ECC Protections against both Observation and Perturbation Attacks

Audrey LUCAS and Arnaud TISSERAND

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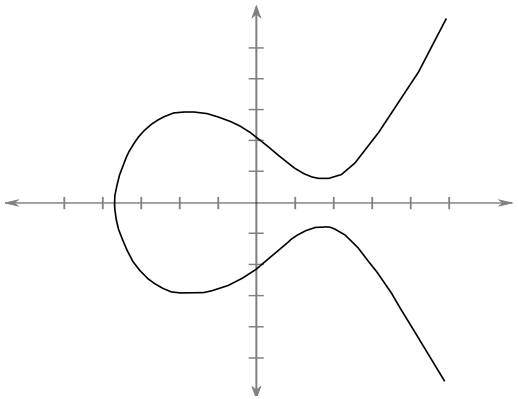
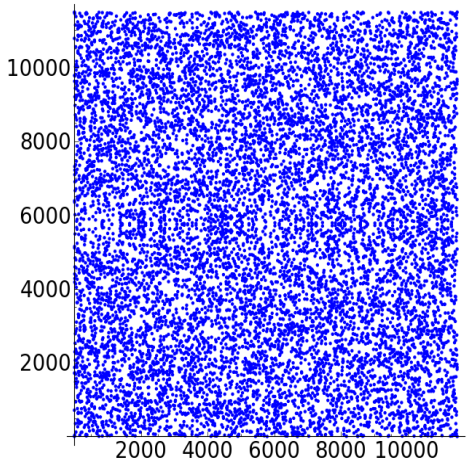
Outline

Elliptic Curves Cryptography (ECC) over $\mathbb{F}_p$



$$\Downarrow$$



$$E : y^2 = x^3 + ax + b$$

Point *doubling*: DBL

$$\neq$$

Point *addition*: ADD

Scalar multiplication

$$\Downarrow$$

$$[k]P = \underbrace{P + P + \ldots + P}_{k \text{ times}}$$

Scalar Multiplication Example: Double and Add

Require: P and $k = (k_{n-1}, \ldots, k_0)_2$.
Ensure: $[k]P$

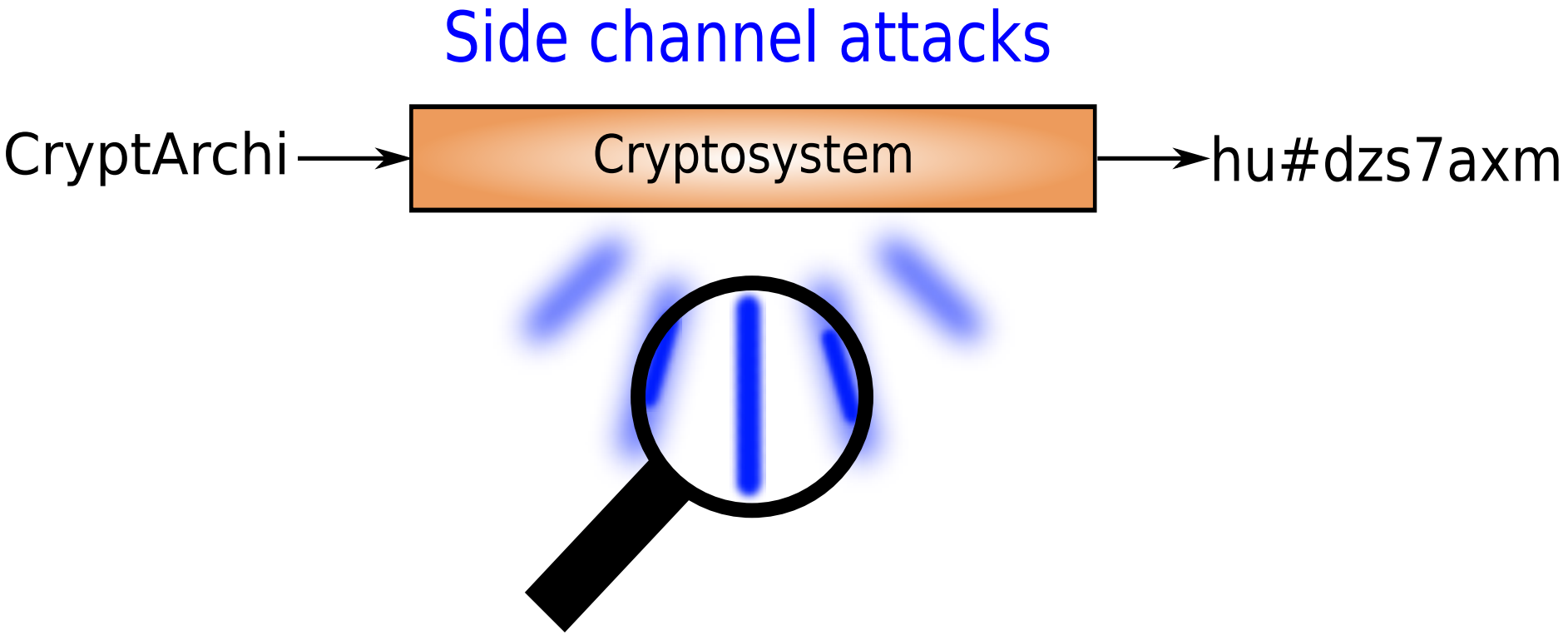
$Q \leftarrow \mathcal{O}$
for $i = n - 1$ **to** 0 **do**
  $Q \leftarrow 2 \cdot Q$
  if $k_i = 1$ **then**
    $Q \leftarrow P + Q$
return Q

