black hat BRIEFINGS

AUGUST 6-7, 2025
MANDALAY BAY / LAS VEGAS

Bypassing PQC Signature Verification with Fault Injection: Dilithium, XMSS, SPHINCS+

Fikret Garipay

Hello!

- Security Engineer at Keysight Device Security Testing
- Passionate about software exploitation and hardware attacks
- Twitter: @erd0spy

Fikret Garipay

Agenda

- Introduction to Post Quantum Cryptography
- Target Implementation
- Voltage Fault Injection in Practice
- Fault Injection Attacks on Dilithium Verification
- Fault Injection Attacks on WOTS+ in XMSS and SPHINCS+
- Fault Injection on Fault Resistance XMSS Library
- Key Takeaways and Conclusions

Introduction to Post Quantum Cryptography

Post-Quantum Crypto Is Getting Real

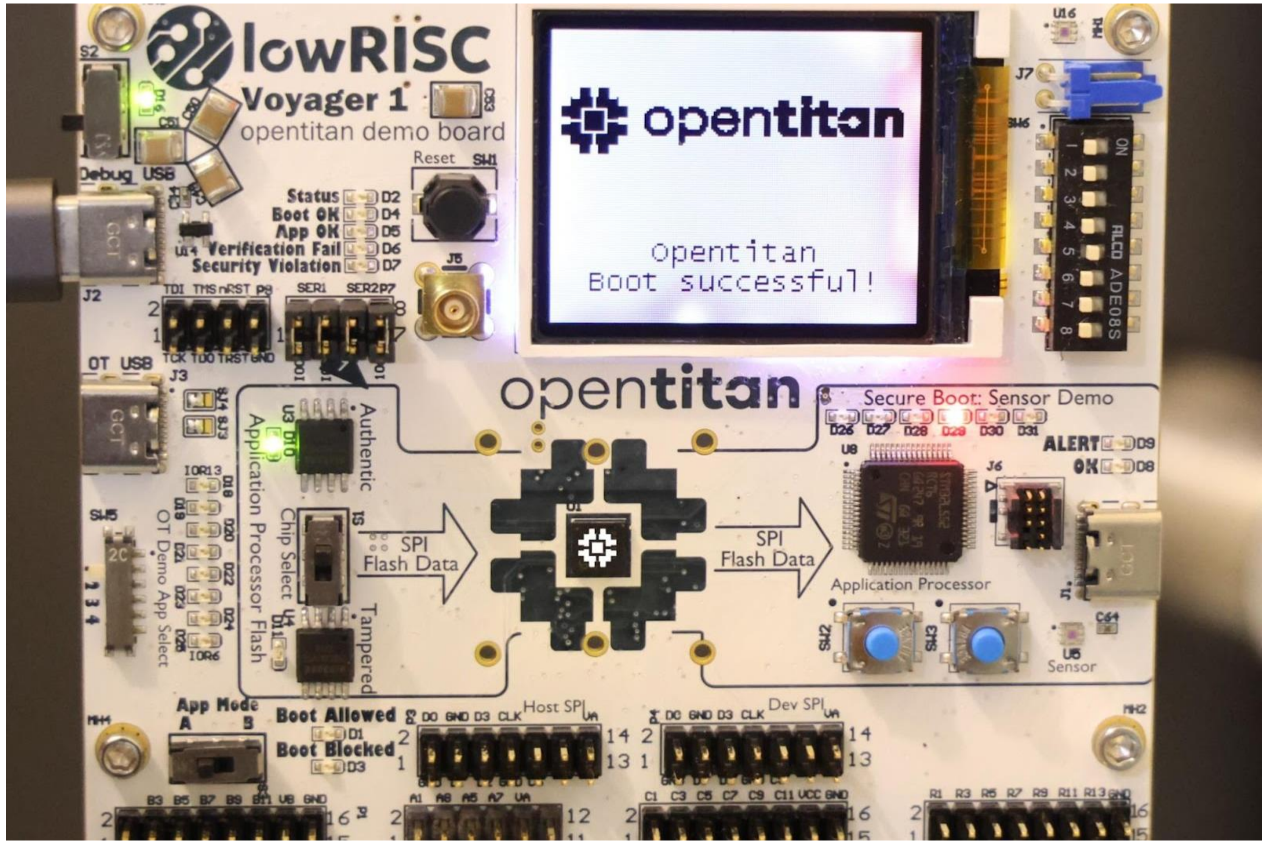
- Quantum computers aren't breaking crypto yet.
- But the shift is underway – **standards**, **vendors**, **firmware**.
- PQC is set to replace RSA, ECC in **secure boot**, **firmware signing**, and more.
- That makes PQC **fresh attack surface**.

PQC Signatures Are Becoming Global Standards

Algorithm	Signature Scheme Type	CNSA 2.0 (NSA)	Standard
Dilithium	Lattice-based	**Required** for all digital signatures (general use)	**NIST FIPS 204** (ML-DSA)
LMS	Stateful hash-based	**Approved** for firmware/software signing	ISO/IEC 14888-4:2024
XMSS	Stateful hash-based	**Approved** for firmware/software signing	ISO/IEC 14888-4:2024
SPHINCS+	Stateless hash-based	**Not approved for any use in NSS**	**NIST FIPS 205** (SLH-DSA)

PQC Signatures in Industry

- Multiple vendors now offer PQC solutions for **Firmware Update**, **Secure Boot**, **Signature Verification**



Source: Fabrication begins for production OpenTitan silicon

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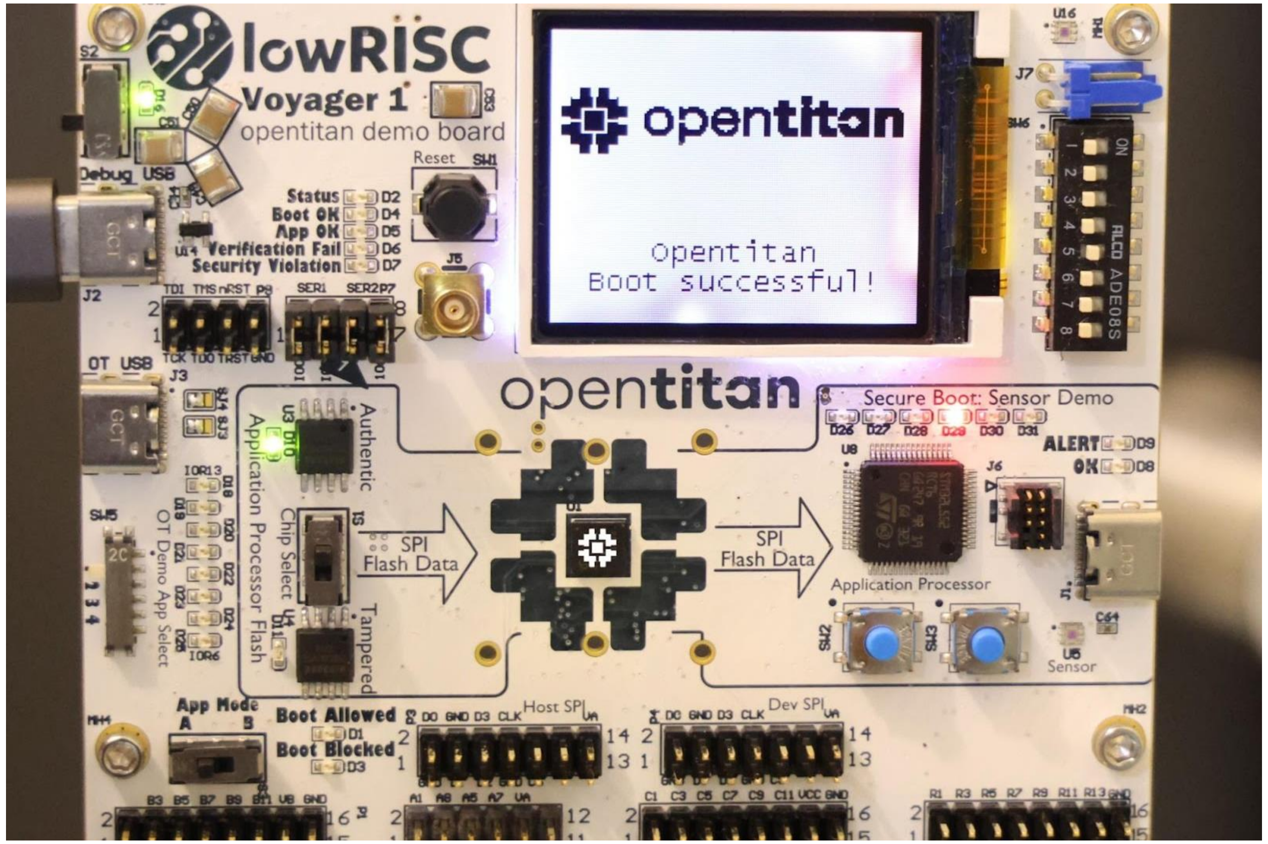
- **OpenTitan** chip uses **SPHINCS+** for PQC secure boot



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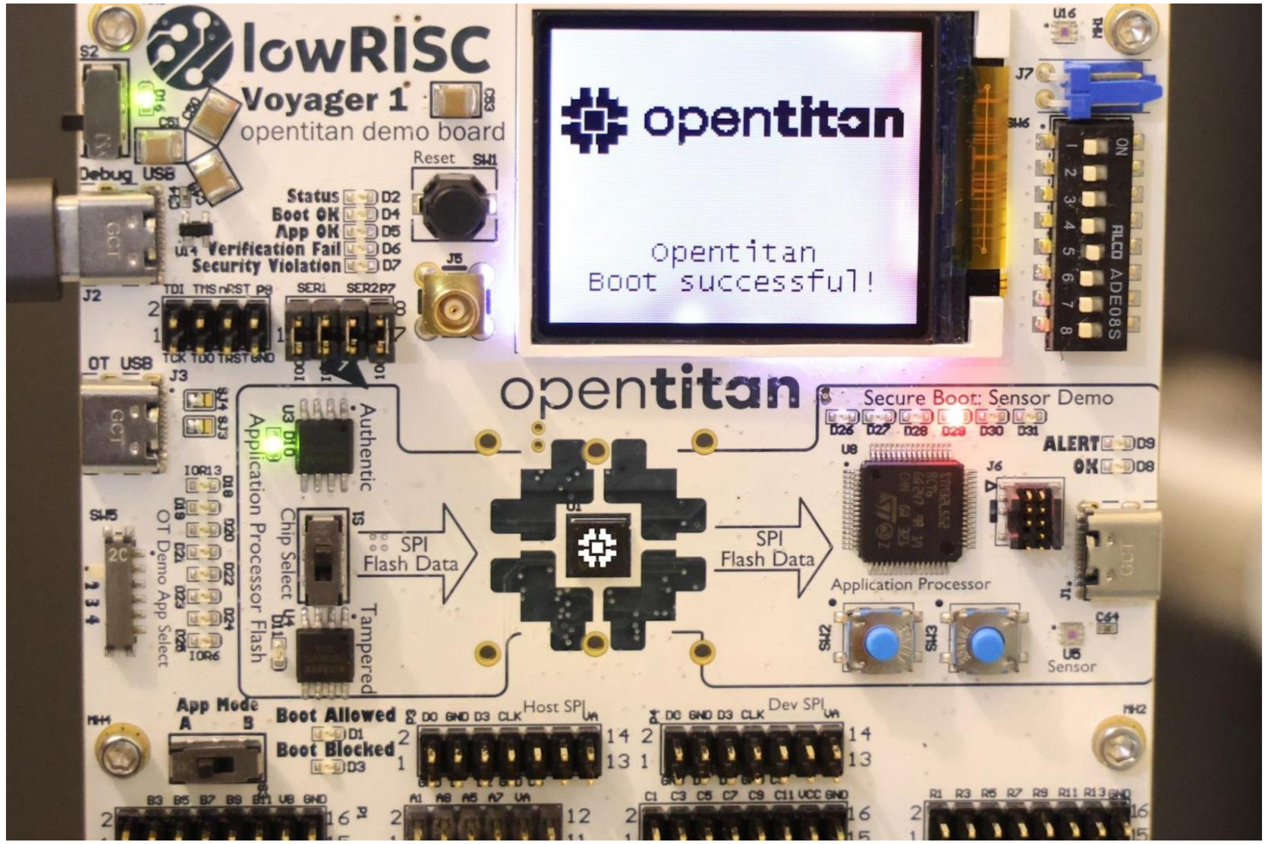
PQC Signatures in Industry

- Multiple vendors now offer PQC solutions for **Firmware Update**, **Secure Boot**, **Signature Verification**
- **OpenTitan** chip uses **SPHINCS+** for PQC secure boot
- **Caliptra 2.0** is adding post-quantum secure boot with **Dilithium** and **Kyber**



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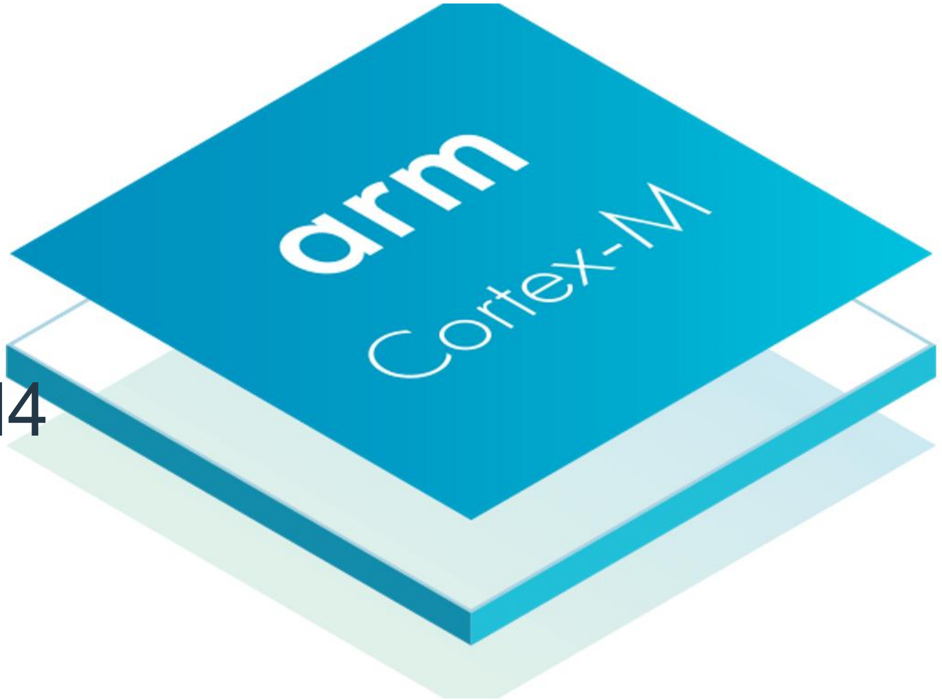
- Public PQC targets aren't widely deployed yet
- So, we:

  Ported public PQC libs to bare-metal firmware

Target Implementation

Target Implementation – Libraries



Dilithium: pqm4

- Post-quantum crypto library for the ARM Cortex-M4

XMSS: xmss-reference

SPHINCS+: sphincsplus

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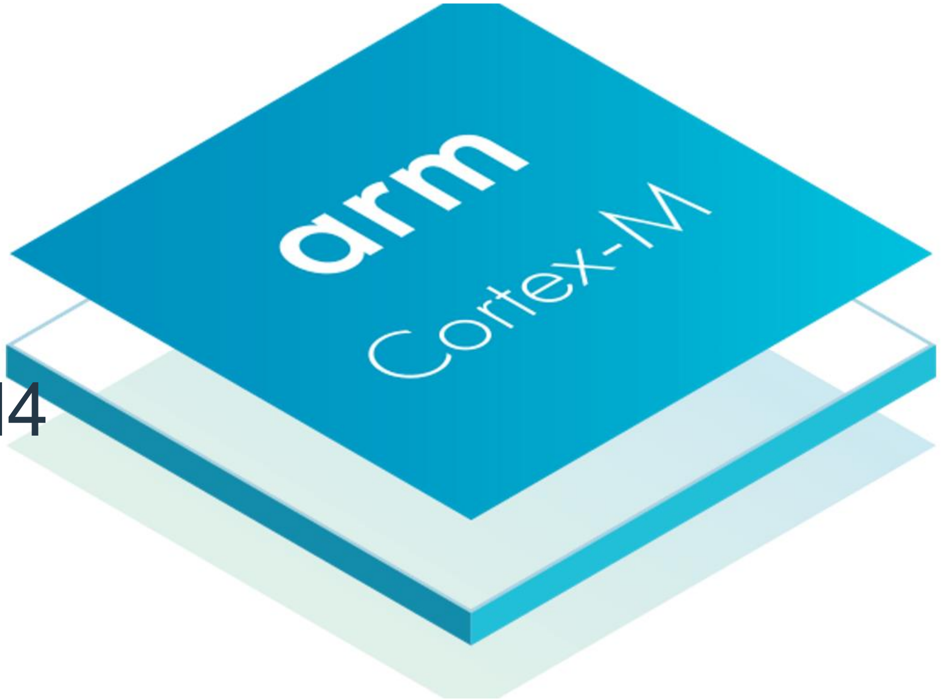

