Hertzbleed: Turning Power Side-Channel Attacks Into Remote Timing Attacks on x86

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ILLINOIS
UNIVERSITY of WASHINGTON

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Power Side Channel vs Remote Timing

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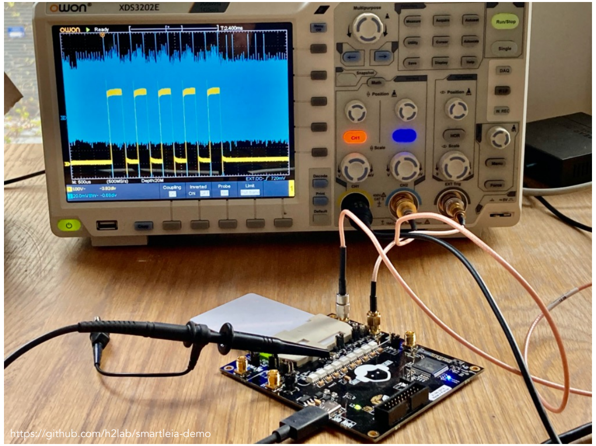
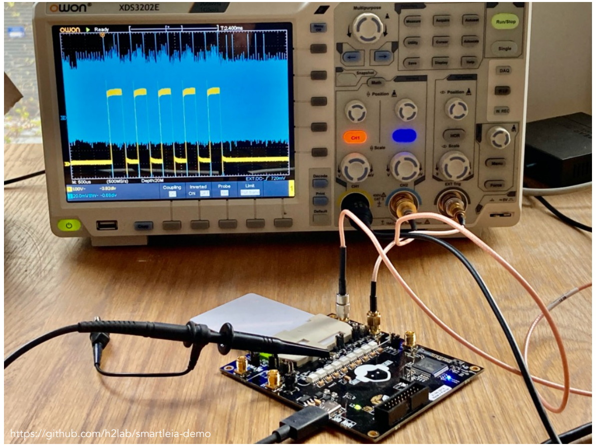
Power Side-Channel Attacks

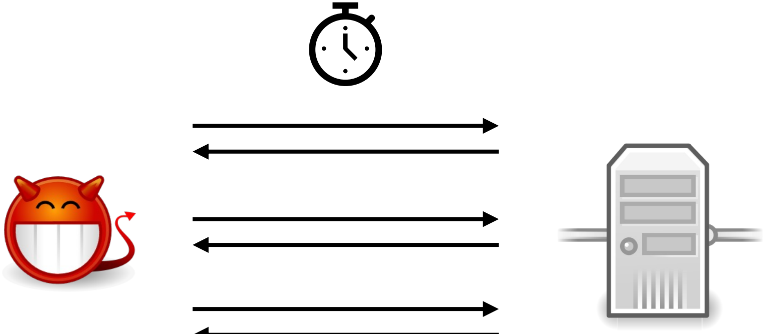


Power Side Channel vs Remote Timing

Power Side-Channel Attacks



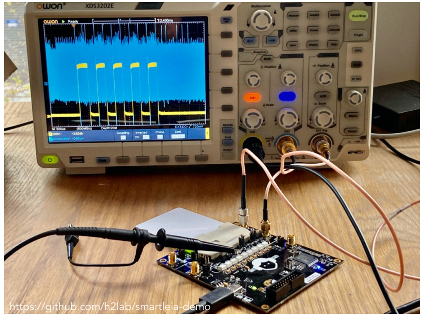
Remote Timing Attacks

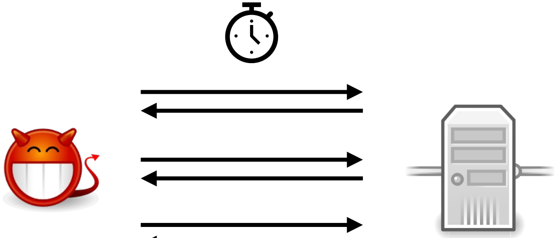


Hertzbleed: a New Class of Attacks

Power Side-Channel Attacks

Remote Timing Attacks





Hertzbleed: a New Class of Attacks

Power Side-Channel Attacks

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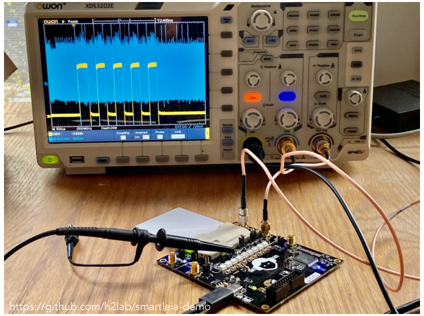

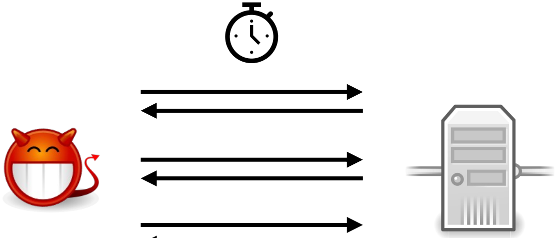

Hertzbleed: exploiting
dynamic frequency scaling (DVFS)