1		0	0	0	1	
DBL	ADD	DBL	DBL	DBL	DBL	ADD

Physical Attacks

Observation: Side Channel Attacks (SCA)

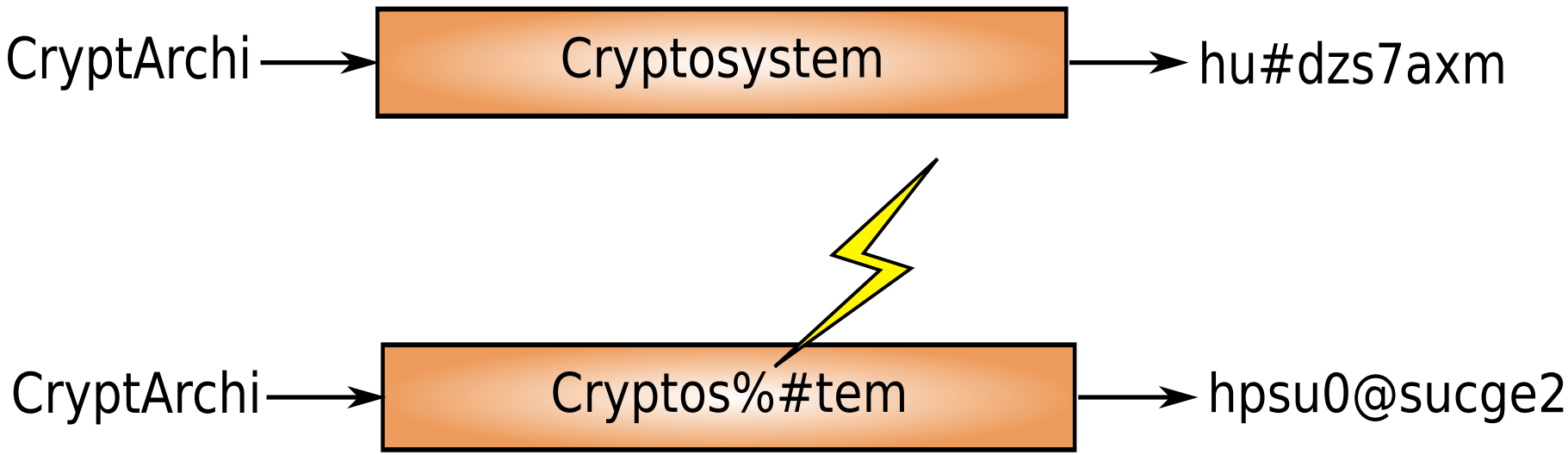
- Computation time, power consumption, ...
- Simple power analysis (SPA), differential power analysis (DPA), ...