Dilithium: pqm4

- Post-quantum crypto library for the ARM Cortex-M4

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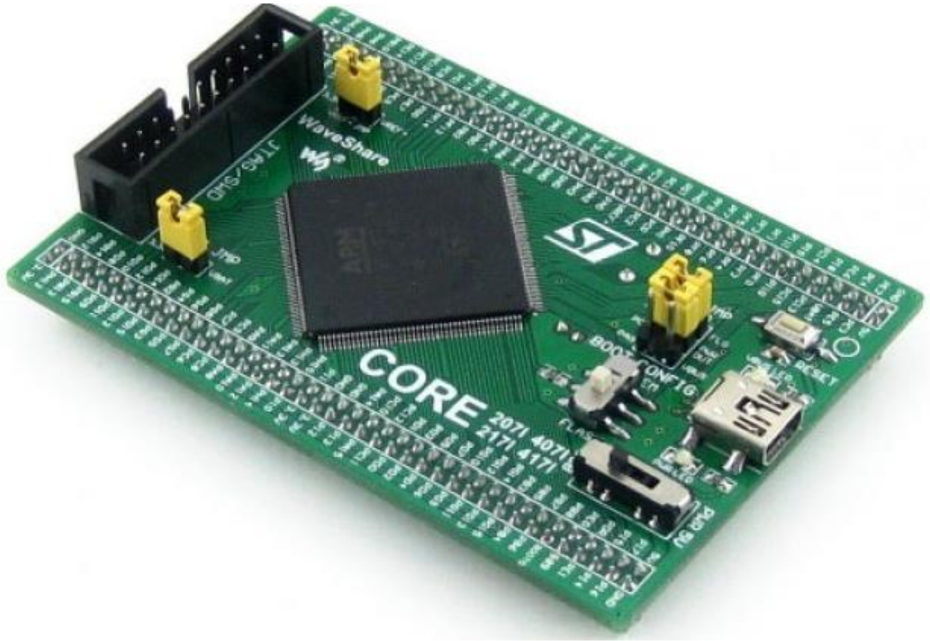
FI focus: cryptographic logic only, no generic bypasses like memcmp() skips or forced returns

Target Implementation – Firmware

STM32F417, Arm Cortex-M4 core

Running **bare metal firmware** (open source on GitHub)

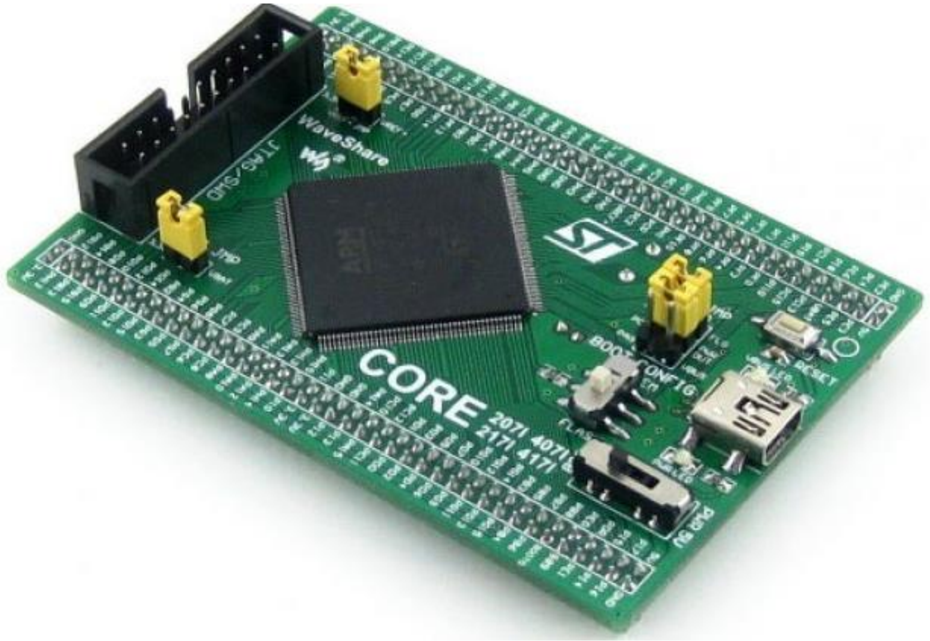


Target Implementation – Firmware

STM32F417, Arm Cortex-M4 core

Running **bare metal firmware** (open source on GitHub)

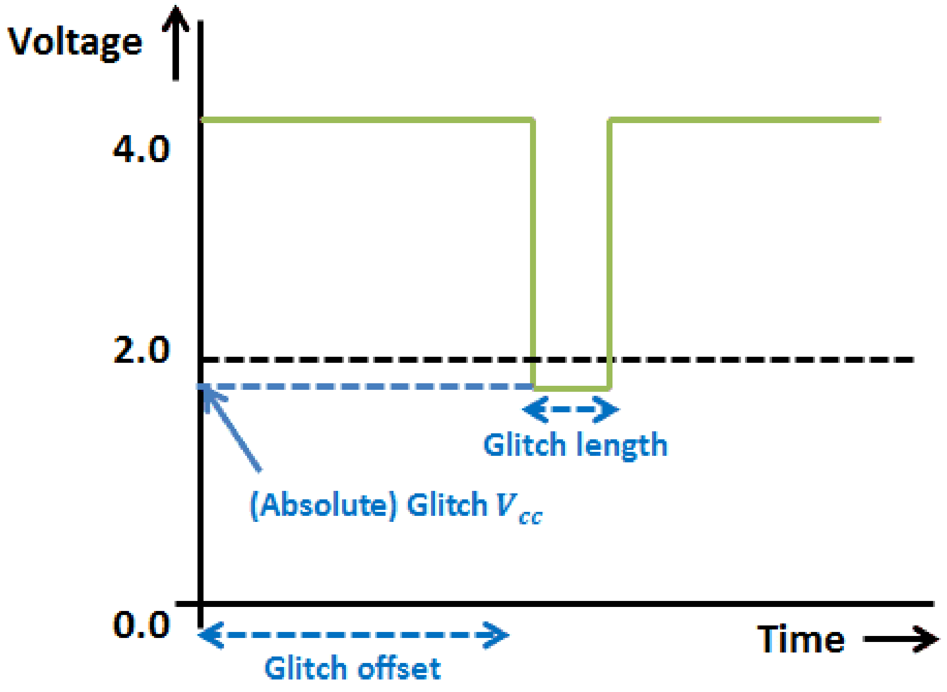
```
case CMD_SW_DILITHIUM_VERIFY: {
    uint8_t* signedMessageBuffer = DilithiumState_getScratchPad(&dilithium);
    get_bytes(DILITHIUM_SIGNED_MESSAGE_SIZE, signedMessageBuffer);
    // Handle the request.
    BEGIN_INTERESTING_STUFF; // []-> Rising Edge Trigger
    int result = DilithiumState_verify(&dilithium, signedMessageBuffer);
    END_INTERESTING_STUFF; // []-> Falling Edge Trigger
    send_char(result == 0 ? 0 : 1);
    break;
}
```

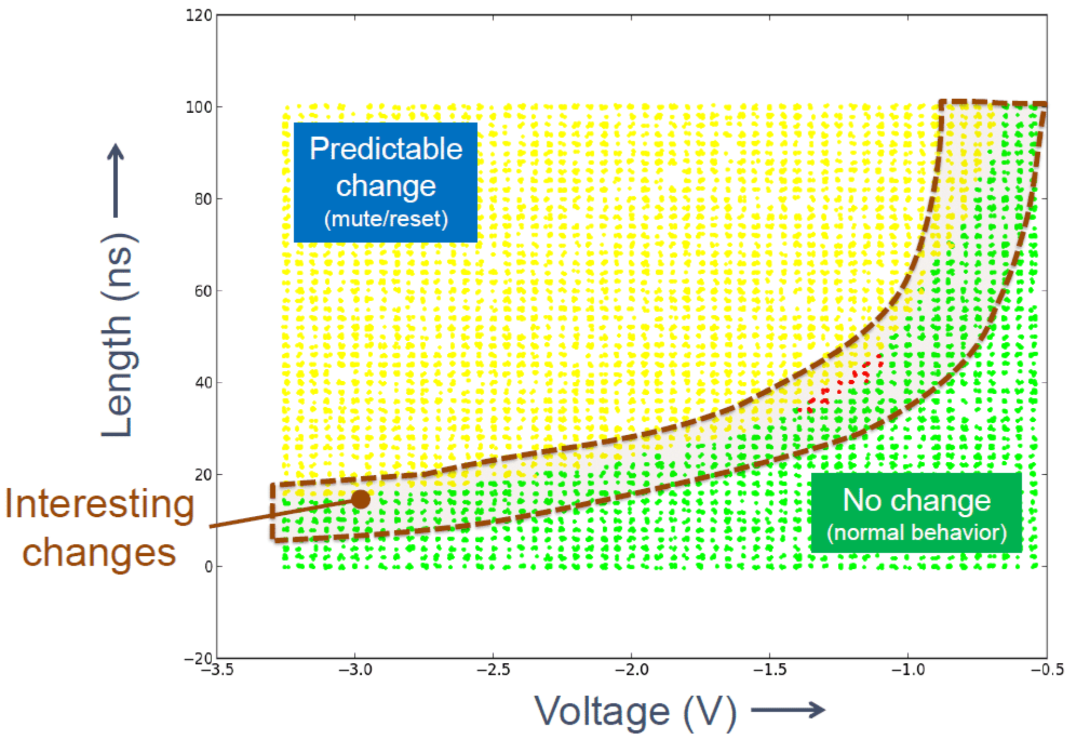


Voltage Fault Injection on Practice

Voltage Fault Injection – Concepts

- Lower the voltage **at the right time** to trigger faults
- Not 'too soft'; Not 'too hard'





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Inject fault(s) to disturb the device, then see what happens:

- Nothing
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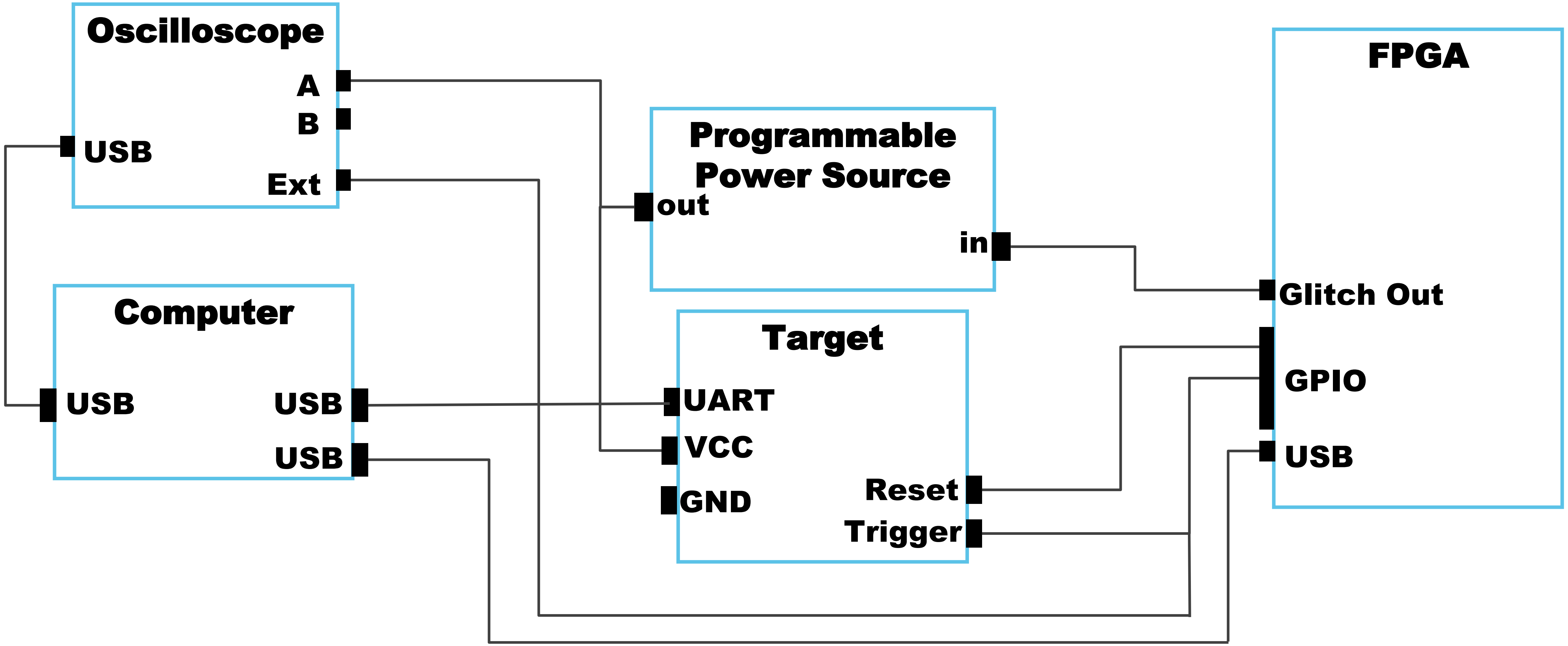
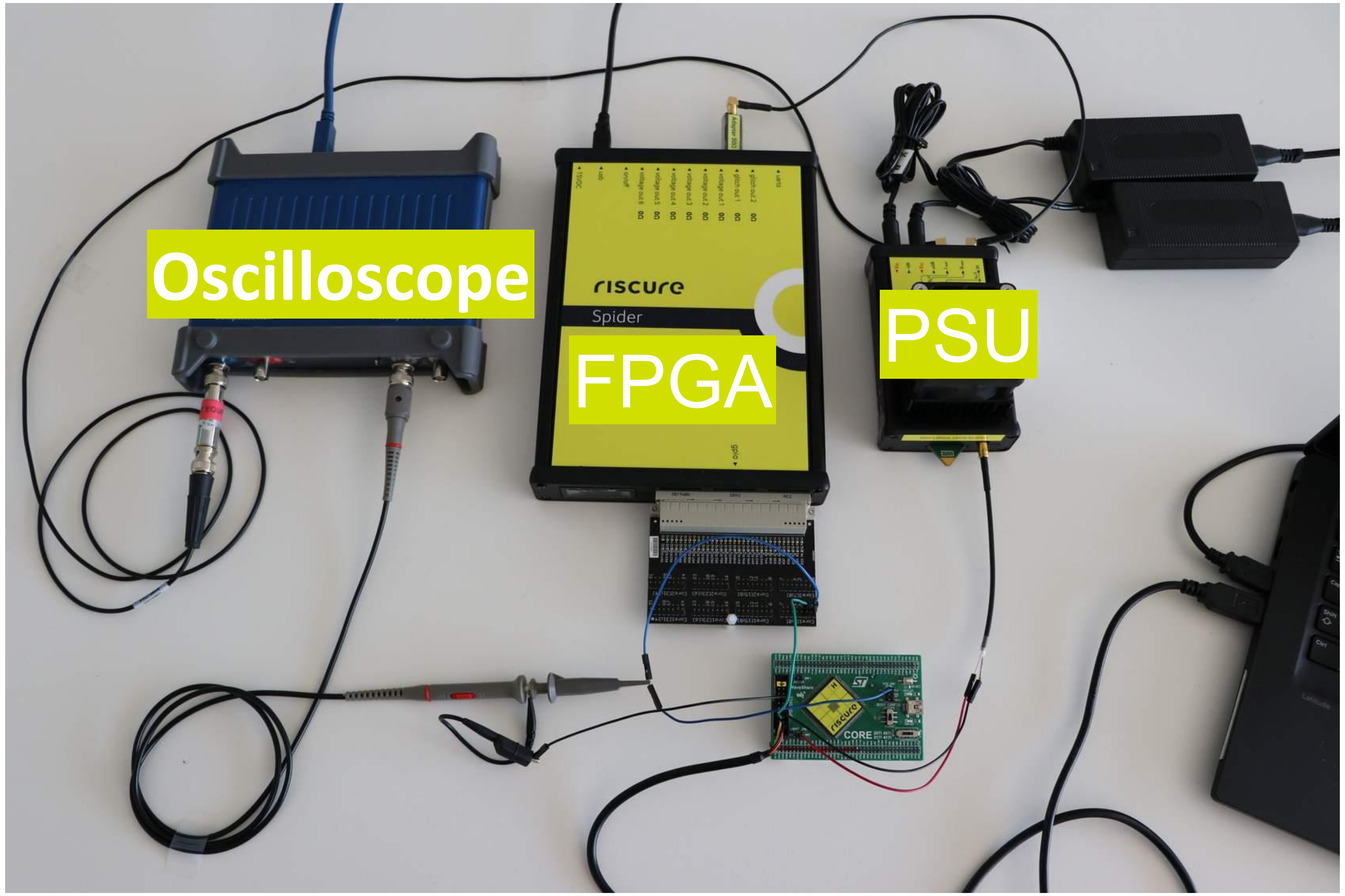
May compromise the device!