DVFS on a modern Intel CPU

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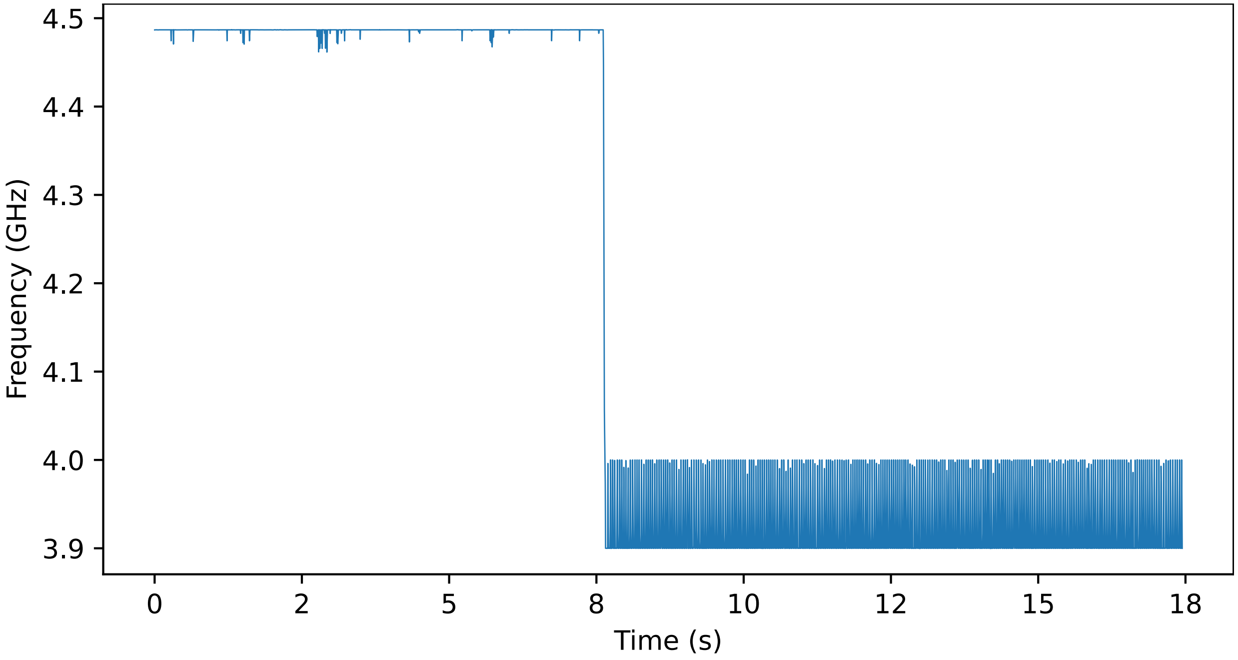
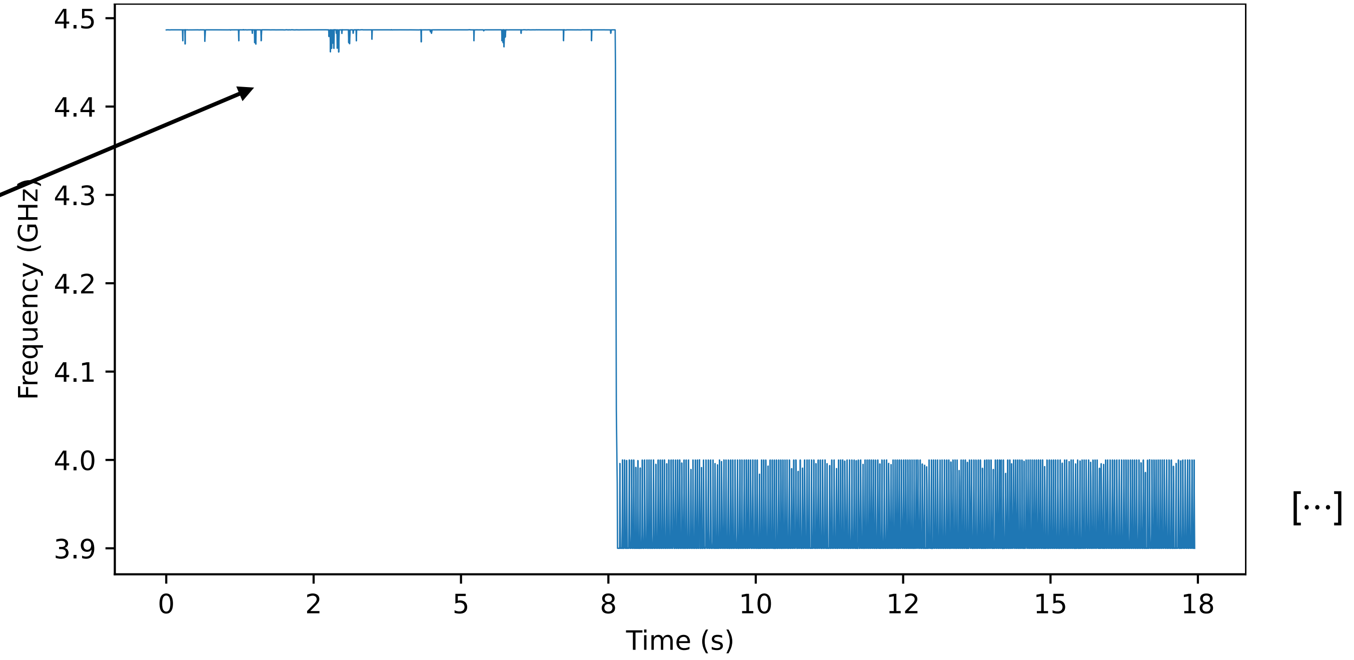


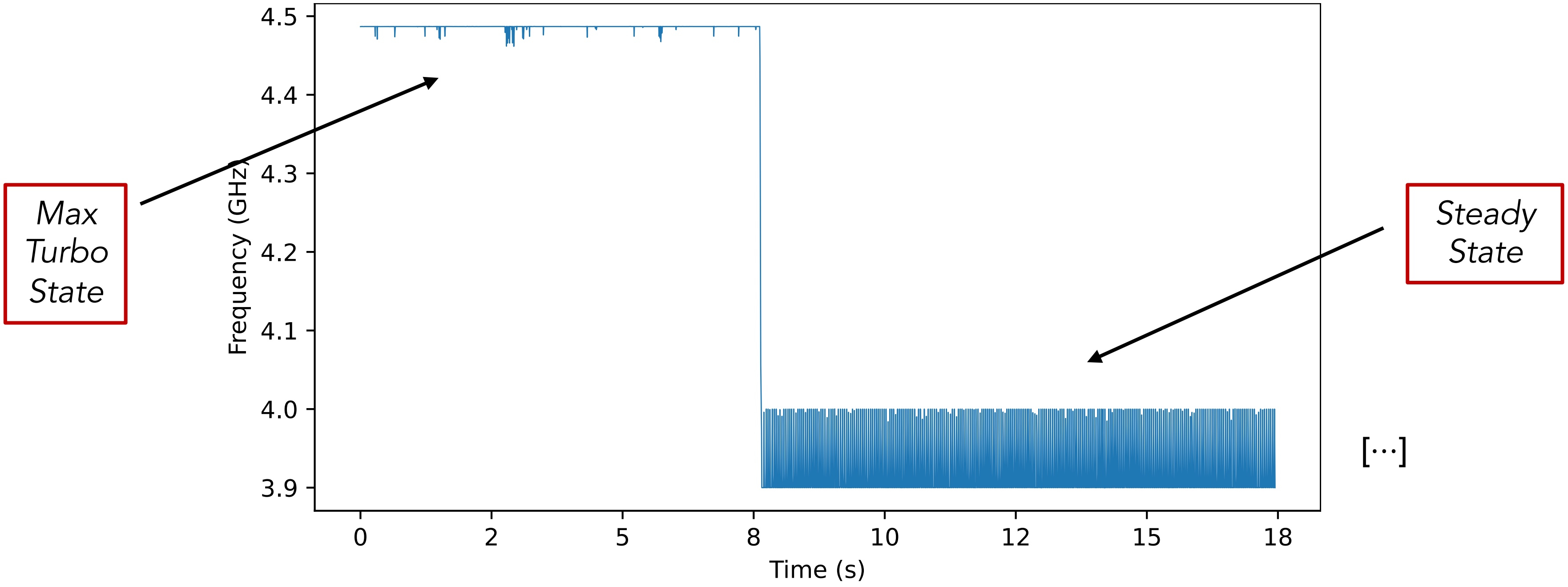
[···]

DVFS on a modern Intel CPU

Max Turbo State



DVFS on a modern Intel CPU



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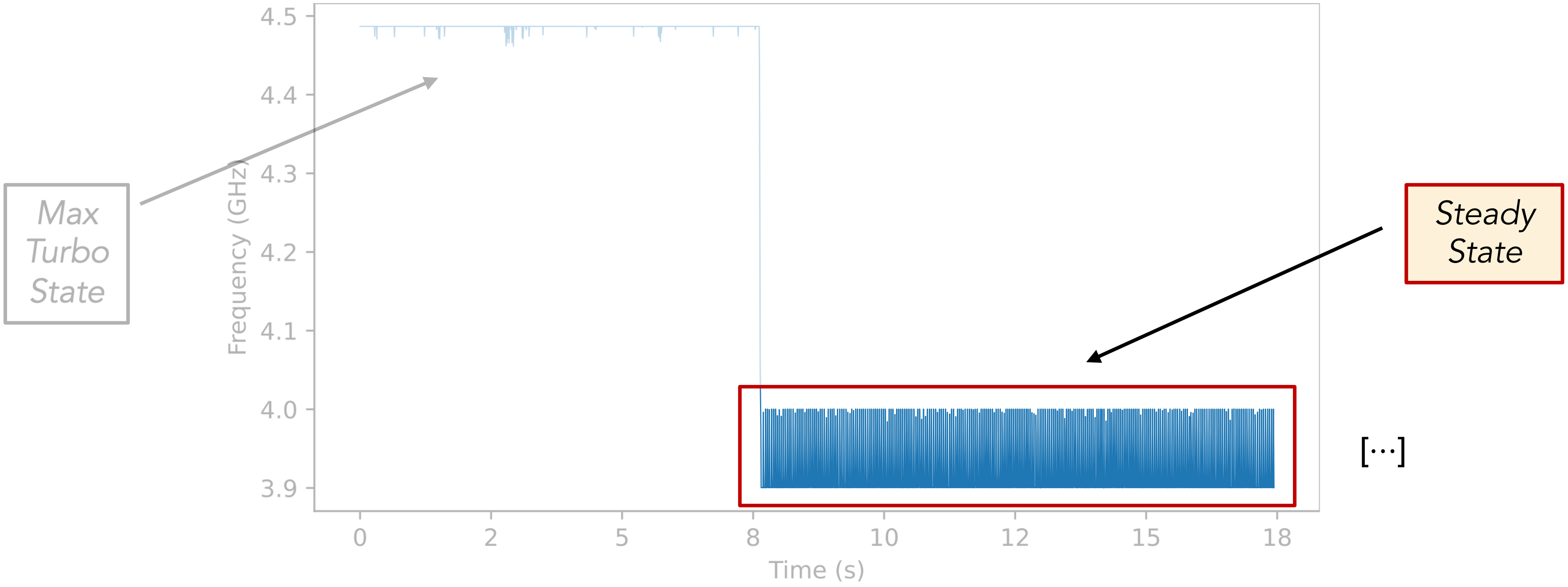