Physical Attacks

Perturbation: Fault Attacks (FA)

- Clock, supply voltage, laser, ...
- Bit flip fault, stuck-at fault, ...
- Safe error, differential fault analysis (DFA), ...



Physical Attacks

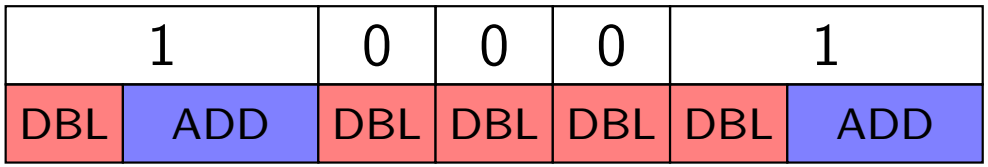
Countermeasures against SCAs

- Randomization: scalar masking, point blinding, scalar recoding, ...
- Uniformization: uniform curve, regular algorithm, ...
- Hardware: specific logic styles, reconfiguration, ...

Countermeasures against FAs

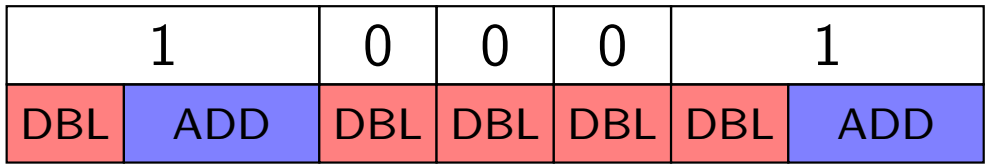
- Hardware: shielding, sensor, ...
- Redundancy calculation: time, space.
- ECC case: verification of point coordinates at the end of scalar multiplication.

Problem



Double and add

Problem



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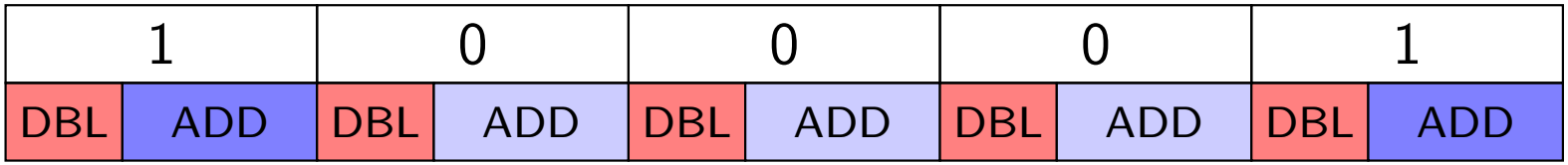
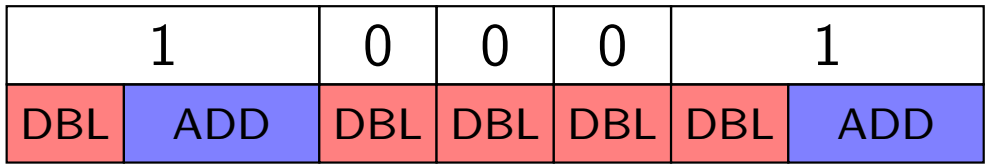
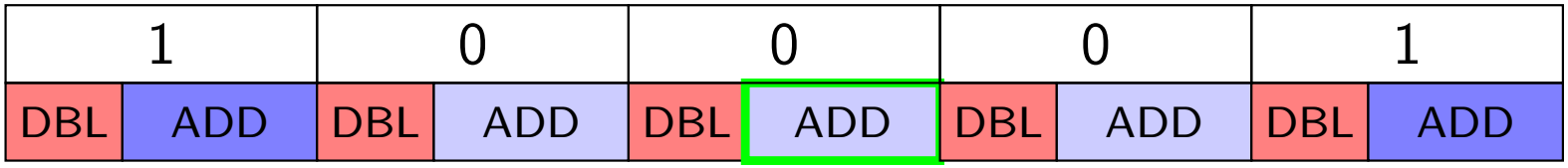