Voltage Fault Injection – Setup Overview



Voltage Fault Injection – Real World



Fault Injection Attacks on Dilithium Verification

Introduction to Dilithium

- Lattice-based digital signature scheme, designed to resist quantum attacks.
- Three security levels: Dilithium-2, Dilithium-3, Dilithium-5
- Supports deterministic and randomized signing for flexibility.
- Optimized using Number Theoretic Transform (NTT) for efficiency.

Keygen

1. $\mathbf{A} \leftarrow R_q^{k \times l}$
2. $(\mathbf{s}_1, \mathbf{s}_2) \leftarrow S_\eta^l \times S_\eta^k$
3. $\mathbf{t} \coloneqq \mathbf{A}\mathbf{s}_1 + \mathbf{s}_2$
4. $(\mathbf{t}_1, \mathbf{t}_0) = \mathbf{Power2Round}(\mathbf{t}, d)$
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Sign $(M, sk = (\mathbf{A}, \mathbf{s}_1, \mathbf{s}_2, \mathbf{t}_0))$

1. $(\mathbf{z}, h) := \perp$
2. $\textbf{while}(\mathbf{z}, h) = \perp \textbf{ do}$
3. $\quad \mathbf{y} \leftarrow S_{\gamma_1}^{l}$
4. $\quad \mathbf{w}_1 := \mathbf{HighBits}(\mathbf{Ay}, 2\gamma_2)$
5. $\quad c \in B_\tau := \mathrm{H}(\boldsymbol{M} \parallel \mathbf{w}_1)$
6. $\quad \mathbf{z} := \mathbf{y} + c\mathbf{s}_1$
7. $\quad \textbf{if}$ rejection conditions met $\rightarrow$ $\textbf{then } \mathbf{z} := \perp$
8. $\quad \textbf{else}$
9. $\qquad h = \mathbf{MakeHint}(-c\mathbf{t}_0, \mathbf{w} - c\mathbf{s}_2 + c\mathbf{t}_0)$
10. $\qquad \textbf{if } \|c\mathbf{t}_0\|_\infty \geq \gamma_2, \textbf{then } (\mathbf{z}, h) = \perp$
11. $\textbf{return } \sigma = (\boldsymbol{c}, \mathbf{z}, h)$

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Verify $(pk = (\mathbf{A}, \mathrm{t}_1), M, \sigma = (c, \mathbf{z}, h))$

1. $\mathbf{w}_1' := \mathrm{UseHint}\left(h, \mathbf{Az} - c\mathbf{t}_1 2^d\right)$
2. **if** $\|\mathbf{z}\|_\infty < \gamma_1 - \beta$ **and** $c = \mathbf{H}(M \parallel \mathbf{w}_1')$ **and** $|h|_{h_j=1} \leq \omega$
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- The paper shows how to recover $\mathbf{w_1}$ using only public inputs.
- It demonstrates how to constrain $\boldsymbol{ct_1 2^d}$ to minimally affect $\boldsymbol{Az}$'s high bits.
- Using this, it presents two signature verification attacks **- exploiting verification with FI.**

Attacks

If either of the following conditions is met during a successful fault injection at verification:

Attack 1.

Attack 2.

- *A signature generated using only public values* ***will be accepted as valid****.*

Attacks

If either of the following conditions is met during a successful fault injection at verification:

Attack 1. $c\mathbf{t}_1 2^d = 0$

Attack 2.

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Attacks

If either of the following conditions is met during a successful fault injection at verification:

Attack 1. $c\mathbf{t}_1 2^d = 0$

Attack 2. $\left\| c\mathbf{t}_1 2^d \right\|_\infty \leq \gamma_2$ **and** $h = \mathbf{MakeHint}\left(c\mathbf{t}_1 2^d,\ \mathbf{Az} - c\mathbf{t}_1 2^d\right)$

Then, $\mathbf{HighBits}\left(Az\ - c\mathbf{t}_1 2^d, 2\gamma_2\right) = \mathbf{HighBits}(\mathbf{w}, 2\gamma_2)$

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Our Signature Generation for Attack 1 $(\boldsymbol{M}, pk = (\mathbf{A}, \mathrm{t}_1))$

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6. $\quad c \in B_\tau \coloneqq \mathrm{H}(\boldsymbol{M} \parallel \mathbf{w}_1)$
7. $\mathbf{return}\ \sigma = (\boldsymbol{c}, \mathbf{z}, h)$

- The generated signature will accept by verification if fault forces $c\mathbf{t}_1 2^d$ **= 0 at signature verification.**

Our Signature Generation for Attack 2 $(\boldsymbol{M}, pk = (\mathbf{A}, \mathrm{t}_1))$

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- The generated signature will accept by verification if fault forces $\|\boldsymbol{c}\mathbf{t}_1 \mathbf{2}^{\boldsymbol{d}}\|_\infty \leq \boldsymbol{\gamma}_2$ **at signature verification.**

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Scenario 1: Unpacking of Public Key*

- **Attack 1** ($c\mathbf{t}_1 2^d = 0$)

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*Depends on implementation and compiler behavior. Requires zero-initialized $\mathbf{t}_1$ coefficients.

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Scenario 2: Sampling of c
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Scenario 3: Shift by d

- **Attack 2** ($c\mathbf{t}_1 2^d = \left\|c\mathbf{t}_1 2^d\right\|_\infty \leq \gamma_2$)

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Scenario 3: Shift by d
- **Attack 2** ($c\mathbf{t}_1 2^d = \left\|c\mathbf{t}_1 2^d\right\|_\infty \le \gamma_2$)

Scenario 4: Subtraction
- **Attack 1** ($c\mathbf{t}_1 2^d = 0$)

*Depends on implementation and compiler behavior. Requires zero-initialized $\mathbf{t}_1$ coefficients.

Where to target?

Scenario 1: Unpacking of Public Key*
- **Attack 1** ($c\mathbf{t}_1 2^d = 0$)

Scenario 2: Sampling of c
- **Attack 1** ($c\mathbf{t}_1 2^d = 0$)

$$\mathbf{w}_1' := \mathbf{UseHint}(h, \mathbf{Az} - c\mathbf{t}_1 2^d)$$

Scenario 3: Shift by d
- **Attack 2** ($c\mathbf{t}_1 2^d = \|c\mathbf{t}_1 2^d\|_\infty \leq \gamma_2$)

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How to Target?

Chose the fault injection point

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1. $(\mathbf{z}) \coloneqq \perp$
2. $\textbf{while}(\mathbf{z}) = \perp \textbf{ do}$
3. $\quad \mathbf{z} \leftarrow S^{l}_{\gamma_1-\beta}$
4. $\quad h = 0$
5. $\quad \mathbf{w}_1 \coloneqq \textbf{UseHint}(h, \mathbf{Az}, 2\gamma_2)$
6. $\quad c \in B_\tau \coloneqq \mathrm{H}(\boldsymbol{M} \parallel \mathbf{w}_1)$
7. $\textbf{return } \sigma = (\boldsymbol{c}, \mathbf{z}, h)$

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4. $\quad h = 0$
5. $\quad \mathbf{w}_1 \coloneqq \textbf{HighBits}(h, \mathbf{Az}, 2\gamma_2)$
6. $\quad c \in B_\tau \coloneqq \mathrm{H}(\boldsymbol{M} \parallel \mathbf{w}_1)$
7. $\quad h = \textbf{MakeHint}(-c\mathbf{t}_1 2^{d'}, \mathbf{Az} - c\mathbf{t}_1 2^{d'})$
8. $\quad \textbf{if } |h|_{h_j=1} > \omega, \textbf{then } (\mathbf{z}, h) = \perp$
9. $\textbf{return } \sigma = (\boldsymbol{c}, \mathbf{z}, h)$

Generate a signature using public key and an **arbitrary message**

How to Target?

Chose the fault injection point

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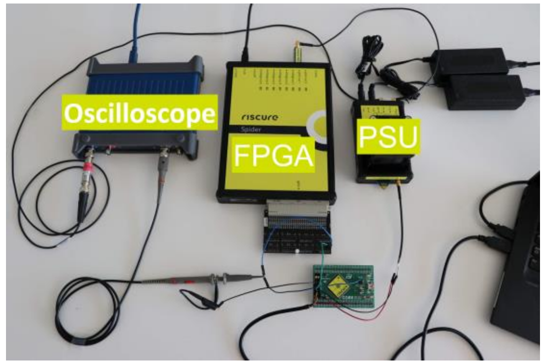
Generate a signature using public key and an **arbitrary message**



Inject the fault at the target **during verification**

Fault Injection Results

Scenario 2: Sampling of c

```c
void poly_challenge(poly *c, const uint8_t seed[SEEDBYTES]) {
  unsigned int i, b, pos;
  ...
  for(i = 0; i < N; ++i)
    c->coeffs[i] = 0;
  for(i = N-TAU; i < N; ++i) {
    ...
    c->coeffs[i] = c->coeffs[b];
    c->coeffs[b] = 1 - 2*(signs & 1);
    ...
}
```

PQM4: Dilithium verification source code

Scenario 2: Sampling of c

```c
void poly_challenge(poly *c, const
 uint8_t seed[SEEDBYTES]) {
  unsigned int i, b, pos;
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for(i = N-TAU; i < N; ++i) {
   ...
   c->coeffs[i] = c->coeffs[b];
   c->coeffs[b] = 1 - 2*(signs & 1);
    ...
}
```
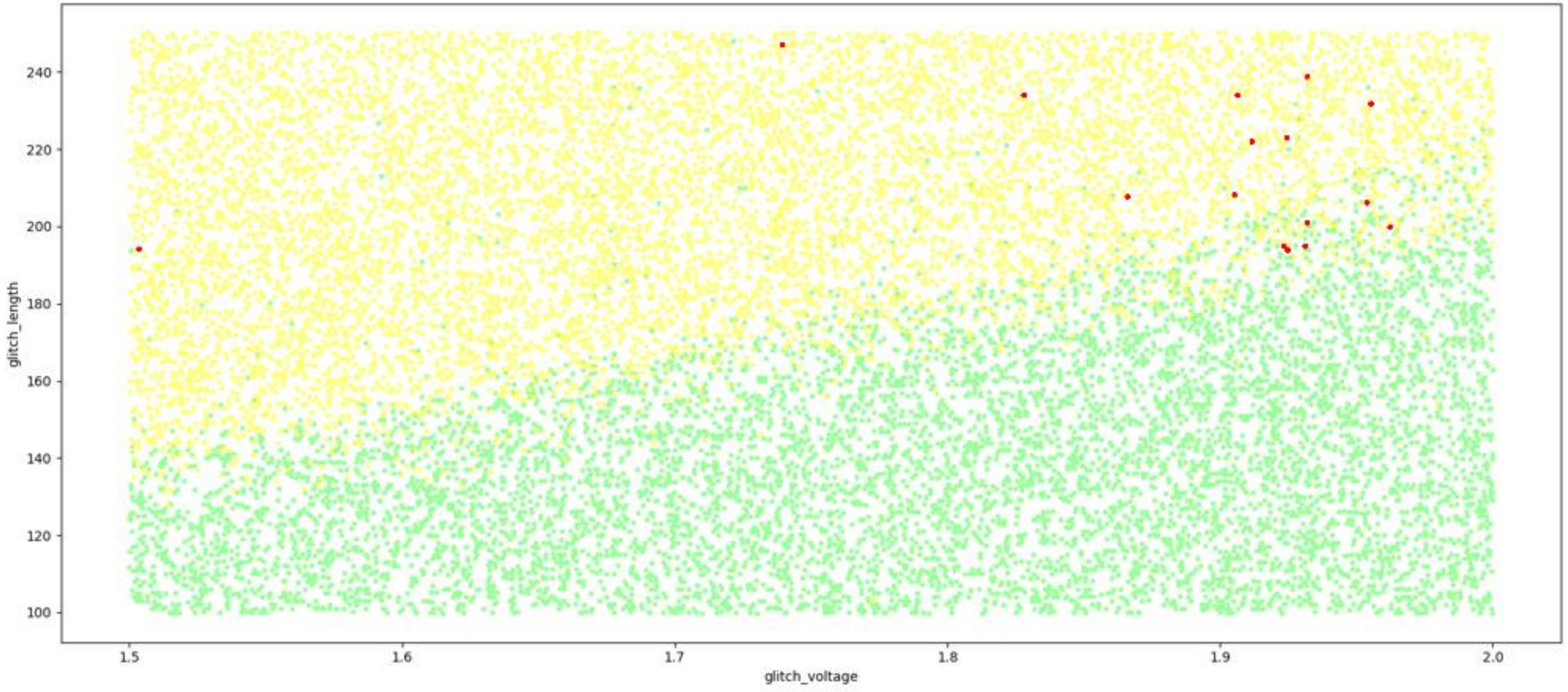

PQM4: Dilithium verification source code

- If the fault is injected in second for loop of the **poly_challenge** function, the **for loop will be skipped.**
- As a result, each coefficient of c will be equal to **zero**, **enabling Attack 1** ($c\mathbf{t}_1 2^d = 0$)

Scenario 2: Sampling of C

- Green: Normal Execution
- Yellow: Mute/Reset
- Red: Success



Fault Injection Plot of Sampling of C Scenario

Scenario 3: Shift by d

```c
void polyveck_shiftl(polyveck *v) {
  unsigned int i;

  for(i = 0; i < K; ++i)
    poly_shiftl(&v->vec[i]);
```

```c
void poly_shiftl(poly *a) {
  ...
  for(i = 0; i < N; ++i)
    a->coeffs[i] <<= D;
```

PQM4: Dilithium verification source code

Scenario 3: Shift by d

```c
void polyveck_shiftl(polyveck *v) {
  unsigned int i;

  for(i = 0; i < K; ++i)
    poly_shiftl(&v->vec[i]);
```

```c
void poly_shiftl(poly *a) {
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  for(i = 0; i < N; ++i)
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Scenario 3: Shift by d

```
void polyveck_shiftl(polyveck *v) {
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```