Frequency Depends on Power

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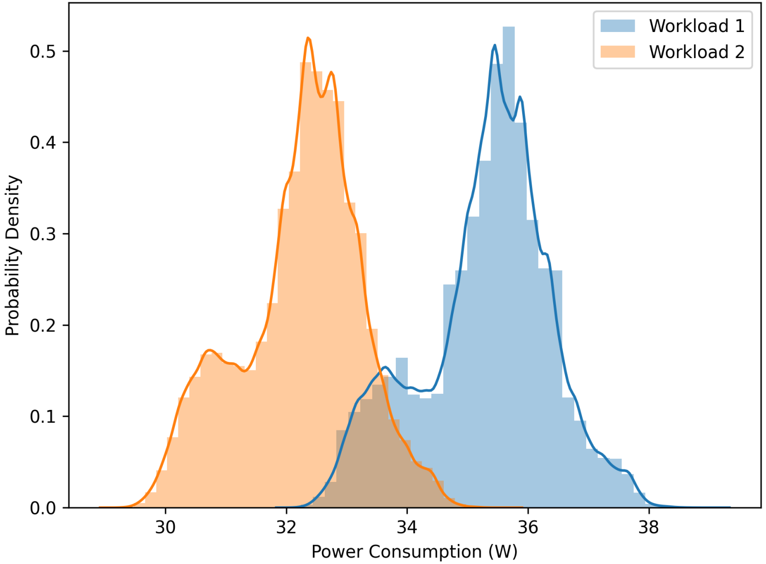
Power Consumption



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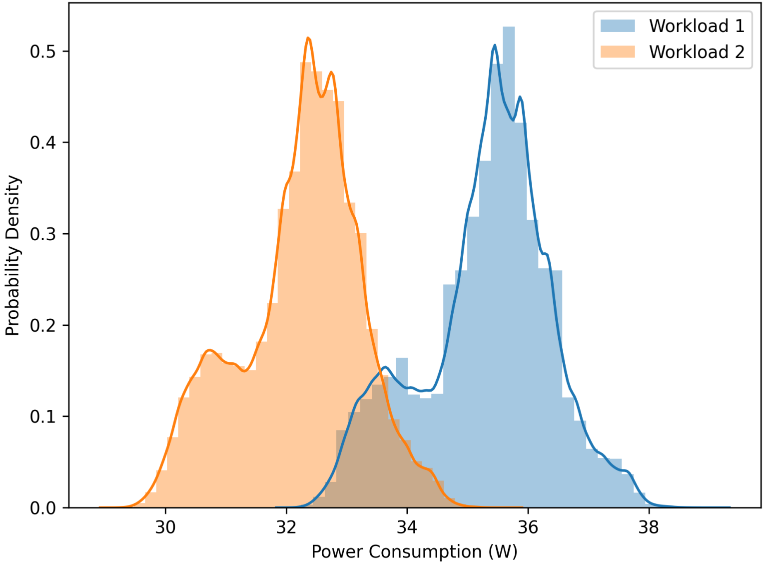
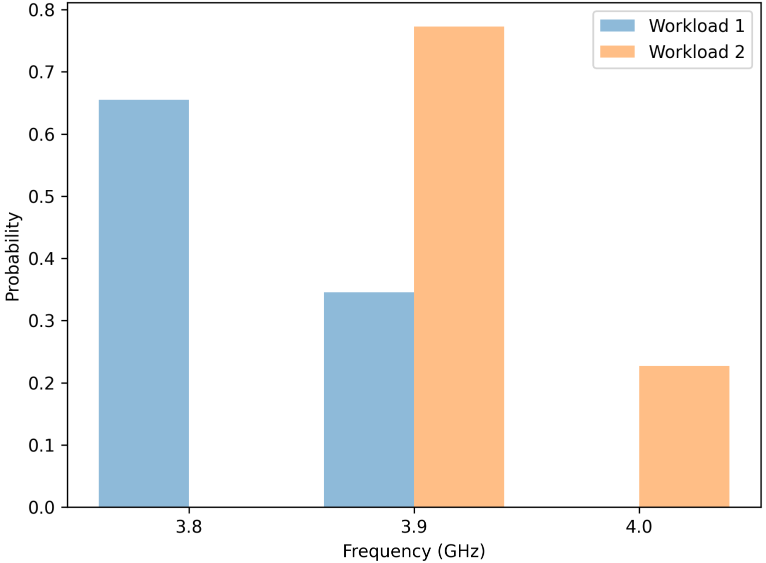


CPU Frequency



Frequency Depends on Data

- Only vary the data values being processed (“Input”).

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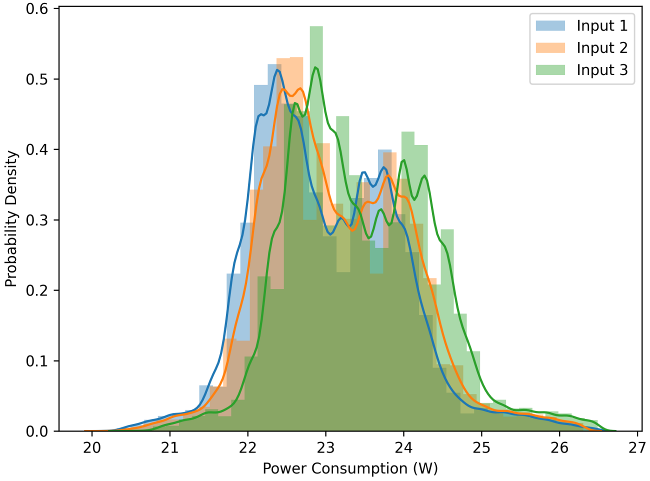

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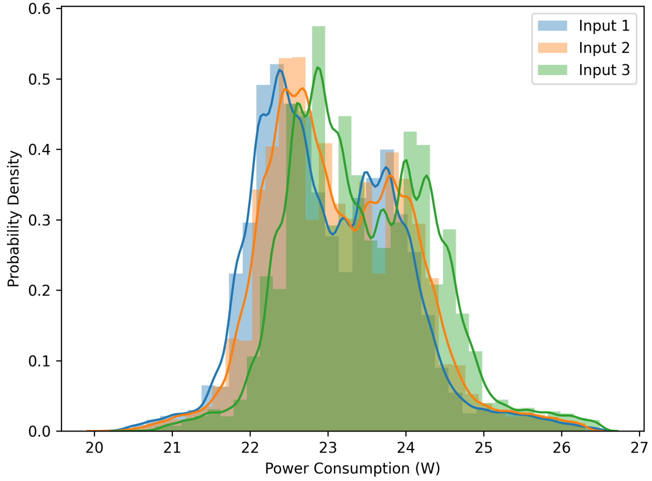
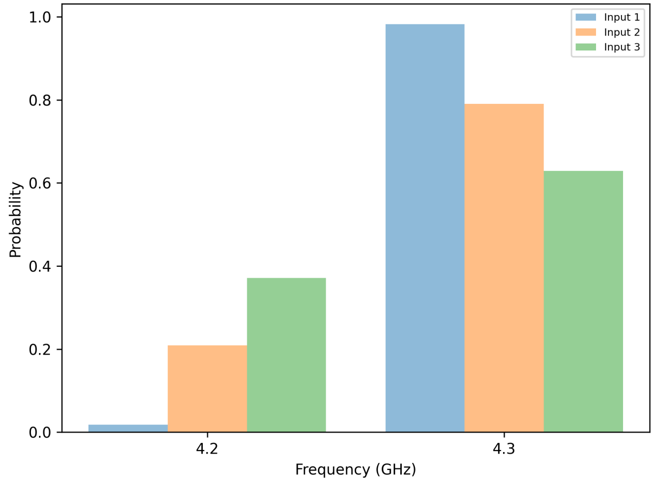