Double and add always

Problem



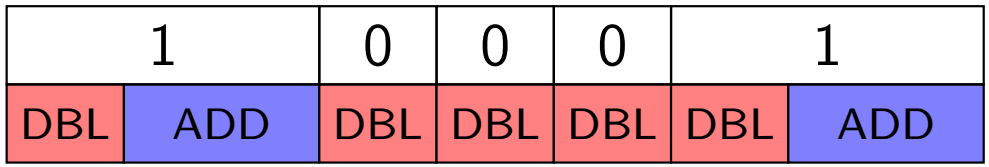
Double and add



Double and add always - safe error

Problem

Protection for one type of attacks may leave the system vulnerable on other type of attacks.



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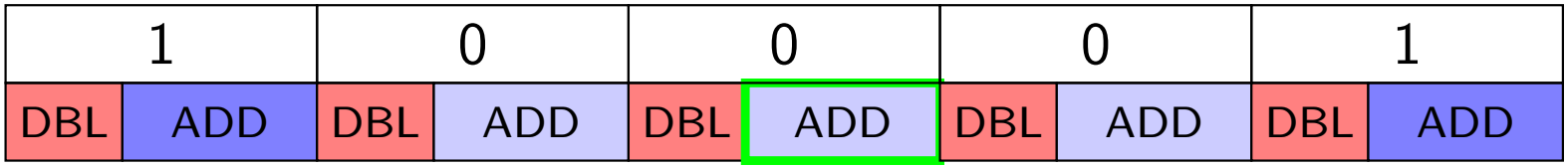

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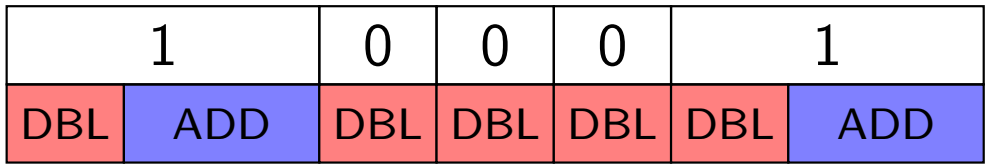

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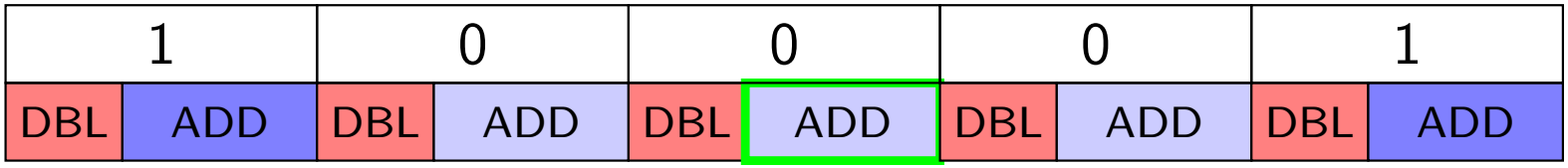


Double and add always - safe error

Protect the system from both types of attacks simultaneously.