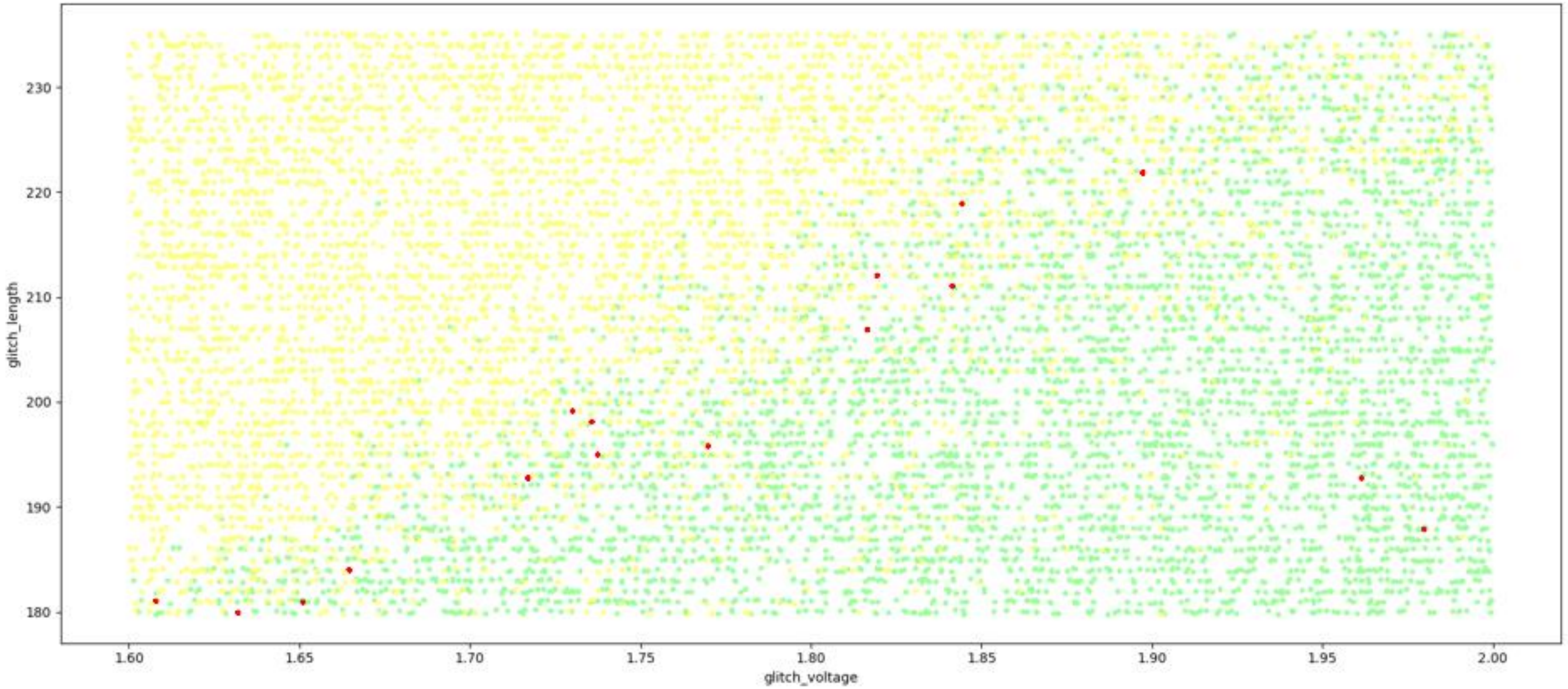
```
void poly_shiftl(poly *a) {
  ...
  for(i = 0; i < N; ++i)
    a->coeffs[i] <<= D;
```

PQM4: Dilithium verification source code

- If the fault is injected at **for loop** of the **polyveck_shiftl** function, the entire **for** loop will be skipped.
- As a result, **each coefficient of $\mathbf{t}_1$ will remain unshifted.**
- $\left\|c\mathbf{t}_1 2^d\right\|_\infty \leq \gamma_2$, enabling **Attack 2** with $d' = 0$

Scenario 3: Shift by d

- Green: Normal Execution
- Yellow: Mute/Reset
- Red: Success



Fault Injection Plot of Shift by d Scenario

Scenario 4: Subtraction

```c
void polyveck_sub(polyveck *w, const polyveck *u, const
polyveck *v) {
  unsigned int i;
  for(i = 0; i < K; ++i) {
    send_char(dilithium_counter);
    poly_sub(&w->vec[i], &u->vec[i], &v->vec[i]); }
}
```

PQM4: Dilithium verification source code

Scenario 4: Subtraction

```
void polyveck_sub(polyveck *w, const polyveck *u, const
polyveck *v) {
  unsigned int i;
  for(i = 0; i < K; ++i) {
    send_char(dilithium_counter);
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PQM4: Dilithium verification source code

Scenario 4: Subtraction