CPU Frequency



Example of Data-Dependent Frequency

```
Function Sum(first, second):
    a = first
    b = second
    sum = a + b
    return sum
```

Example of Data-Dependent Frequency

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  a = first
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Test 1 (CVE 1 number)**:**
first = 2022
second = 23823

Example of Data-Dependent Frequency

Function `Sum`(*first*, *second*):
  a = first
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  sum = a + b
  return sum

Test 1 (CVE 1 number):
first = 2022
second = 23823

Test 2 (CVE 2 number):
first = 2022
second = 24436

Example of Data-Dependent Frequency

Function `Sum`(*first*, *second*):

$$a = \text{first}$$

$$b = \text{second}$$

$$\text{sum} = a + b$$

return sum

Test 1 (CVE 1 number):

first = 2022

second = 23823

Test 2 (CVE 2 number):

first = 2022

second = 24436

Which Runs at a Higher Frequency?

Example of Data-Dependent Frequency

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Test 1 (CVE 1 number):
first = 2022
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Test 2 (CVE 2 number):
first = 2022
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Which Runs at a Higher Frequency?

We construct a *leakage model*
to answer this question.

Frequency Leakage Model

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Three *independent* effects:

1. Hamming distance (HD)
2. Hamming weight (HW)
3. Bit positions!

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```
ax ← 0000000011111111
ax ← 0001111111100000
```

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HD = 10

Frequency Leakage Model

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```
ax ← 0000000011111111
ax ← 0001111111100000
```

HD = 10

```
ax ← 0000000011111111
ax ← 0000011111111000
```

HD = 6

Frequency Leakage Model

Three *independent* effects:

1. **Hamming distance (HD)**
2. Hamming weight (HW)
3. Bit positions!

ax ← 0000000011111111
ax ← 0001111111100000

HD = 10

Consumes less power

Runs at a higher frequency!

→

ax ← 0000000011111111
ax ← 0000011111111000

HD = 6

Frequency Leakage Model

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1. Hamming distance (HD)
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Frequency Leakage Model

Three *independent* effects:

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```
ax ← 1111001111001111
ax ← ax | ax
```

Frequency Leakage Model

Three *independent* effects:

1. Hamming distance (HD)
2. **Hamming weight (HW)**
3. Bit positions!

```
ax ← 1111001111001111
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```

HW = 12

Frequency Leakage Model

Three *independent* effects:

1. Hamming distance (HD)
2. Hamming weight (HW)
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```
ax ← 1111001111001111
ax ← ax | ax
```

HW = 12

```
ax ← 1100110011001100
ax ← ax | ax
```

HW = 8

Frequency Leakage Model

Three *independent* effects:

1. Hamming distance (HD)
2. **Hamming weight (HW)**
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```
ax ← 1111001111001111
ax ← ax | ax
```

HW = 12

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Runs at a higher frequency!

→

```
ax ← 1100110011001100
ax ← ax | ax
```

HW = 8

Frequency Leakage Model

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`ax ← 1111111100000000`

`ax ← ax | ax`

HW = 8

Frequency Leakage Model

Three *independent* effects:

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Frequency Leakage Model

Three *independent* effects:

