntt(&cp);
polyveck_shiftl(&t1);
polyveck_ntt(&t1);
polyveck_pointwise_poly_montgomery(&t1, &cp, &t1);

polyveck_sub(&w1, &w1, &t1);
polyveck_reduce(&w1);
...
```

← skip this call with fault injection

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290     ...
```

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single fault to skip instruction

In our setup, line 288 compiles to this Cortex-M4 code:

```
...
0x80030c4 <crypto_sign_verify+252> adds r2, #16
0x80030c6 <crypto_sign_verify+254> bl 0x80028f8 <polyveck_sub>
0x80030ca <crypto_sign_verify+258> add.w r0, sp, #10304
...
```


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Countermeasures

- Generic countermeasures to ensure control flow integrity.
- Replace

$$w_1' \leftarrow \mathtt{UseHint}(\mathbf{h}, \mathbf{Az} - \mathtt{c}\mathbf{t}_1, 2\gamma_2)$$

with

$$w_1' \leftarrow \mathtt{UseHint}(\mathbf{h}, (\mathbf{Az} + \mathbf{u}) - (\mathtt{c}\mathbf{t}_1 + \mathbf{u}), 2\gamma_2),$$

where $\mathbf{u}$ is a random vector.

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Alternative attack

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```
...
/* Reconstruct w1 */
polyveck_caddq(&w1);
polyveck_use_hint(&w1, &w1, &h);
polyveck_pack_w1(buf, &w1);

/* Call random oracle and verify challenge */
shake256_inc_init(&state);
shake256_inc_absorb(&state, mu, CRHBYTES);
shake256_inc_absorb(&state, buf, K*POLYW1_PACKEDBYTES);
shake256_inc_finalize(&state);
...
```

skip this call with fault injection

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FALCON signature verification: quick recap

Require: A message m, a signature $\texttt{sig} = (r, s)$, a public key $\texttt{pk} = h \in \mathbb{Z}_q[x]/(\phi)$

Ensure: Accept or reject

```
c ← HashToPoint(r||m)                                   ▷ c ∈ Z_q[x]
s_2 ← Decompress(s)                                     ▷ s_2 ∈ Z[x]
if s_2 = ⊥ then
    reject
s_1 ← c − s_2 h mod q                                   ▷ coefficients of s_1 normalized to be between ⌈−q/2⌉ and ⌊q/2⌋
if ||(s_1, s_2)||^2 ≤ ⌊β^2⌋ then
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$= 0$

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In code (example from `pqm4` project, `crypto_sign/falcon-512/m4-ct/vrfy.c`)

```
...
/*
 * Compute -s1 = s2*h - c0 mod phi mod q (in tt[]).
 */
mq_NTT(tt, logn);
mq_poly_montymul_ntt(tt, h, logn);
mq_iNTT(tt, logn);
mq_poly_sub(tt, c0, logn);
...
```

skip this call with fault injection

or force logn to zero

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In code (example from `pqm4` project, `crypto_sign/falcon-512/m4-ct/vrfy.c`)

```
664     ...
665     /*
666      * Compute -s1 = s2*h - c0 mod phi mod q (in tt[]).
667      */
668     mq_NTT(tt, logn);
669     mq_poly_montymul_ntt(tt, h, logn);
670     mq_iNTT(tt, logn);
671     mq_poly_sub(tt, c0, logn);
672     ...
```

skip this call with fault injection

or force logn to zero

In our setup, the function call in line 671 is inlined by the compiler!

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The inlined function and how to adapt the attack

```
...
0x800d834 <verify_raw+136> bl      0x800d62c <mq_iNTT>
0x800d83a <verify_raw+142> movw    r1, #12289
0x800d83e <verify_raw+146> ldrh.w  r3, [r4, #2]!
0x800d842 <verify_raw+150> ldrh.w  r2, [r6, #2]!
0x800d846 <verify_raw+154> subs    r3, r3, r2
0x800d848 <verify_raw+156> and.w   r2, r1, r3, asr #31
0x800d84c <verify_raw+160> add     r3, r2
0x800d84e <verify_raw+162> cmp     r9, r4
0x800d850 <verify_raw+164> strh    r3, [r4, #0]
0x800d852 <verify_raw+166> bne.n   0x800d83e <verify_raw+146>
...
```


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The inlined function and how to adapt the attack

```
...
0x800d834 <verify_raw+136> bl      0x800d62c <mq_iNTT>
0x800d83a <verify_raw+142> movw    r1, #12289
0x800d83e <verify_raw+146> ldrh.w  r3, [r4, #2]!
0x800d842 <verify_raw+150> ldrh.w  r2, [r6, #2]!
0x800d846 <verify_raw+154> subs    r3, r3, r2
0x800d848 <verify_raw+156> and.w   r2, r1, r3, asr #31
0x800d84c <verify_raw+160> add     r3, r2
0x800d84e <verify_raw+162> cmp     r9, r4
0x800d850 <verify_raw+164> strh    r3, [r4, #0]
0x800d852 <verify_raw+166> bne.n   0x800d83e <verify_raw+146>
...
```

1. Choose signature component r such that first coefficient of $c = \texttt{HashToPoint}(r \| m)$ is 0.
2. Skip `bne.n` with a single fault.

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Countermeasures

Similar as for DILITHIUM:

- Generic countermeasures to ensure control flow integrity.
- Replace

$$s_1 \leftarrow c - s_2 h \bmod q$$

with

$$s_1 \leftarrow (c + u) - (s_2 h + u) \bmod q$$

where u is a random vector.

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Summary

- A successful fault attack against signature verification can completely compromise the security of a device.
- There are places in signature verification functions which are obvious targets for a fault attack.
- An experienced developer will protect these places with suitable countermeasures.
- There are also less obvious places to attack.
- These are easily overlooked when hardening the code of a signature verification function.
- We have identified some places like this in DILITHIUM and FALCON.

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Contact

Sven Bauer, Fabrizio De Santis
Siemens AG Technology

Otto-Hahn-Ring 6
81739 München
Germany

E-mail svenbauer[at]siemens.com, fabrizio.desantis[at]siemens.com

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