```c
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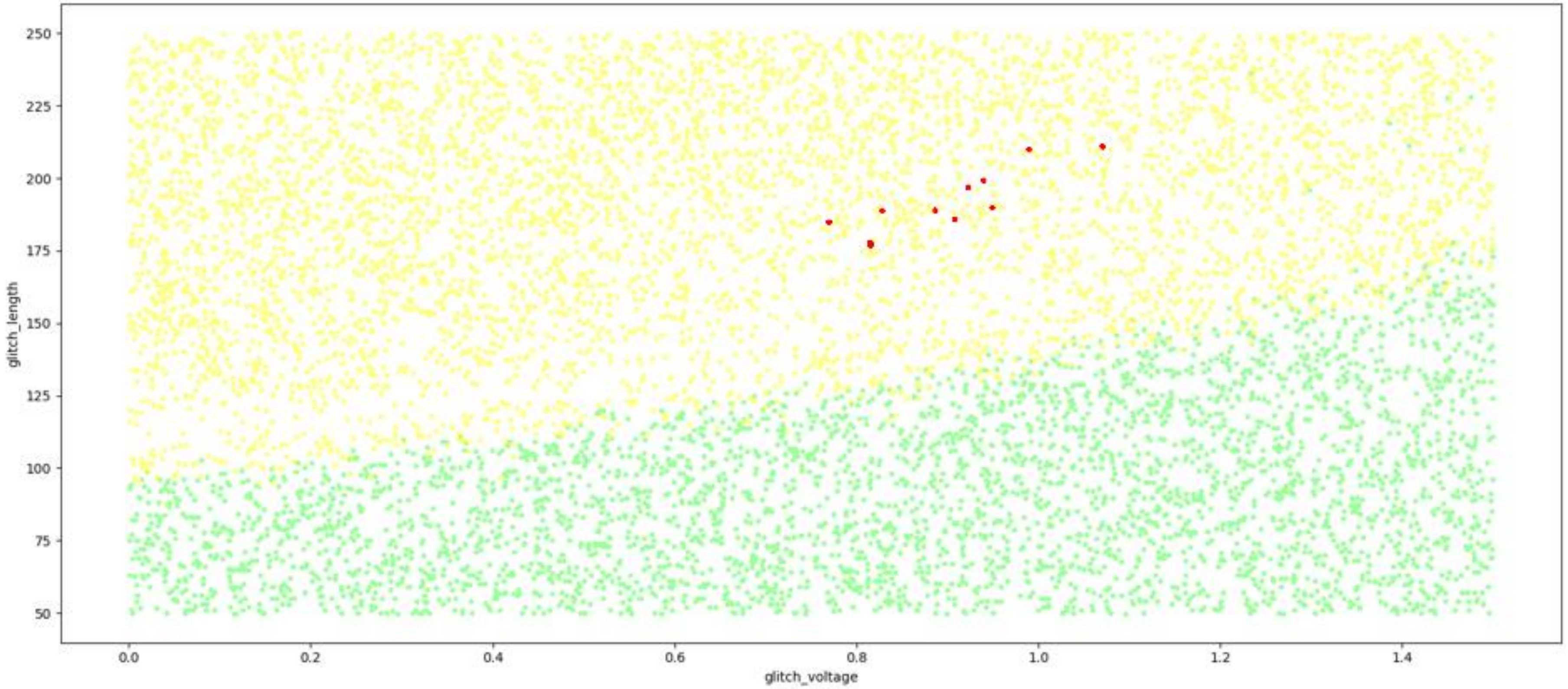
    send_char(dilithium_counter);
    poly_sub(&w->vec[i], &u->vec[i], &v->vec[i]); }
}
```

PQM4: Dilithium verification source code

- If a fault is injected at **for loop** of the **polyveck_sub** function, the entire **for** loop will be skipped
- As a result, the subtraction is not performed, so: $\mathbf{Az} - c\,\mathbf{t}_1 2^d = \mathbf{Az}$ (Attack 1)

Scenario 4: Subtraction

- Green: Normal Execution
- Yellow: Mute/Reset
- Red: Success



Fault Injection Plot of Subtraction Scenario

Summary of FI on Dilithium

- Fault Injection on **Dilithium**, can target verification operations like **initialization, challenge generation, shifting,** or **subtraction**.

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- Fault Injection on **Dilithium**, can target verification operations like **initialization, challenge generation, shifting,** or **subtraction**.
- **These faults allow bypassing the scheme's logic to accept attacker-generated signatures.**
- The **attack surface and behavior vary significantly across implementations**, making fault resistance hard to generalize.

Bypassing WOTS+ Based Hash Based Signature Verification via Fault Injection

Introduction to Hash Based Signatures

- Hash-based cryptography builds on the cryptographic hash functions.
- Since quantum computers struggle to break secure hash functions, these schemes remain resistant .
- This talk focuses on their fundamental building block: **Winternitz One-Time Signature (WOTS+).**

Introduction to WOTS