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ax ← 1111111100000000

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HW = 8

Case Study: Bit Positions

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```
rax = rcx = … = r11 = INPUT
loop:
  or %rax,%rcx     // rcx = rax | rcx
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  or %rax,%rsi     // rsi = rax | rsi
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jmp loop
```

We control `INPUT`.

Case Study: Bit Positions

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We control `INPUT`.

- HD = 0
- HW: # of 1s in `INPUT`
- Bit positions: positions of 1s in `INPUT`

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rax = rcx = … = r11 = INPUT
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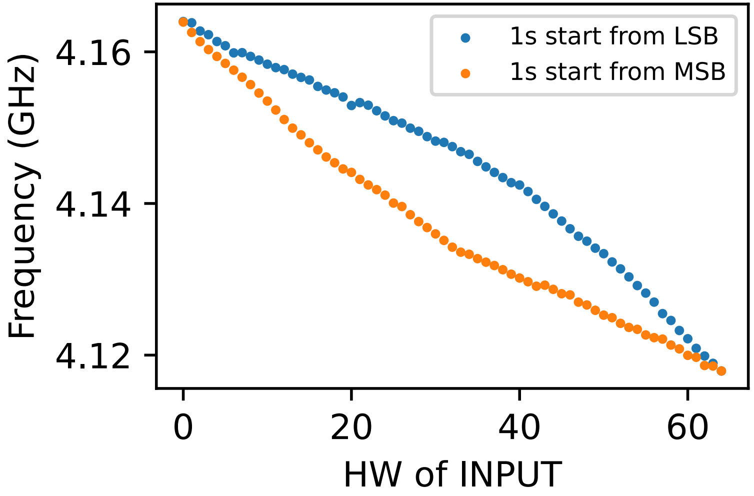

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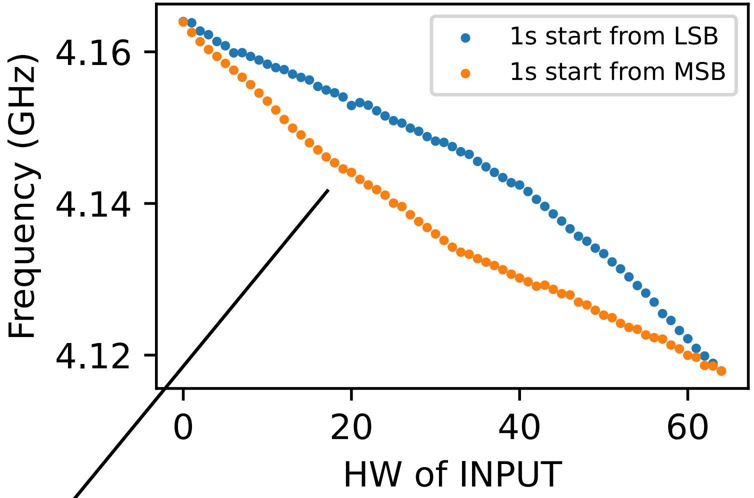

nonlinear?

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Delta freq between setting byte *i* to `0xff` (all 1s) and `0x00` (all 0s).

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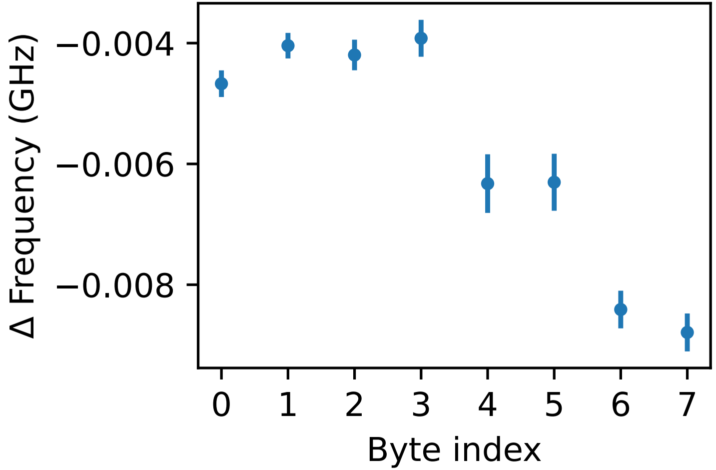

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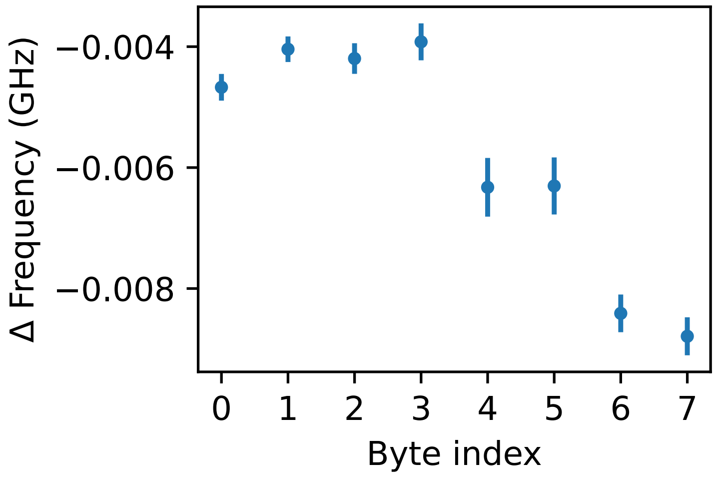
1s in the most significant bytes affect frequency (and power) more than 1s in the least significant bytes!

Delta freq between setting byte *i* to `0xff` (all 1s) and `0x00` (all 0s).



More experiments in the paper!

- We also show that these effects are ***independent*** and ***additive***.

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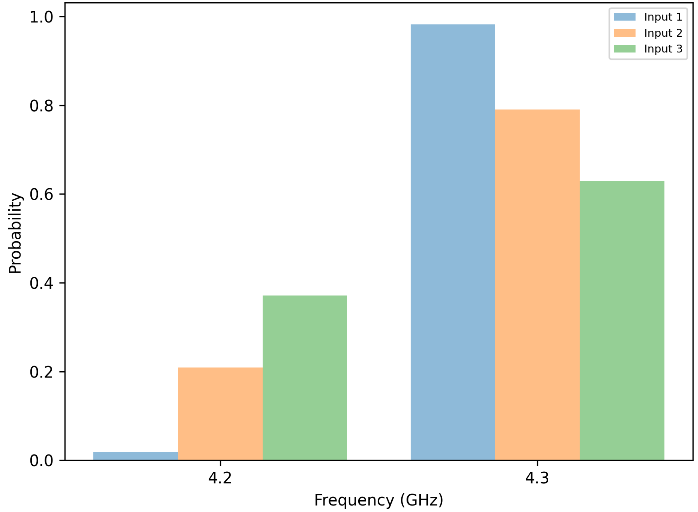
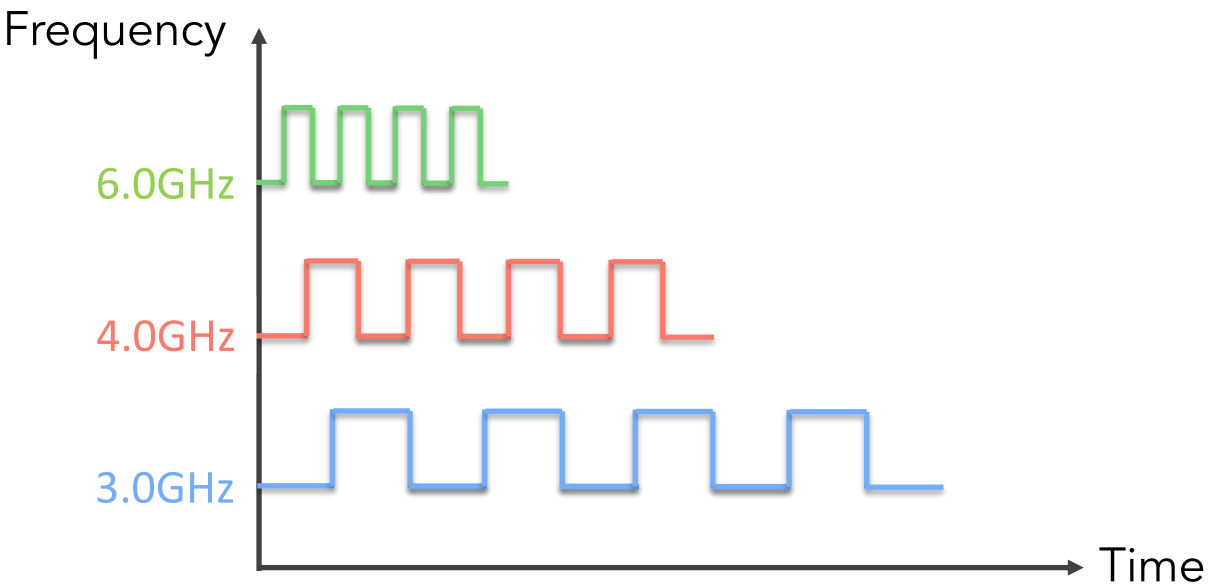
- We also show that these effects are ***independent*** and ***additive***.
- <u>Takeaway so far</u>: computing on data with different HD, HW, or bit patterns can result in different CPU frequencies



Frequency Shows Through Timing!



Supersingular Isogeny Key Encapsulation

- SIKE: public key encryption scheme used to secure a shared key

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  - A key generation algorithm: $(pk, sk) \leftarrow \texttt{KeyGen}()$
  - An encapsulation algorithm: $(k, c) \leftarrow \texttt{Encaps}(pk)$
  - A decapsulation algorithm: $k \leftarrow \texttt{Decaps}(sk, c)$

Supersingular Isogeny Key Encapsulation

- SIKE: public key encryption scheme used to secure a shared key
  - A key generation algorithm: $(pk, sk) \leftarrow$ `KeyGen`()
  - An encapsulation algorithm: $(k, c) \leftarrow$ `Encaps`(pk)
  - A decapsulation algorithm: $k \leftarrow$ `Decaps`(sk, c)
    - c can be anything

SIKE is a widely studied PQC scheme

CLOUDFLARE

Introducing CIRCL: An Advanced Cryptographic Library

06/20/2019

microsoft/
PQCrypto-SIDH

SIDH Library is a fast and portable software library that implements state-of-the-art supersingular isogeny cryptographic schemes. The chosen parameters aim...

NIST

PQC Standardization Process: Announcing Four Candidates to be Standardized, Plus Fourth Round Candidates

July 05, 2022

AWS KMS and ACM now support the latest hybrid post-quantum TLS ciphers

Posted On: Mar 16, 2022

aws

SIKE Attack Overview

$c' \rightarrow$ `Decapsulation(sk)`

SIKE Attack Overview

$c' \to$ `Decapsulation(sk)`

First bit = 0

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[18257987050416722270 10199691716891914004 5400919966884858033 442692516914010372 12773429574585753468 6570432586462705433
[18257987050416722270 10199691716891914004 5400919966884858033 442692516914010372 12773429574585753468 6570432586462705433
[16825517838011775506 9371345100327880239 15742012313593718125 10072166590248559322 4496384122748719145 4334614431051425958
[16825517838011775506 9371345100327880239 15742012313593718125 10072166590248559322 4496384122748719145 4334614431051425958
[16740411979447774187 12800619824809723005 10853297027917591334 14982452220610001381 3800581514987461454 14564706225204848 9
[16825517838011775506 9371345100327880239 15742012313593718125 10072166590248559322 4496384122748719145 4334614431051425958
[15266560997122586383 12357889650077672103 2140980805765852605 11095593088850010277 4943695249444786644 3789592123877698465
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[6399333684299274457 13212325817985983642 17337857241394967822 17279086886397221 17809839742204337052 1762074623773052795 5
[16825517838011775506 9371345100327880239 15742012313593718125 10072166590248559322 4496384122748719145 4334614431051425958
[7661921139160543741 14707234213449645962 12995640548762497303 6366902398648164883 8159614558565625434 1699352089132060401
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[14502626884453394147 15471763763527174 74 16458194833336887993 11353529865322400496 18111664530210683277 14913675946160555 3
[16825517838011775506 9371345100327880239 15742012313593718125 10072166590248559322 4496384122748719145 4334614431051425958
[16292054110271644132 16402476987519138840 15295718925489978418 11943223229381717154 3939738083047782821 7326838894173812 78
[16825517838011775506 9371345100327880239 15742012313593718125 10072166590248559322 4496384122748719145 4334614431051425958
[3109004547777643616 11545393661624748910 13937898936545491063 17877233530308340276 12362683729304085816 13533668621992669 0
[16825517838011775506 9371345100327880239 15742012313593718125 10072166590248559322 4496384122748719145 4334614431051425958
[14038051704368540915 5562911119597974536 6094927895374002108 15637883509309970852 13225965834113072042 16448264607636784 36
[16825517838011775506 9371345100327880239 15742012313593718125 10072166590248559322 4496384122748719145 4334614431051425958
[18026979082695398473 4545160433979536065 8917105521003255669 8960042842321690905 14664092097322583836 17637668258660114635
[18026979082695398473 4545160433979536065 8917105521003255669 8960042842321690905 14664092097322583836 17637668258660114635
[11077978705126494 49 3973889343021377473 15397880414487620049 16447202818859113108 13000223568372994767 11226627242531480 57
[11077978705126494 49 3973889343021377473 15397880414487620049 16447202818859113108 13000223568372994767 11226627242531480 57
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[14258829650860490490 3159096382619497511 1628360891341362022 188059088762649621 3407697486830288305 5337080128759733026 67
[14258829650860490490 3159096382619497511 1628360891341362022 188059088762649621 3407697486830288305 5337080128759733026 67
[3595963780190459985 717527953757986 42 1255466713598110361 7 1100338600145278727 9 1659580706669562711 0 1628175452102986565 2
[3595963780190459985 717527953757986 42 1255466713598110361 7 1100338600145278727 9 1659580706669562711 0 1628175452102986565 2
[16439123124117376047 9302501002909150857 16313838798130370411 3270836818630356446 2783122717285403776 1391244912843384146 1
[3595963780190459985 717527953757986 42 1255466713598110361 7 1100338600145278727 9 1659580706669562711 0 1628175452102986565 2
```