- Winternitz Parameter:

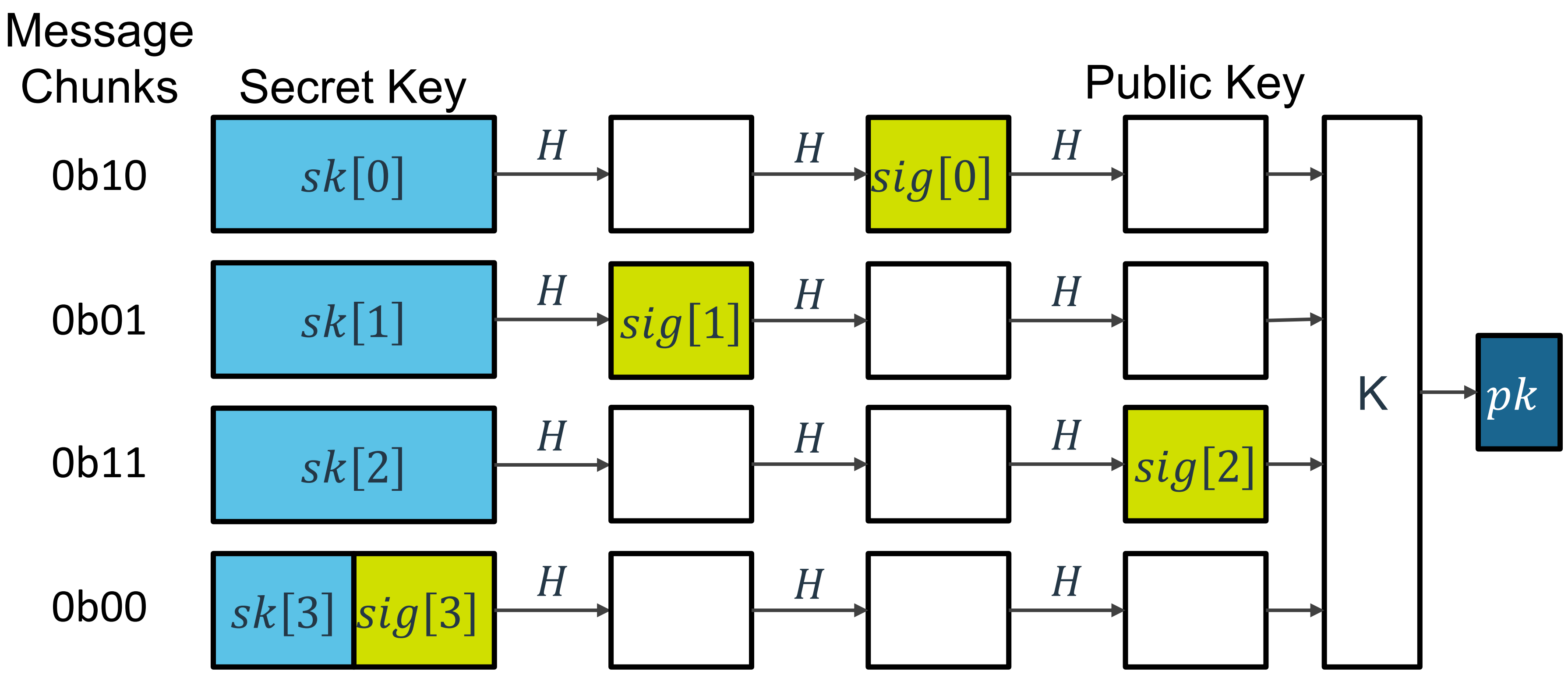
  $w = 4$

- Hash Chain Length:

  $w - 1 = 3$

- Chunk Bit Size:

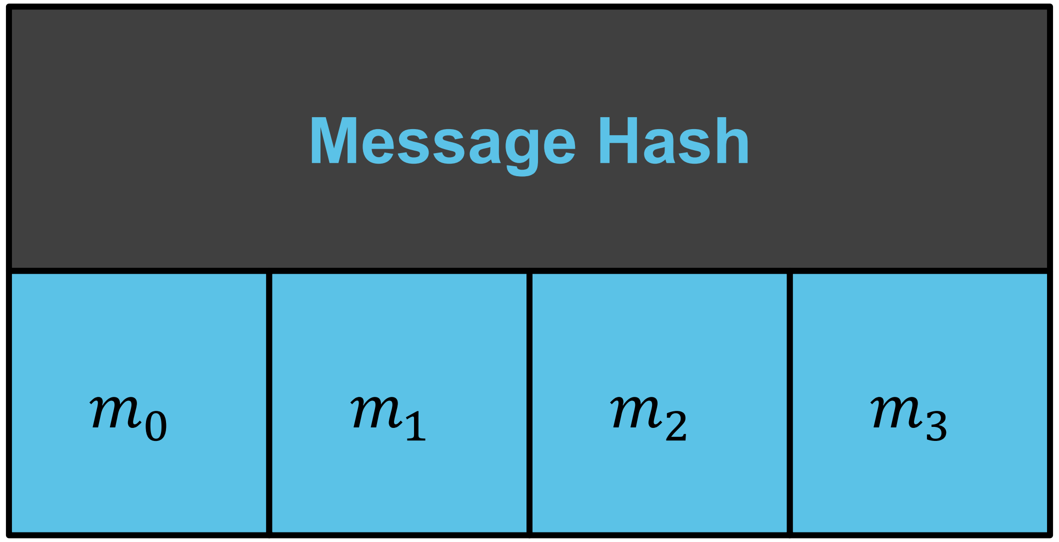
  $log_2(w) = 2$



Signature Generation: Split message hash into chunks

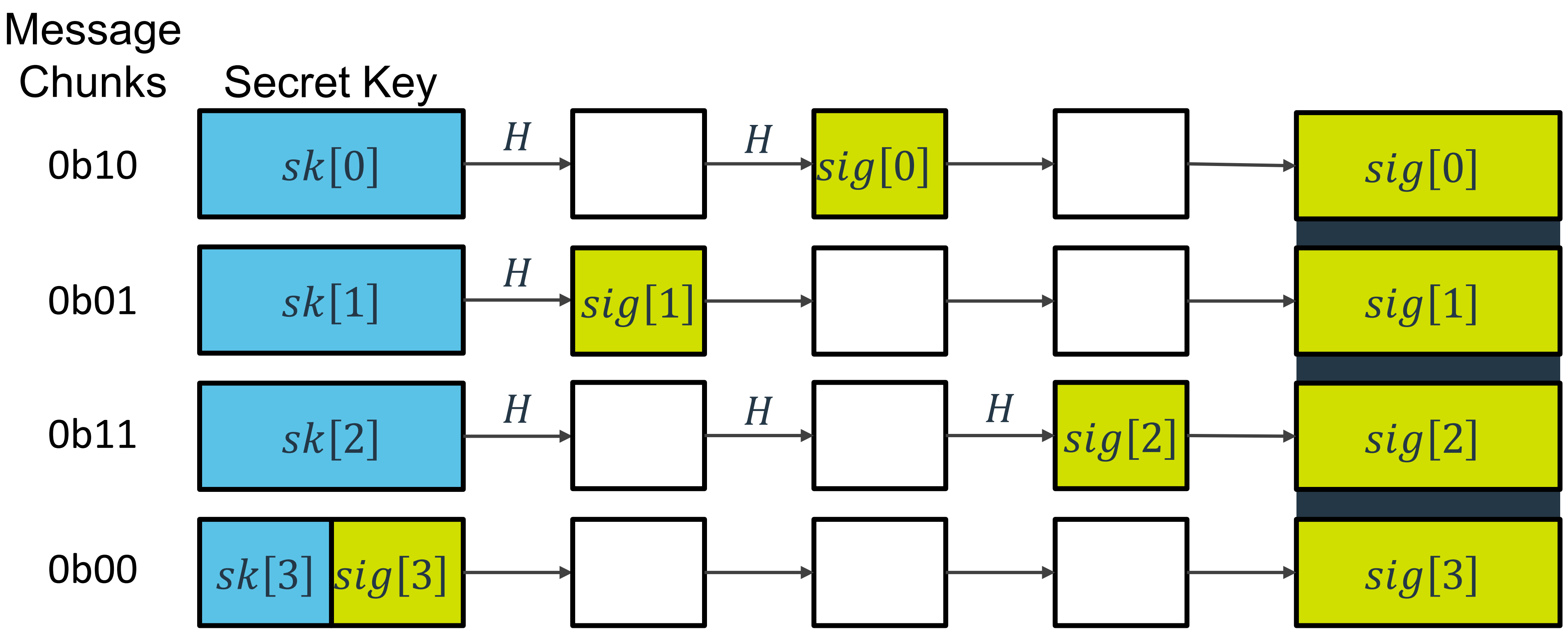
- $m = [m_0, m_1, \ldots, m_{l1-1}]$

  (Each m_i *is in* $[0, w-1]$*)*



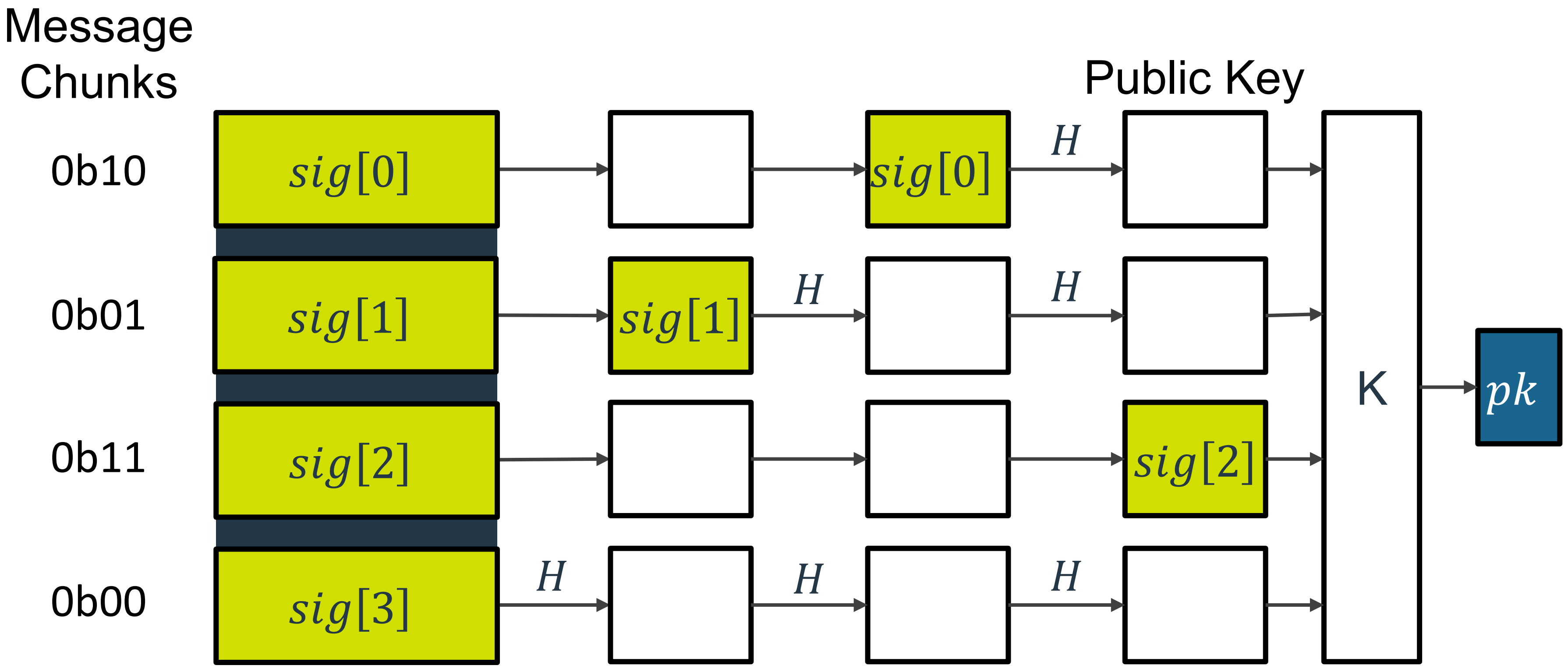
Signature Generation: Signing

- $sig[i] = hash\_chain(sk[i],\ steps = m[i])$



Signature Verification:

- $pk[i] == hash\_chain(sig[i],\ steps = w\ - 1\ - m[i])$



Brute-Force Forgery on WOTS

- If the attacker brute forces $m' \geq m$, **they can forge a valid signature**.

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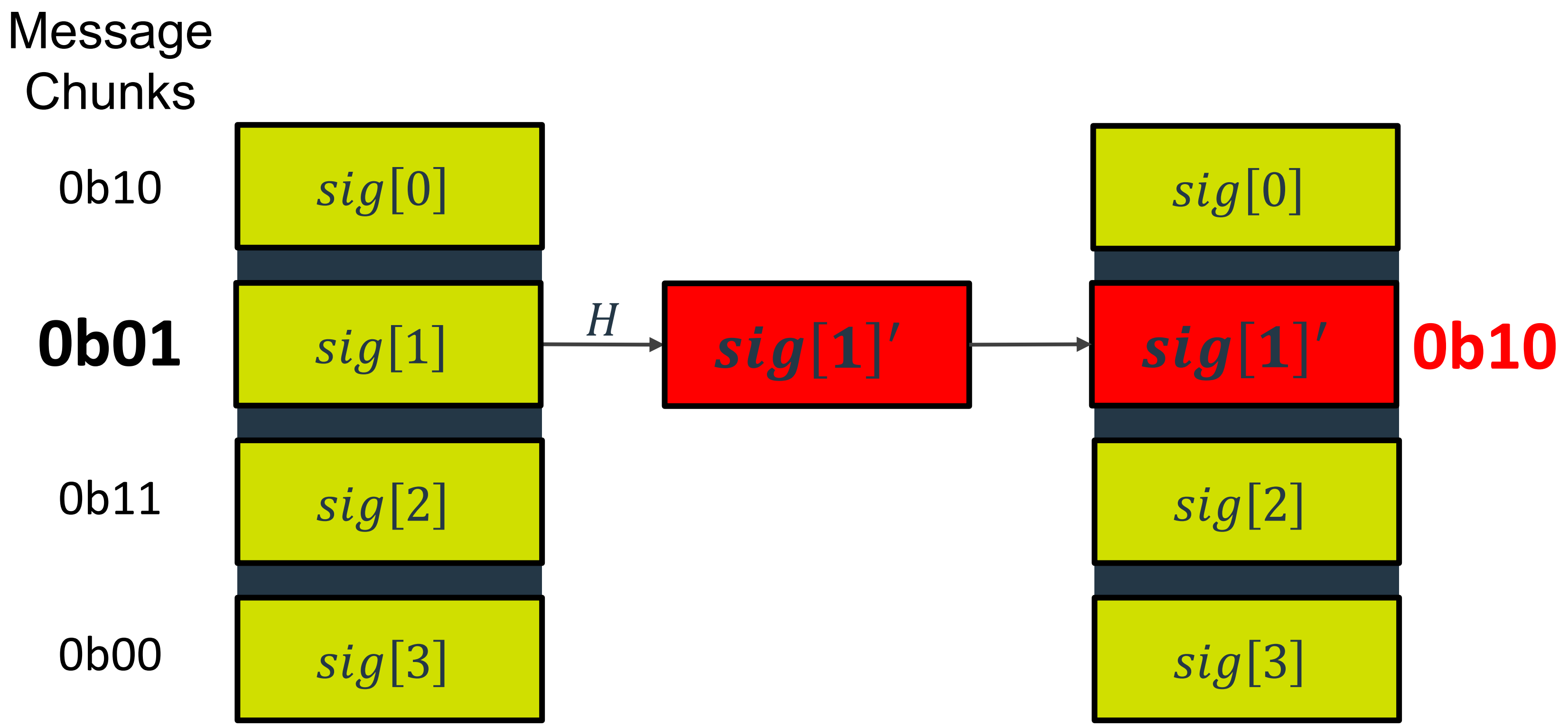

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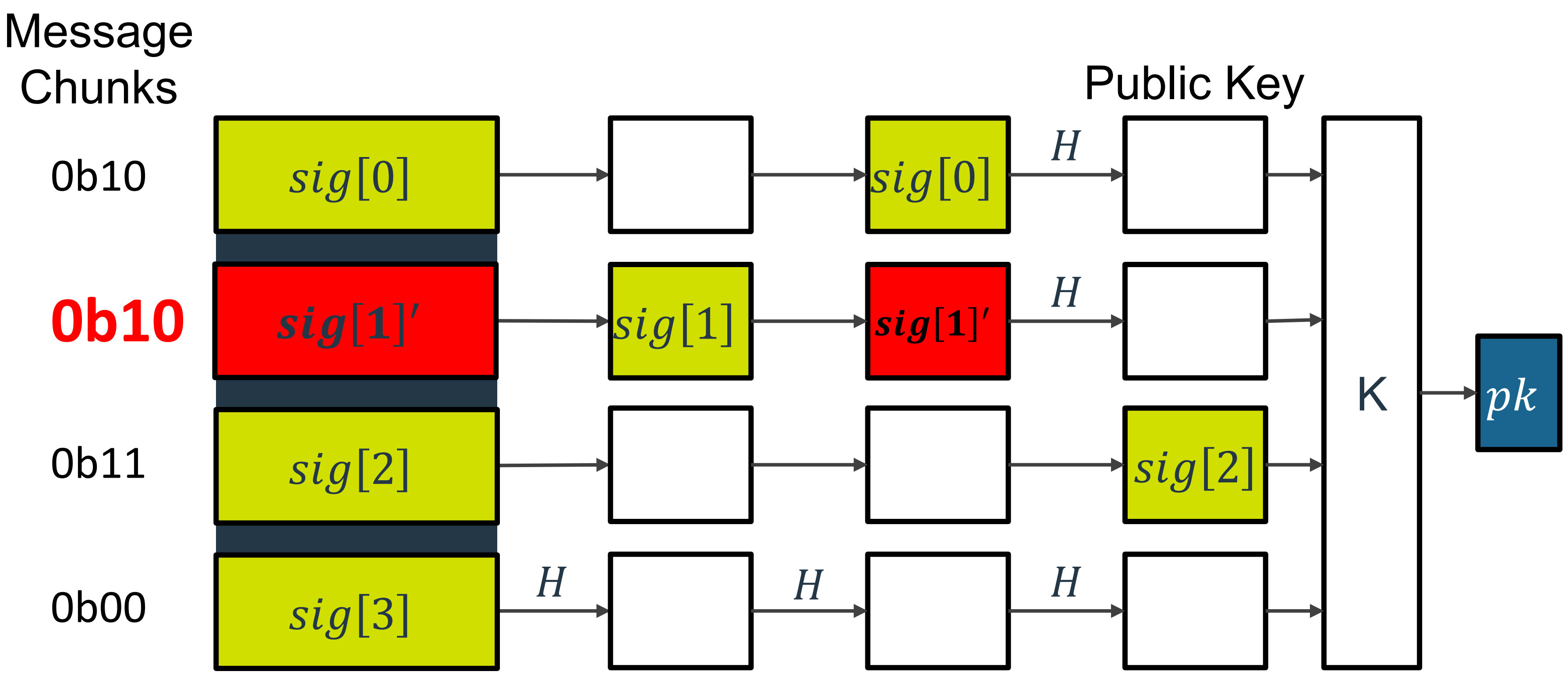


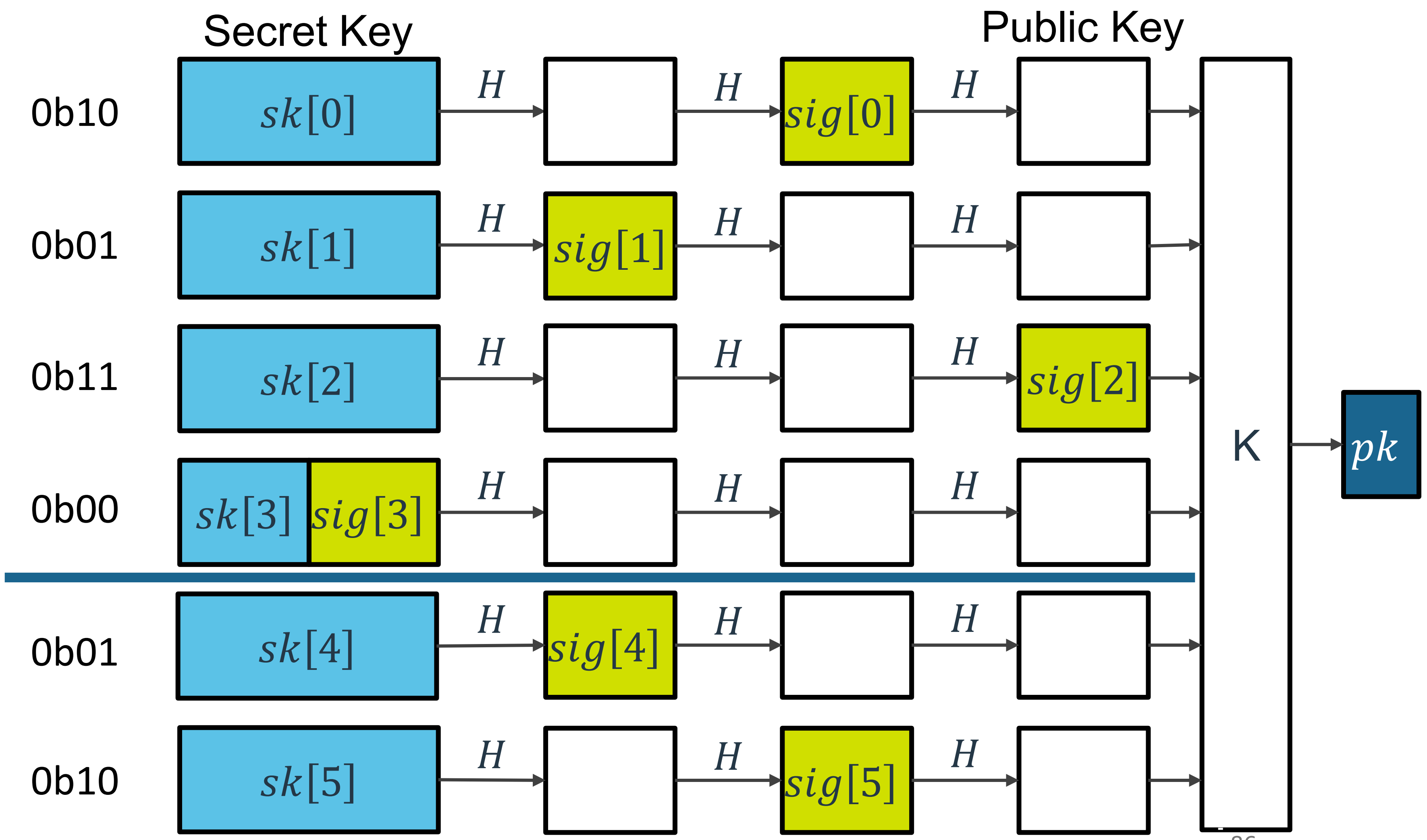
How WOTS+ Adds a Checksum

Checksum:

$$c = C(m) = \sum_{i=0}^{l_1} (w - 1 - m_i)$$

$$c = 1 + 2 + 0 + 3$$

$$c = 6 = 0b0110$$



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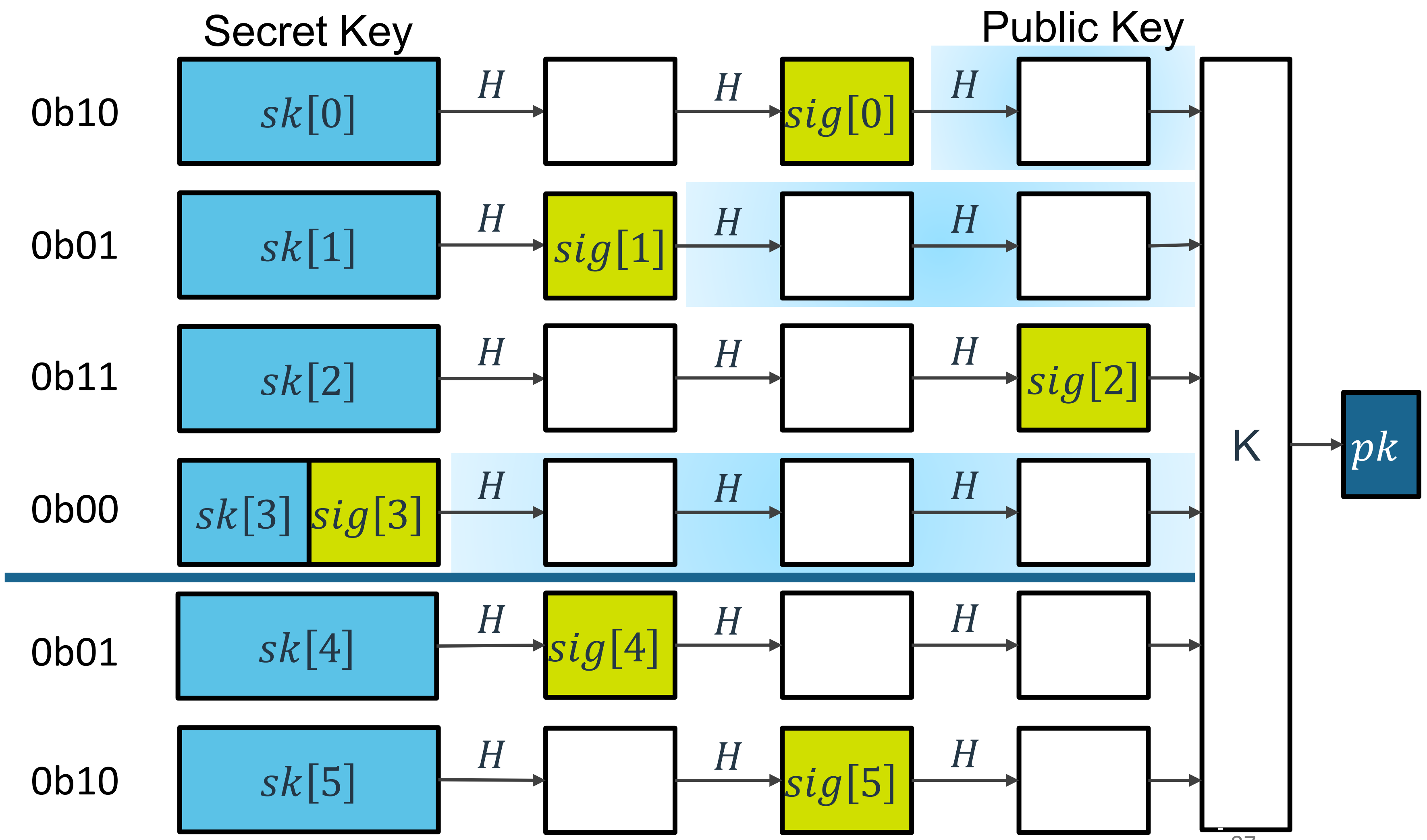

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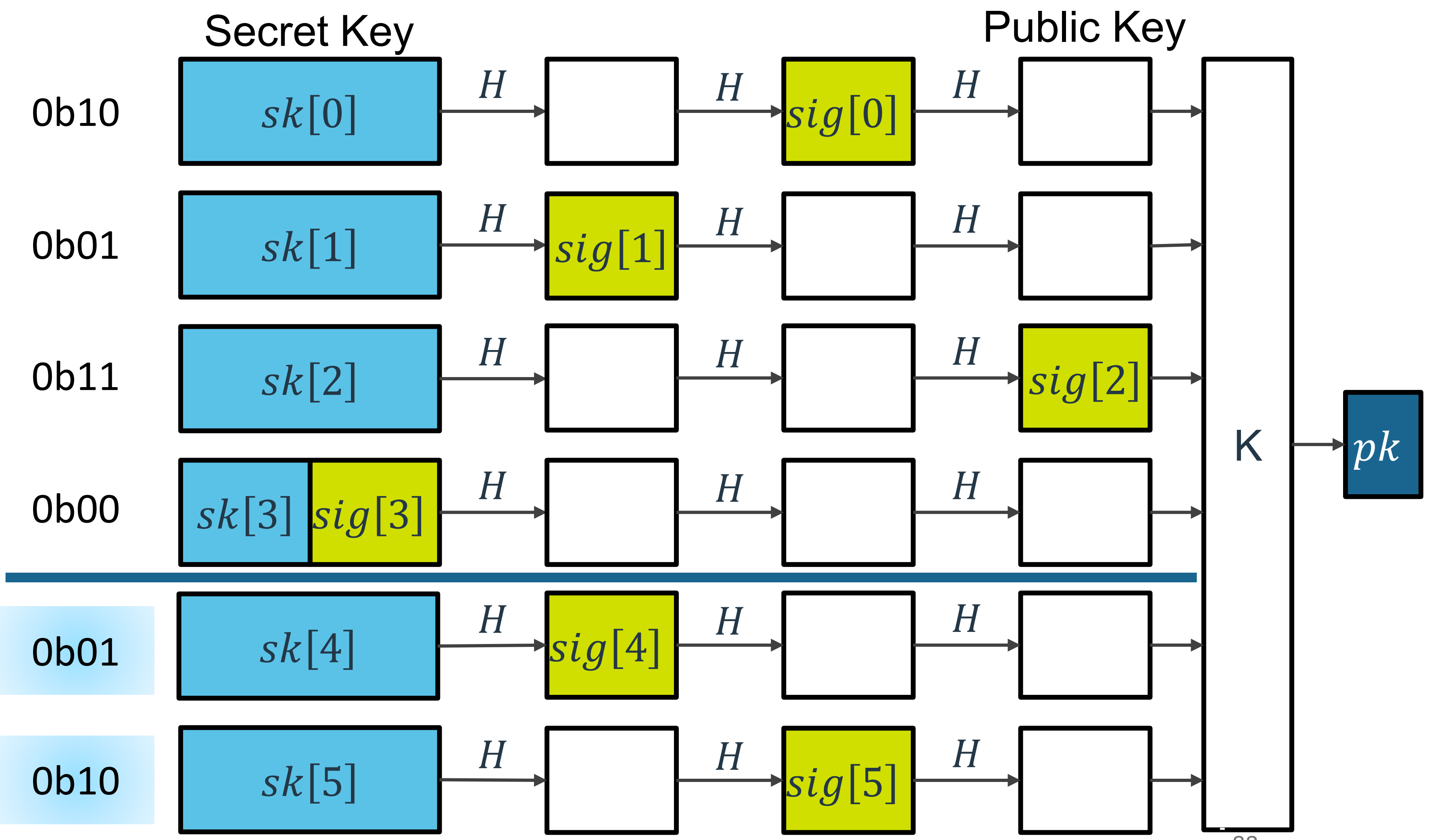
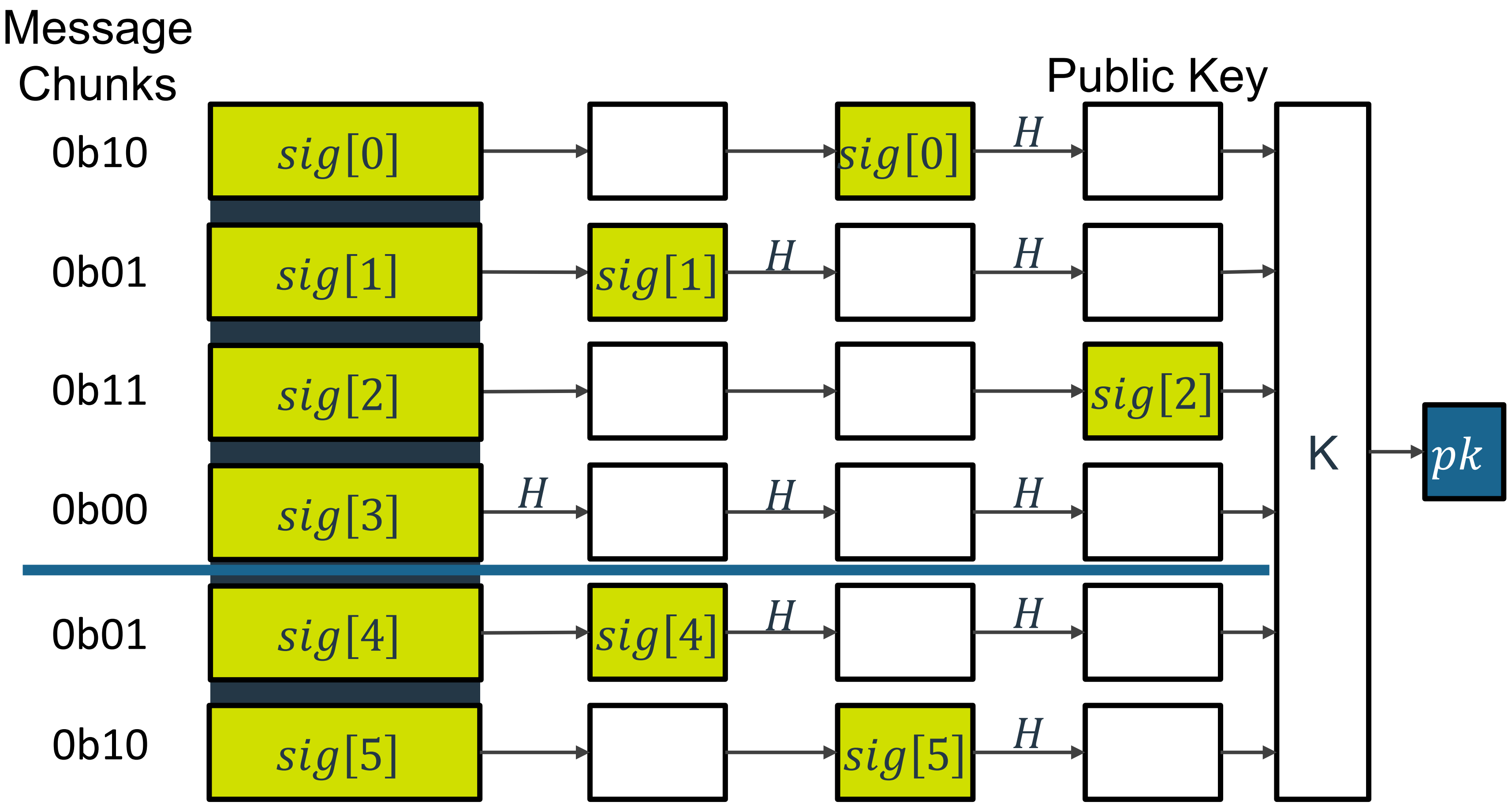


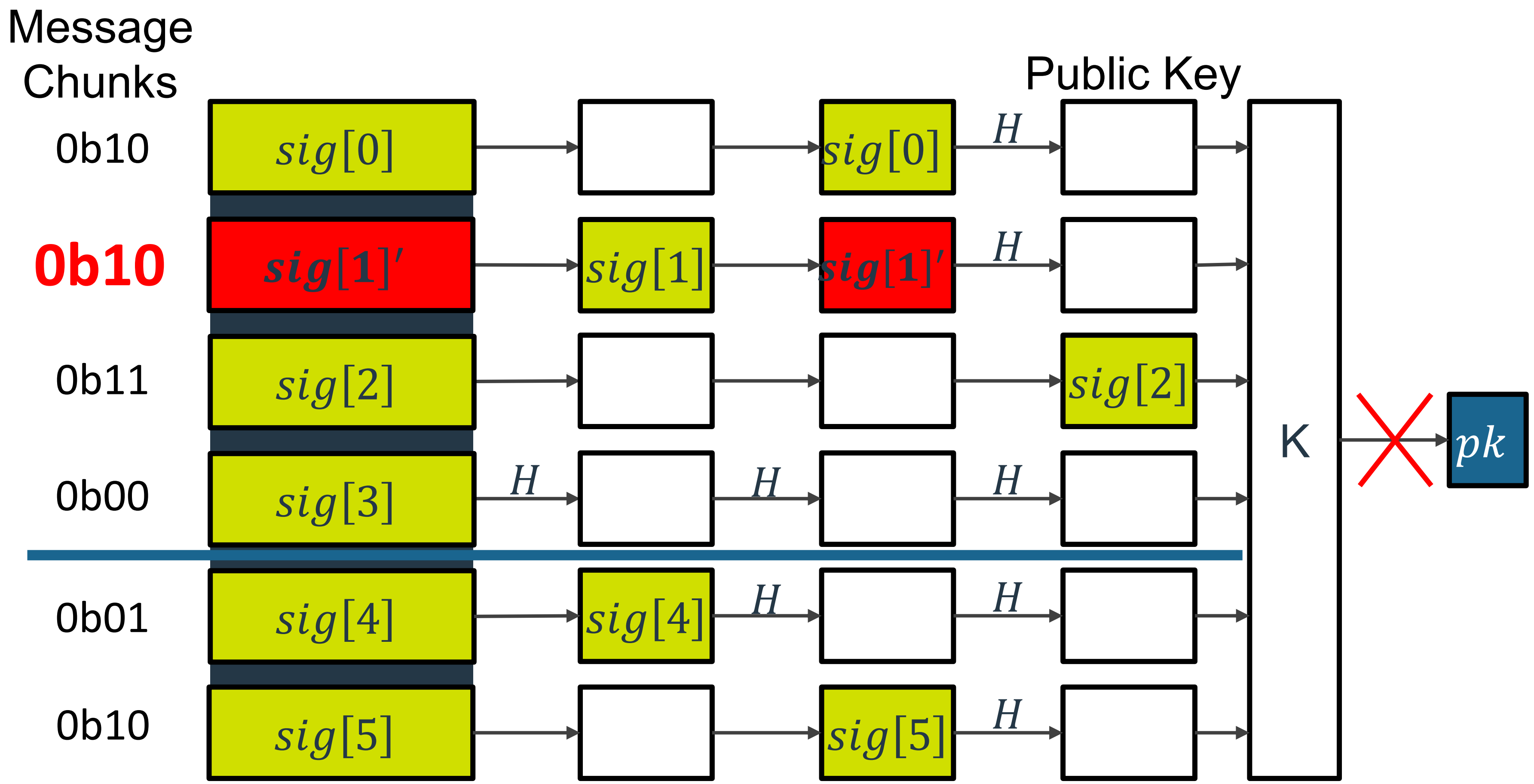
How WOTS+ Protects Against Forgery

- $pk[i] == hash\_chain(sig[i],\ steps = w\ - 1\ - m[i])$



How WOTS+ Protects Against Forgery

- $c = 1 + \mathbf{1} + 0 + 3 = \mathbf{5}$



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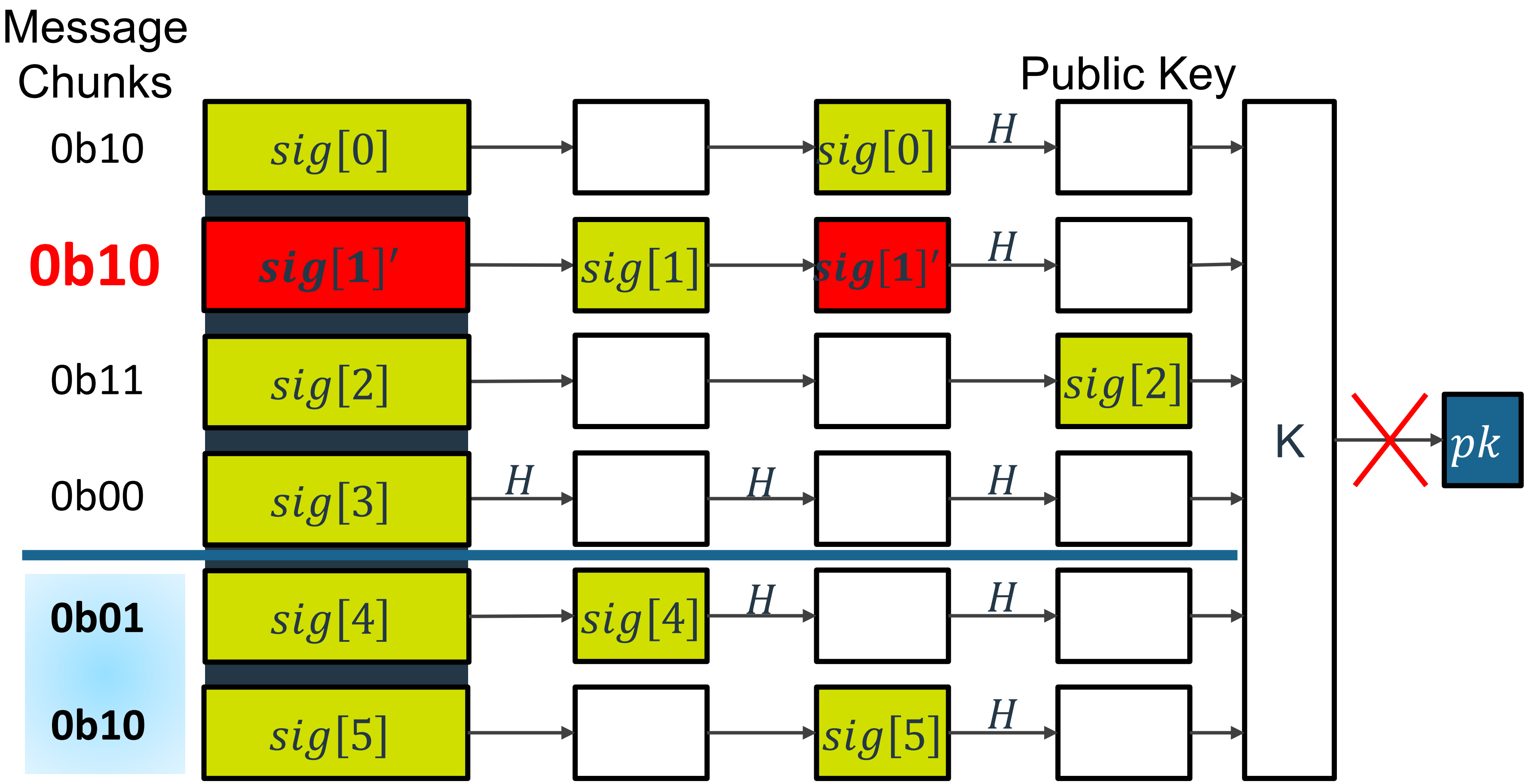

Faulting WOTS+ to forge Hash Based Signature

- This research builds on Faulting Winternitz One-Time Signatures to forge LMS, XMSS, or SPHINCS+ signatures (PQCrypto 2023)

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$$sig\_checksum[j] \rightarrow hash\_chain(steps = w - 1 - c'[j])$$

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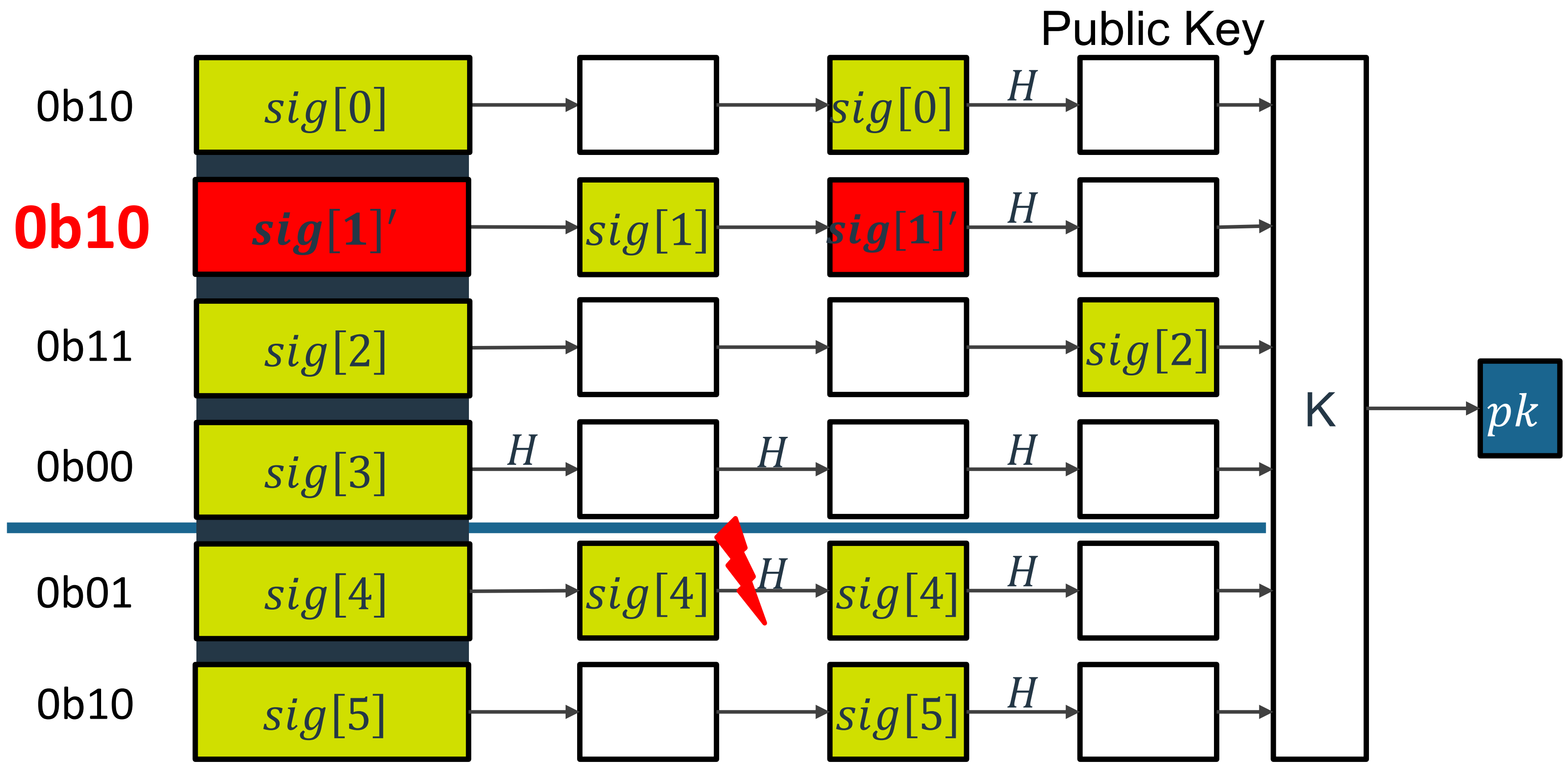
- The paper demonstrates an attack on the checksum calculation during signature verification using fault injection to alter normal behavior:

$$sig\_checksum[j] \rightarrow hash\_chain(steps = w - 1 - c'[j])$$

- **Partial hash chain skip**
- **Full hash chain skip**

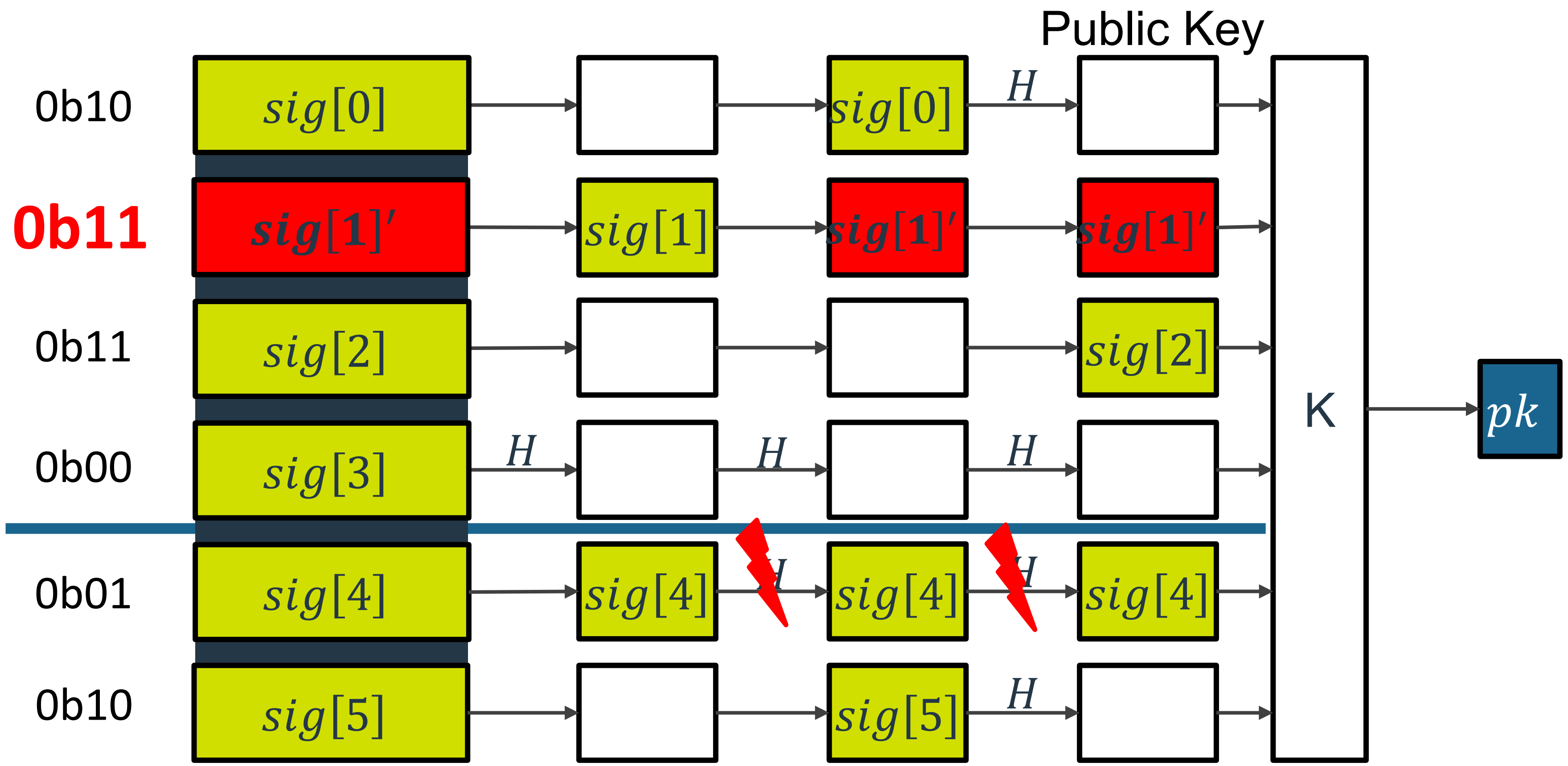
Partial hash chain skip

- $sig\_checksum[j] \rightarrow hash\_chain(steps = v') \; where \; v' < (w - 1 - c'[j])$



Full hash chain skip

- $sig\_checksum[j] \rightarrow hash\_chain(steps = 0)$



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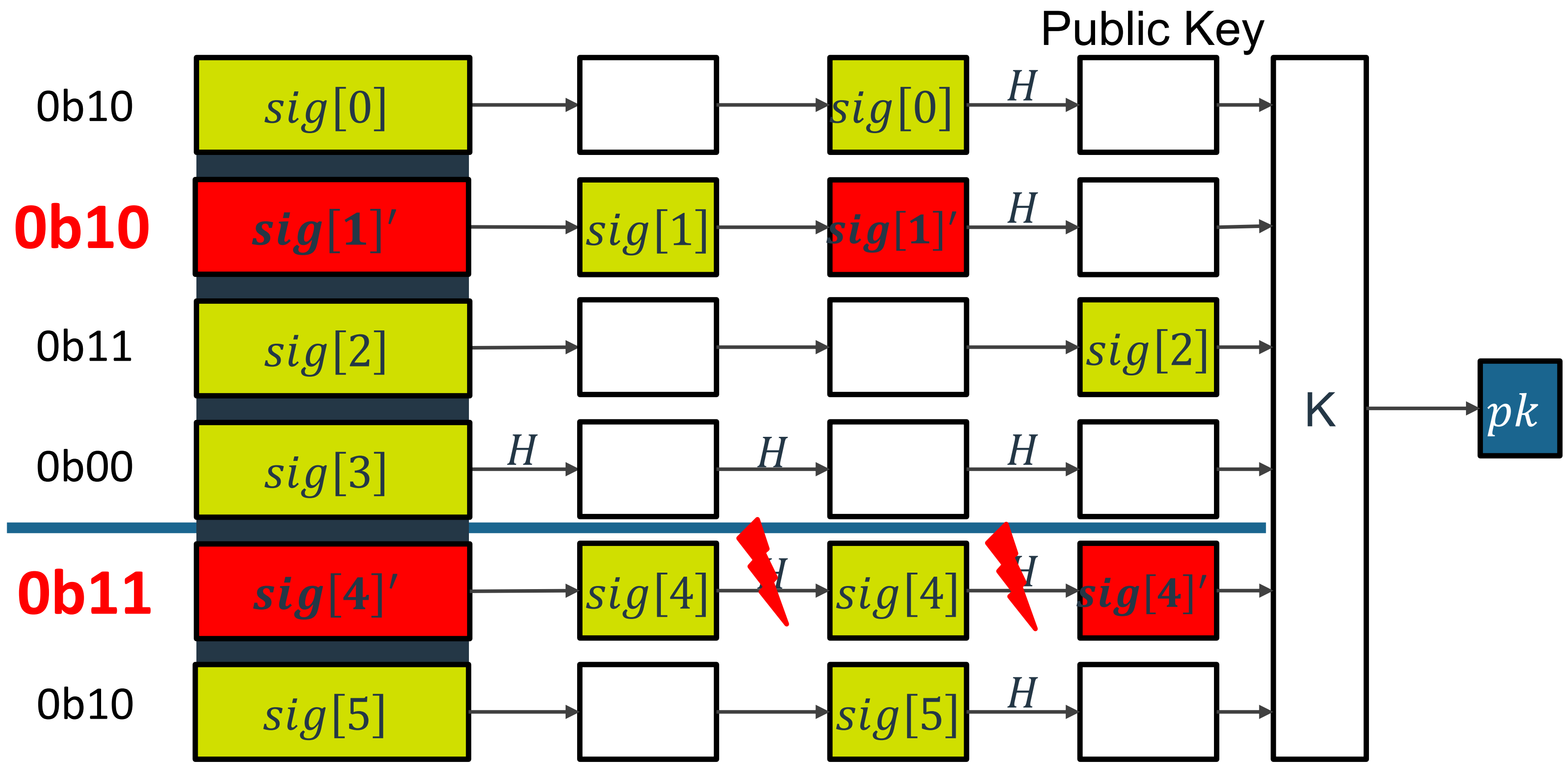

XMSS and SPHINCS+

- **XMSS (eXtended Merkle Signature Scheme)** is a stateful hash-based signature scheme built on WOTS+ and a Merkle tree.

  Requires tracking a secret index to avoid key reuse.

XMSS and SPHINCS+

- **XMSS (eXtended Merkle Signature Scheme)** is a stateful hash-based signature scheme built on WOTS+ and a Merkle tree.

  Requires tracking a secret index to avoid key reuse.

- **SPHINCS+** is a stateless hash-based scheme that combines **FORS** and a **hypertree of XMSS instances**.

  Eliminates state management and supports flexible trade-offs in size and speed.

Code Review of the WOTS+ Component in the Reference XMSS Implementation