SIKE Attack Overview

$c' \rightarrow$ `Decapsulation(sk)`

First bit = 0

First bit = 1


```
[18257987050416722270 10199691716891914004 5400919966884858033 442692516914010372 12773429574585753468 6570432586462705433
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```

SIKE Attack Overview

`c′ → Decapsulation(sk)`

First bit = 0


```
[18257987050416722270 10199691716891914004 5400919966884858033 442692516914010372 12773429574585753468 6570432586462705433
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```


First bit = 1


```
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```

SIKE Attack Overview

$c' \rightarrow$ `Decapsulation(sk)`

First bit = 0

$a = a \times R_1$
$a = a \times R_2$
$a = a \times R_3$
…
$a = a \times R_n$

First bit = 1

$a = a \times 0$
$a = a \times R_2$
$a = a \times R_3$
…
$a = a \times R_n$

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$a = a \times R_3$
...
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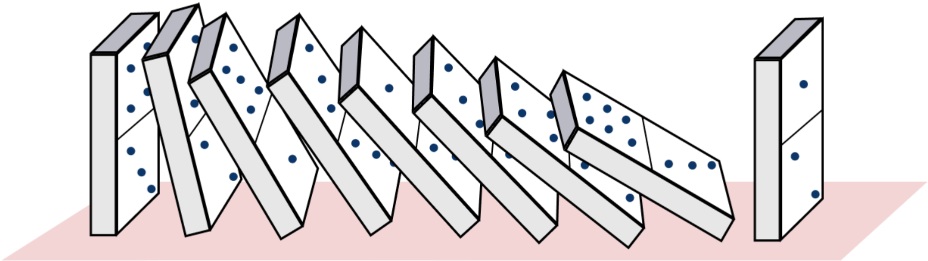

SIKE Attack Overview

$c' \rightarrow$ `Decapsulation(sk)`

First bit = 0

$a = a \times R_1$
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$a = a \times R_3$
…
$a = a \times R_n$

More power
Lower frequency
Longer runtime

First bit = 1

$a = a \times 0$
$a = a \times R_2$
$a = a \times R_3$
…
$a = a \times R_n$

Less power
Higher frequency
Shorter runtime

An Important Step of SIKE's Decapsulation

Algorithm 8: Three point ladder

function `Ladder3pt`

Input: $m = (m_{\ell-1}, \ldots, m_0)_2 \in \mathbb{Z}$, (x_P, x_Q, x_{Q-P}), and $(A : 1)$

Output: $(X_{P+[m]Q} : Z_{P+[m]Q})$

$((X_0 : Z_0), (X_1 : Z_1), (X_2 : Z_2)) \leftarrow ((x_Q : 1), (x_P : 1), (x_{Q-P} : 1))$

$a_{24}^{+} \leftarrow (A + 2)/4$

for $i = 0$ **to** $\ell - 1$ **do**

  if $m_i = 1$ **then**

    $((X_0 : Z_0), (X_1 : Z_1)) \leftarrow \texttt{xDBLADD}((X_0 : Z_0), (X_1 : Z_1), (X_2 : Z_2), (a_{24}^{+} : 1))$

  else

    $((X_0 : Z_0), (X_2 : Z_2)) \leftarrow \texttt{xDBLADD}((X_0 : Z_0), (X_2 : Z_2), (X_1 : Z_1), (a_{24}^{+} : 1))$

return $(X_1 : Z_1)$

Taken from SIKE's specification
Actual implementation has **no branches**

An Important Step of SIKE's Decapsulation

Algorithm 8: Three point ladder

```
function Ladder3pt
    Input: m = (m_{ℓ-1}, ..., m_0)_2 ∈ ℤ, (x_P, x_Q, x_{Q-P}), and (A : 1)
    Output: (X_{P+[m]Q} : Z_{P+[m]Q})
((X_0 : Z_0), (X_1 : Z_1), (X_2 : Z_2)) ← ((x_Q : 1), (x_P : 1), (x_{Q-P} : 1))
a24+ ← (A + 2)/4
for i = 0 to ℓ − 1 do
    if m_i = 1 then
        ((X_0 : Z_0), (X_1 : Z_1)) ← xDBLADD((X_0 : Z_0), (X_1 : Z_1), (X_2 : Z_2), (a24+ : 1))
    else
        ((X_0 : Z_0), (X_2 : Z_2)) ← xDBLADD((X_0 : Z_0), (X_2 : Z_2), (X_1 : Z_1), (a24+ : 1))
return (X_1 : Z_1)
```

Taken from SIKE's specification
Actual implementation has no branches

m is the (static) secret key

P and *Q* are points included in the ciphertext

An Important Step of SIKE's Decapsulation

Algorithm 8: Three point ladder

```
function Ladder3pt
    Input: m = (m_{ℓ-1}, ..., m_0)_2 ∈ Z, (x_P, x_Q, x_{Q-P}), and (A : 1)
    Output: (X_{P+[m]Q} : Z_{P+[m]Q})
((X_0 : Z_0), (X_1 : Z_1), (X_2 : Z_2)) ← ((x_Q : 1), (x_P : 1), (x_{Q-P} : 1))
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    else
        ((X_0 : Z_0), (X_2 : Z_2)) ← xDBLADD((X_0 : Z_0), (X_2 : Z_2), (X_1 : Z_1), (a^+_{24} : 1))
return (X_1 : Z_1)
```

Taken from SIKE's specification
Actual implementation has no branches

m is the (static) secret key

P and *Q* are points included in the ciphertext

At each loop iteration, the data flow depends on *P*, *Q* and m_i

An Important Step of SIKE's Decapsulation

$2U,\ U{+}V \leftarrow$ `xDBLADD(` U, V, W `)` where $W = U - V$

An Important Step of SIKE's Decapsulation

$$2U,\ U{+}V \leftarrow \texttt{xDBLADD}(U, V, W) \quad \text{where} \quad W = U - V$$

$W \in \{ T, O \}$ → $2U,\ (0{:}0) \leftarrow \texttt{xDBLADD}(U, V, W)$

An Important Step of SIKE's Decapsulation

$2U,\ U+V \leftarrow$ `xDBLADD`(U, V, W) where $W = U - V$

W ∈ { T, O } → $2U,\ (0{:}0) \leftarrow$ `xDBLADD`(U, V, W)

(0:0) is not a point

An Important Step of SIKE's Decapsulation

$2U,\ U+V \leftarrow$ `xDBLADD(` U, V, W `)` where $W = U - V$

$W \in \{ T, O \}$ → $2U,\ (0{:}0) \leftarrow$ `xDBLADD(` U, V, W `)`

$(0{:}0)$ is not a point

U or V or $W = (0{:}0)$ → $2U,\ (0{:}0) \leftarrow$ `xDBLADD(` U, V, W `)`

An Important Step of SIKE's Decapsulation

Algorithm 8: Three point ladder

function Ladder3pt

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Output: $(X_{P+[m]Q} : Z_{P+[m]Q})$

$((X_0 : Z_0), (X_1 : Z_1), (X_2 : Z_2)) \leftarrow ((x_Q : 1), (x_P : 1), (x_{Q-P} : 1))$

$a_{24}^{+} \leftarrow (A + 2)/4$

for $i = 0$ **to** $\ell - 1$ **do**

  if $m_i = 1$ **then**

    $((X_0 : Z_0), (X_1 : Z_1)) \leftarrow \texttt{xDBLADD}((X_0 : Z_0), (X_1 : Z_1), (X_2 : Z_2), (a_{24}^{+} : 1))$

  else

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return $(X_1 : Z_1)$

Taken from SIKE's specification
Actual implementation has no branches

An Important Step of SIKE's Decapsulation

Iteration *i*

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T or O

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$(0{:}0)$

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(0:0) T or O

$2U, (0{:}0) \leftarrow \texttt{xDBLADD}(U, V, W)$ if $W \in \{T, O\}$

An Important Step of SIKE's Decapsulation

Iteration i+1

for $i = 0$ **to** $\ell - 1$ **do**
  if $m_i = 1$ **then**
    $((X_0 : Z_0), (X_1 : Z_1)) \leftarrow \texttt{xDBLADD}((X_0 : Z_0), (X_1 : Z_1), (X_2 : Z_2), (a_{24}^{+} : 1))$
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(0:0)

An Important Step of SIKE's Decapsulation

Iteration $i+1$

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(0:0)   (0:0)   (0:0)

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$2U, (0{:}0) \leftarrow \texttt{xDBLADD}(U, V, W)$ if U or V or $W = (0{:}0)$

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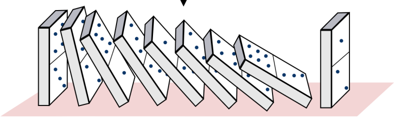

T or O

Adaptive Chosen-Ciphertext Attack Idea

$$\mu_i = (m_i, \ldots, m_0)_2$$

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```
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```

μ_{k-1} ✓

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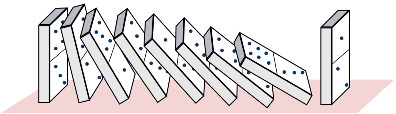

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μ_{k-1} ✓ → Ciphertext c′

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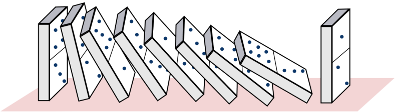