```
void wots_pk_from_sig(const xmss_params *params, unsigned char *pk,
                      const unsigned char *sig, const unsigned char *msg,
                      const unsigned char *pub_seed, uint32_t addr[8]) {
    ...
    chain_lengths(params, lengths, msg);

    for(i = 0; i < params->wots_len; i++) {
        set_chain_addr(addr, i);
        gen_chain(params, pk + i*params->n, sig + i*params->n,
                  lengths[i], params->wots_w - 1 - lengths[i], pub_seed0, addr);
    }
}
```

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    ...
  1 chain_lengths(params, lengths, msg); // [1]-> Attack to checksum calculation

    for(i = 0; i < params->wots_len; i++) {
        set_chain_addr(addr, i);
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    ...
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    for(i = 0; i < params->wots_len; i++) {
        set_chain_addr(addr, i);
      2 gen_chain(params, pk + i*params->n, sig + i*params->n, //[2]->Attack to checksum chunk
                  lengths[i], params->wots_w - 1 - lengths[i], pub_seed0, addr);
    }
}
```

Code Review of the WOTS+ Component in the Reference XMSS Implementation

```
static void wots_checksum(...) {
    ...
    /* Compute checksum. */
    for (i = 0; i < params->wots_len1; i++) {
        csum += params->wots_w - 1 - msg_base_w[i];
    }
    /* Convert checksum to base_w. */
    csum = csum << (8 - ((params->wots_len2 * params->wots_log_w) % 8));
    ull_to_bytes(csum_bytes, sizeof(csum_bytes), csum);
    base_w(params, csum_base_w, params->wots_len2, csum_bytes);
}

static void chain_lengths(...) {
    base_w(params, lengths, params->wots_len1, msg);
    wots_checksum(params, lengths + params->wots_len1, lengths);
}
```

Code Review of the WOTS+ Component in the Reference XMSS Implementation

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    }
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    ull_to_bytes(csum_bytes, sizeof(csum_bytes), csum);
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static void chain_lengths(...) {
    base_w(params, lengths, params->wots_len1, msg);
    wots_checksum(params, lengths + params->wots_len1, lengths);
}
```

Code Review of the WOTS+ Component in the Reference XMSS Implementation

```
static void gen_chain(...)
{
    uint32_t i;

    /* Initialize out with the value at position 'start'. */
    memcpy(out, in, params->n);

    /* Iterate 'steps' calls to the hash function. */
    for (i = start; i < (start+steps) && i < params->wots_w; i++) {
        set_hash_addr(addr, i);
        thash_f(params, out, out, pub_seed, addr);
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}
```

Code Review of the WOTS+ Component in the Reference SPHINCS+ Implementation

- **SPHINCS+** reuses the same **WOTS+** code as **XMSS** for signature verification.
- As a result, all fault injection **attacks** demonstrated against XMSS also apply directly to SPHINCS+.

How to Target?

Chose the fault injection point

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Brute-force search for a hash digest m'

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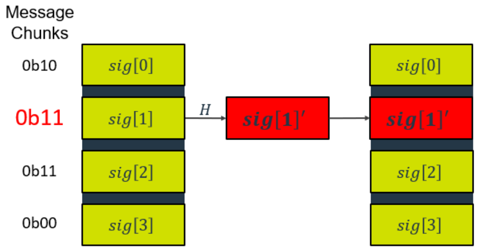
Brute-force search for a hash digest m'



Forge a signature for m'

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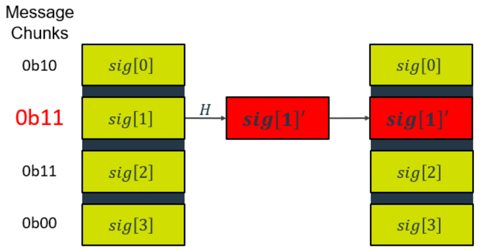
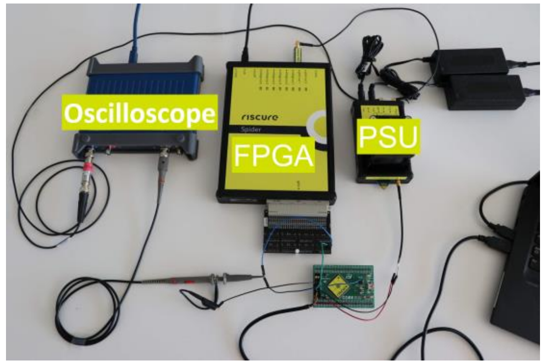
Brute-force search for a hash digest m'



Forge a signature for m'

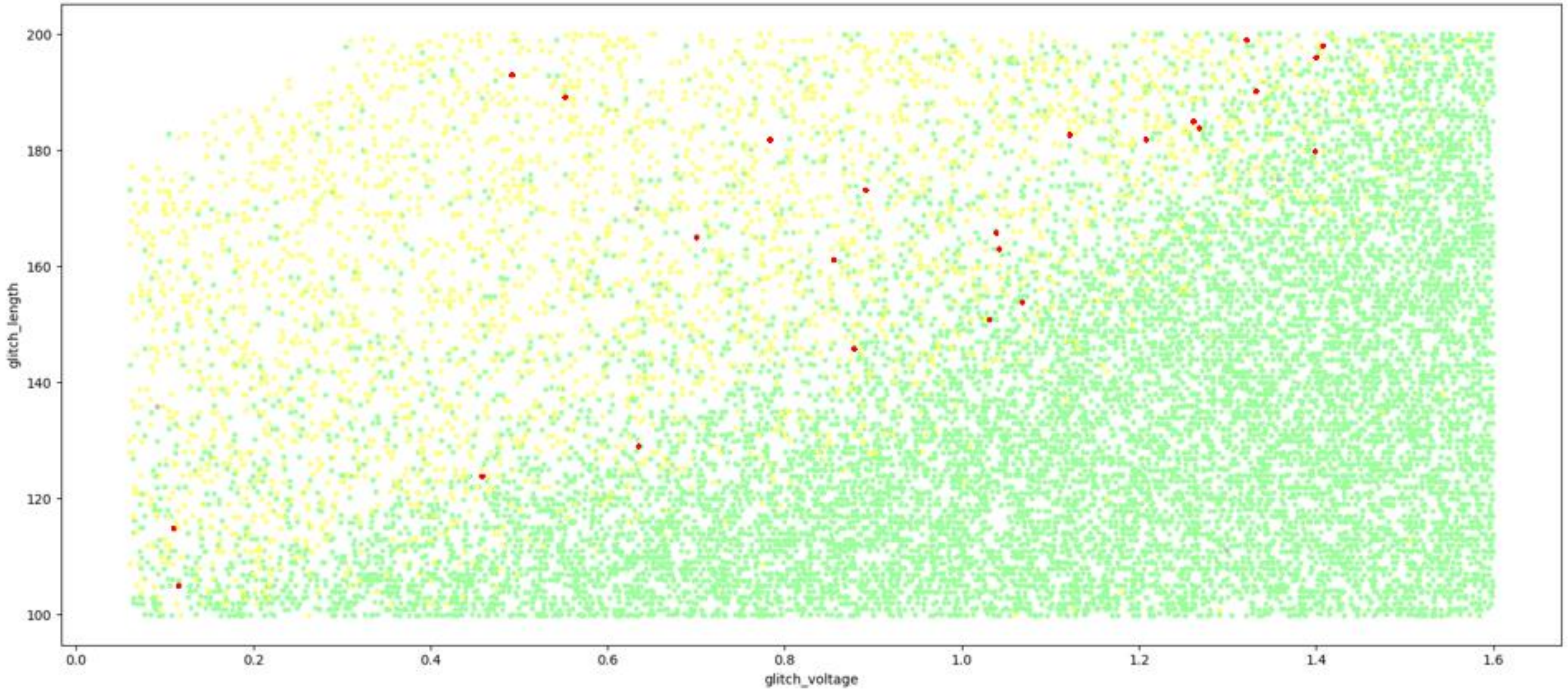


Inject the fault at the target **during verification**

Fault Injection Results of XMSS

Fault Injection Results – Skipping Hash Chains

- Green: Normal Execution
- Yellow: Mute/Reset
- Red: Success



Fault Injection Plot of Sampling of C Scenario

Summary – XMSS & SPHINCS+

- We identified multiple fault injection targets in **WOTS+**, which is used in both **XMSS** and **SPHINCS+**.

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Summary – XMSS & SPHINCS+

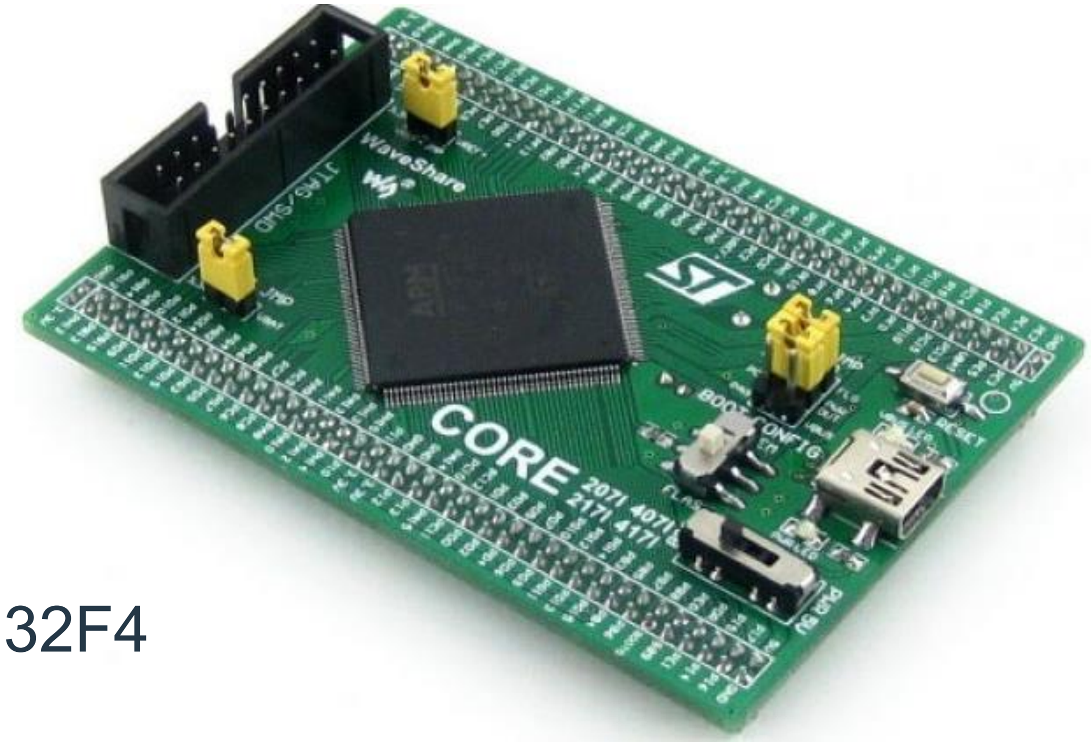
- We identified multiple fault injection targets in **WOTS+**, which is used in both **XMSS** and **SPHINCS+**.
- The **checksum calculation** is a broad and critical target. While skipping hash chains is easy, attacking the checksum calculation requires **precise local fault injection** (e.g., laser FI, EMFI).
- Since **SPHINCS+ reuses the same WOTS+ code**, all attack techniques against XMSS verification **apply to SPHINCS+.**

Bonus: Fault Injection on Fault Resistance XMSS Library

Introduction

- Fox Crypto released XMSS v1.0 **before** fault injection attacks on WOTS+ were published.
- The library includes **fault injection resistance** for **verification**, as stated in their documentation and presentations*.

- **Our goal:** Apply the attack on WOTS+
- We implemented Fox Crypto's XMSS library on our STM32F4 target
- We used the same Voltage Fault Injection Setup from our earlier XMSS research.



Source: Production ready XMSS

Vulnerability We Found in Fox Crypto XMSS Implementation

```
static void chain(...) {
    ...
    input_prf->M.ADRS.typed.OTS_Hash_Address.hash_address = start_index; // [1]

    assert(start_index + num_steps < W); // [2]

    native_256_copy(output, input);

    for (uint_fast8_t i = 0; i < num_steps; i++) { // [3]
        ...
        input_prf->M.ADRS.typed.OTS_Hash_Address.keyAndMask = 1;
        xmss_PRF(HASH_ABSTRACTION(hashes) &input_f.M, input_prf);
        for (uint_fast8_t j = 0; j < XMSS_VALUE_256_WORDS; j++) {
            input_f.M.data[j] ^= output->data[j];
        }
        xmss_F(HASH_ABSTRACTION(hashes) output, &input_f);
        input_prf->M.ADRS.typed.OTS_Hash_Address.hash_address += 1; // [4]
    }
}
```

Vulnerability We Found in Fox Crypto XMSS Implementation

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        for (uint_fast8_t j = 0; j < XMSS_VALUE_256_WORDS; j++) {
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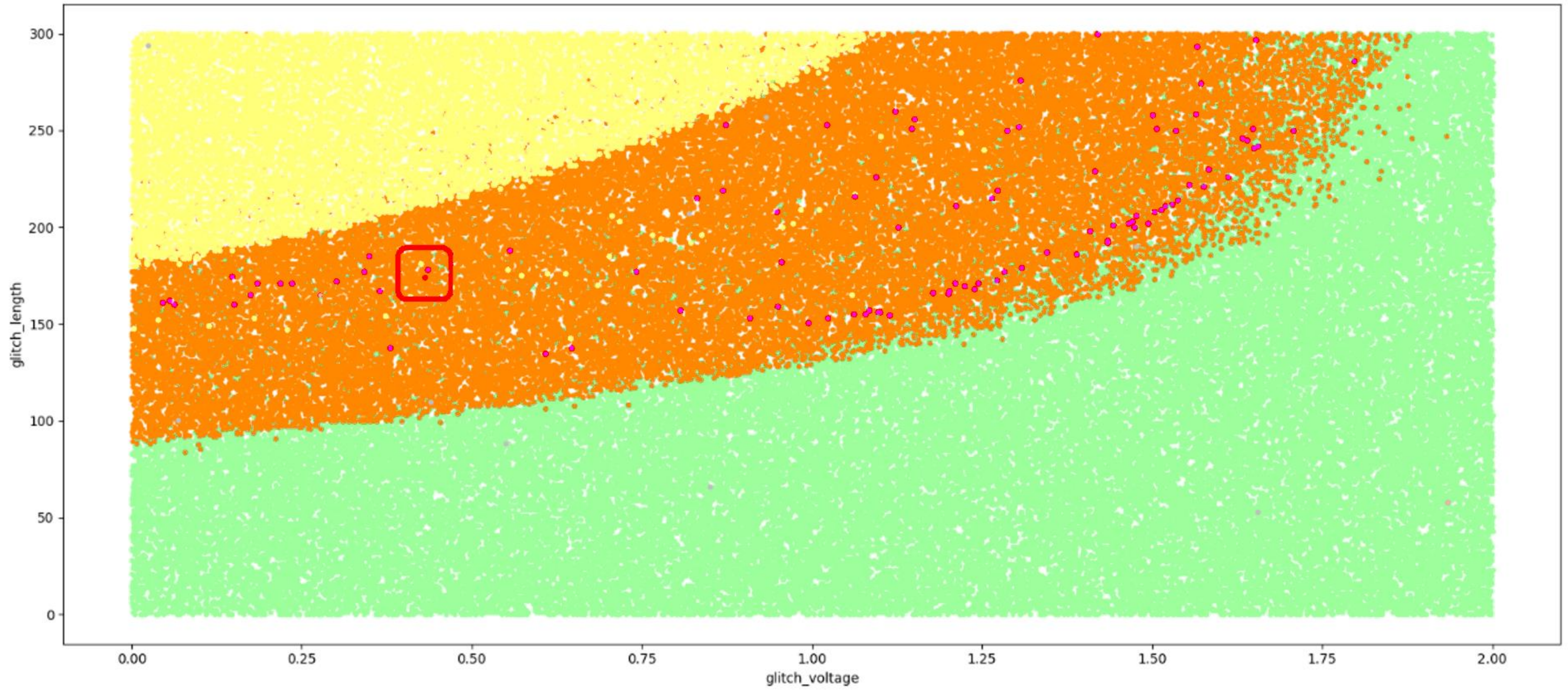
    }
}
```

Fault Injection Results of Fox Crypto XMSS Implementation

- We used same Voltage Fault Injection Setup
- Green: Normal Behaviour
- Orange and Purple: Hash chain skip is performed, but the library **returns an error** due to the **countermeasure checks**
- Yellow: Mute/Reset
- Red: Success



Fault Injection Plot of Full Hash Chain Skip

Vulnerability Disclosure Timeline

- **Discovery & Validation:**
  - [26.04.2024] – Vulnerability identified and validated internally.
- **Initial Contact with Fox Crypto:**
  - [02.05.2024] – Notified Fox Crypto about the identified vulnerability.
  - [16.05.2024] – We presented the vulnerability and FI results to Fox Crypto.
- **Public Disclosure:**
  - [17.05.2024] – Fox Crypto created a public security issue on GitHub regarding the vulnerability.
- **Fox Crypto Fix Released:**
  - [08.10.2024] – Fox Crypto released version 2.0 of the XMSS library, confirming the fix for the vulnerability.
  - We appreciate Fox Crypto's timely response and transparency in addressing the issue.

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- **Signature forgery** is possible **without breaking** crypto, just by skipping checks.
- New fault targets continue to emerge. Attackers adapt quickly, so defenses must evolve just as fast.
- Implementation security is the **next battleground** for post-quantum crypto.

KEYSIGHT

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Thank you