- $m_k = m_{k-1}$ → T



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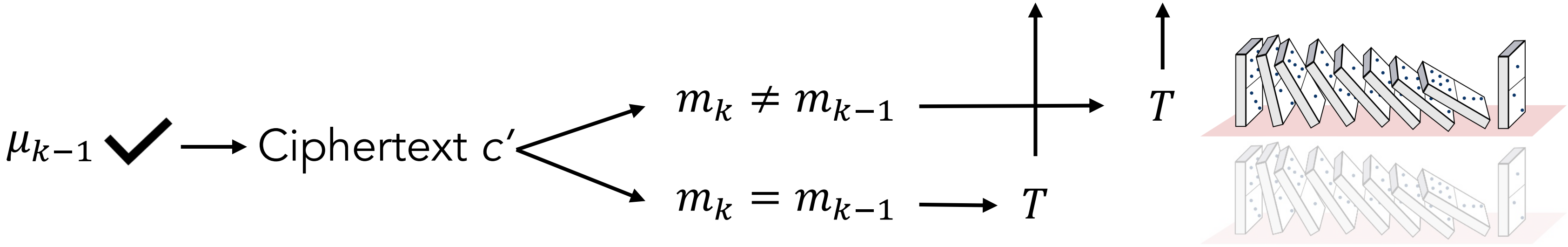

Adaptive Chosen-Ciphertext Attack Idea

- An attacker who knows the i least significant bits of m (the key) can construct ciphertext c′ such that:

Adaptive Chosen-Ciphertext Attack Idea

- An attacker who knows the *i* least significant bits of *m* (the key) can construct ciphertext c′ such that:
  - If $m_i \neq m_{i-1}$
  - If $m_i = m_{i-1}$

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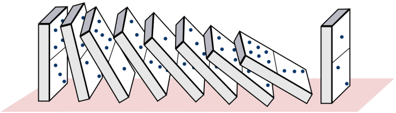

Data flow has low HW and low HD →
lower power consumption →
higher frequency →
shorter runtime!

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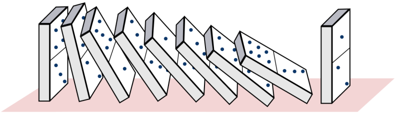

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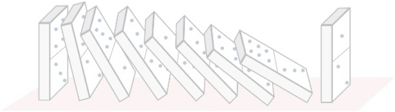
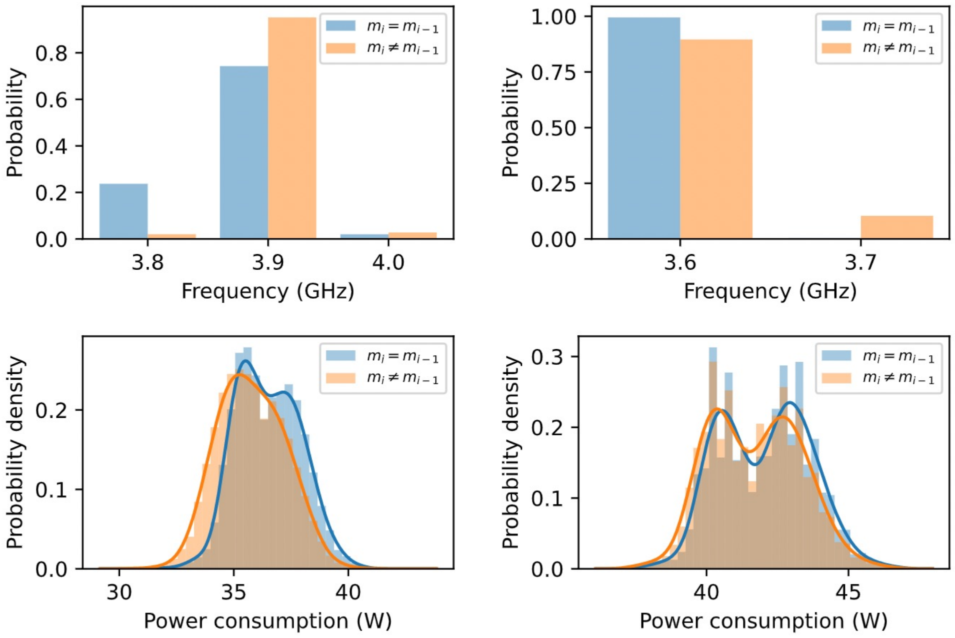


Data flow does not have low HW and low HD
→ higher power consumption →
lower frequency →
longer runtime!

Target Implementation

- Cloudflare's CIRCL (Go)
- Microsoft's PQCrypto-SIDH (C)
  - NIST Post-Quantum Cryptography competition submission

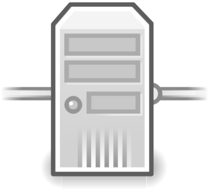
Frequency and Power Measurement



(a) CIRCL data (b) PQCrypto-SIDH data

Remote Timing Attack Model

Client



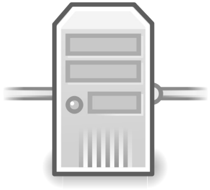
Server

Remote Timing Attack Model

`Decap`(sk, c’)

Ciphertext c’ →

Client



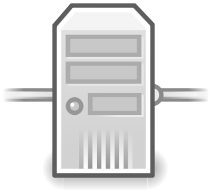
Server

CIRCL
PQCrypto-SIDH

Remote Timing Attack Model

`Decap`(sk, c′)

Ciphertext c′

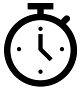


ACK!

Client

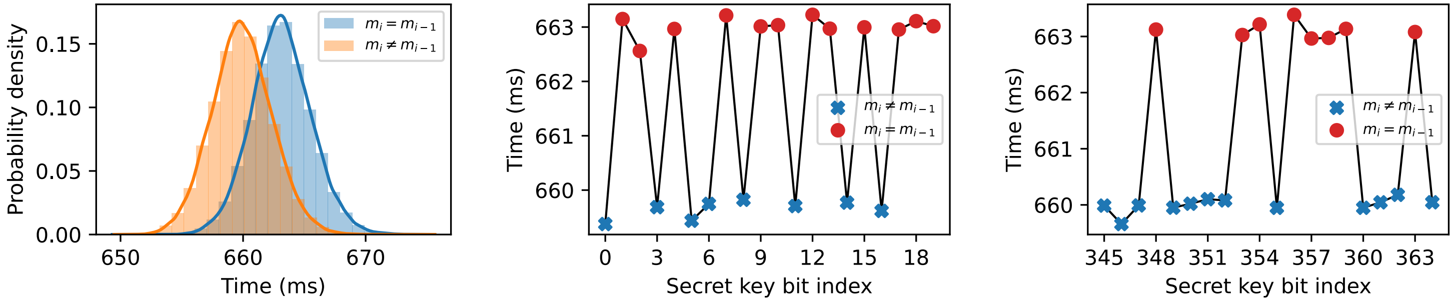
Server

How long it takes to finish *n* concurrent requests



CIRCL
PQCrypto-SIDH

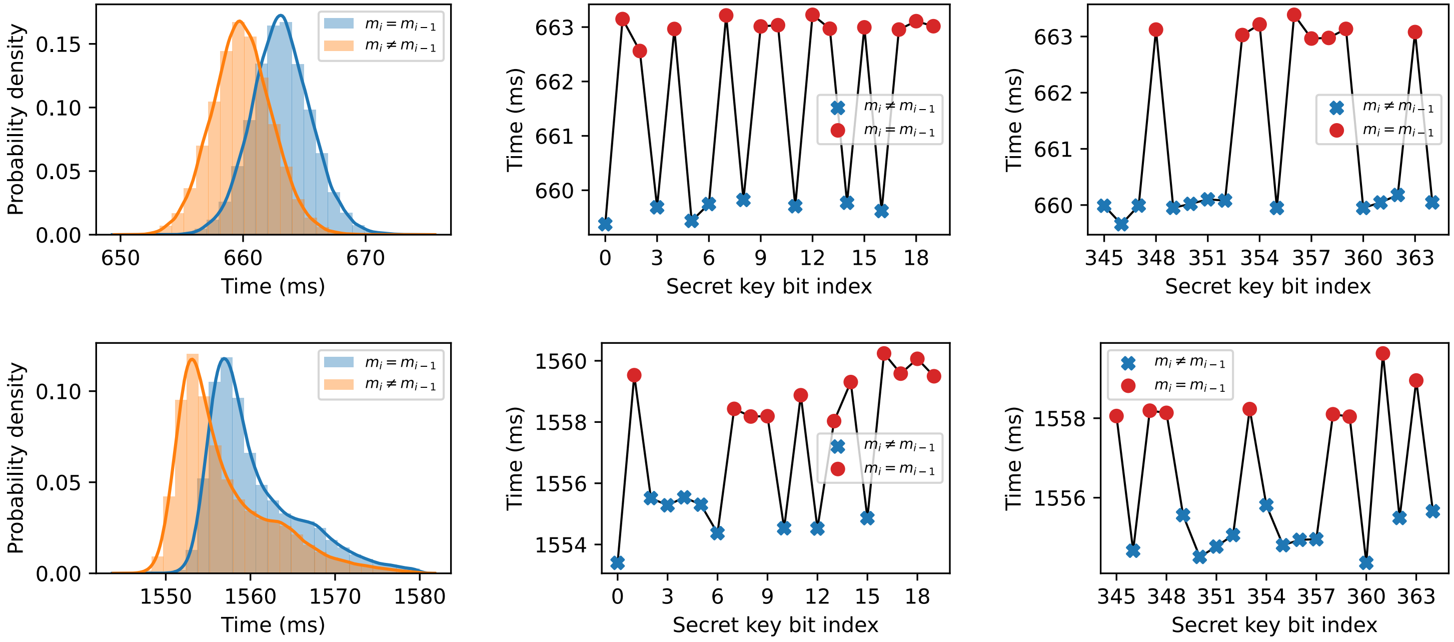
Remote Timing Attack Results



CIRCL:

Recovered full key in 36 hours

Remote Timing Attack Results



CIRCL:
Recovered full key in 36 hours

PQCrypto-SIDH:
Recovered full key in 89 hours

Discussion & Takeaway

Discussion & Takeaway

$$\text{if } secret == 1 \text{ then} \quad routine();$$

No secret-dependent branches

$$state = array[secret]$$

No secret-dependent memory accesses

$$res = x * secret \ / \ 255.0\text{f}$$

No secret inputs to variable-time instructions

Discussion & Takeaway

- Current practices for how to write constant-time code are no longer sufficient to guarantee constant-time execution.

$$\text{if } \mathit{secret} == 1 \text{ then } \mathit{routine}();$$

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$$\mathit{state} = \mathit{array[secret]}$$

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Discussion & Takeaway

- Current practices for how to write constant-time code are no longer sufficient to guarantee constant-time execution.
- Hertzbleed turns power leakage into timing leakage.

$$\text{if } \mathit{secret} == 1 \text{ then} \quad \mathit{routine}();$$

No secret-dependent branches

$$\mathit{state} = \mathit{array}[\mathit{secret}]$$

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All prior timing attacks

Discussion & Takeaway

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All prior timing attacks

Hertzbleed

NEW

Conclusion

- Frequency leaks information about the data values being processed.
- SIKE is vulnerable to a new CCA attack that can be exploited remotely using Hertzbleed.
- Current practices for how to write constant-time code are no longer sufficient to guarantee constant time execution.

www.hertzbleed.com

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