Outline

Point Verification

Principle:

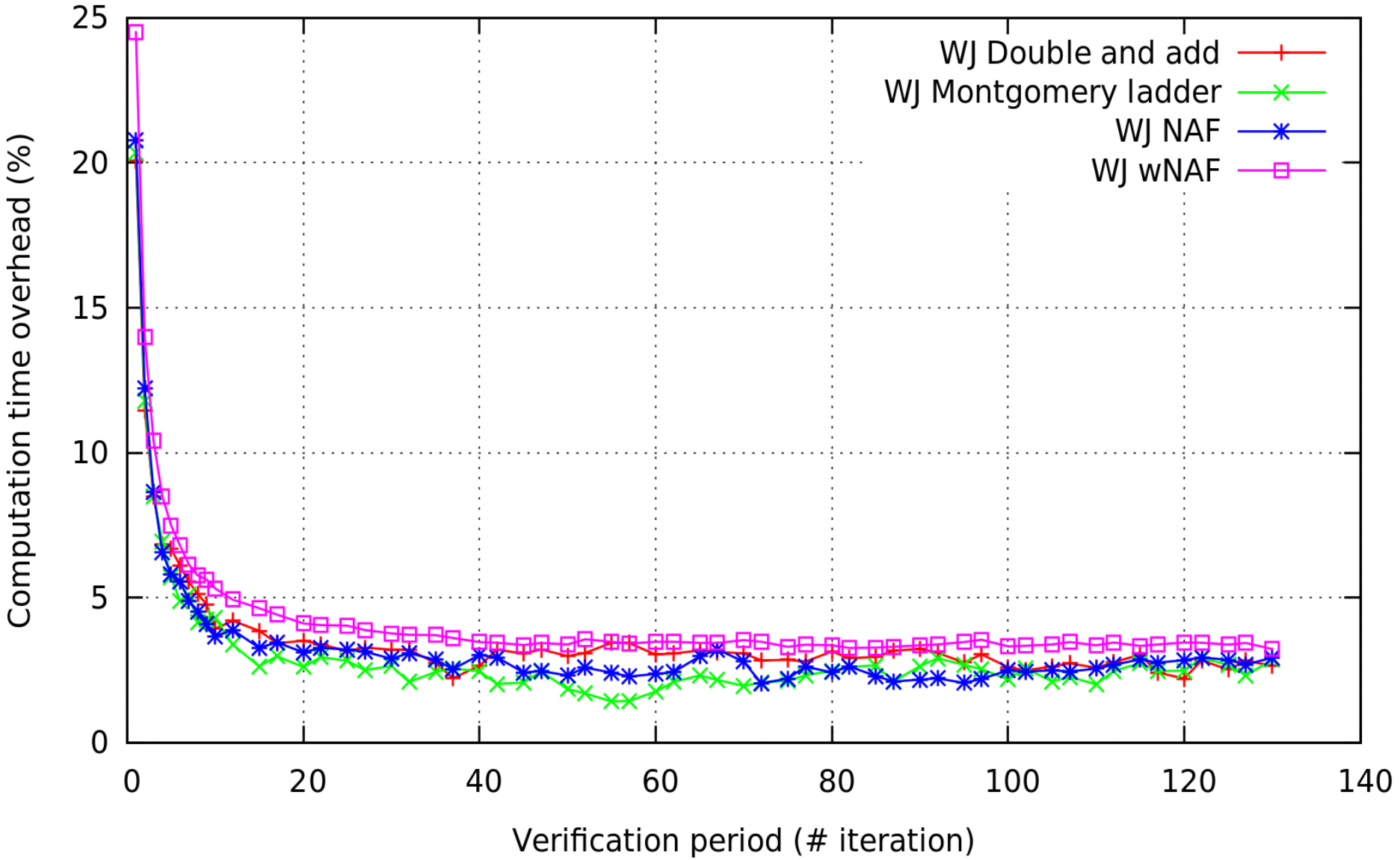
- Verify if the current/final point is on the curve [BMM].
- Adaptable for many curves and many coordinates.

Verification period:

- At the very end: very low cost but late detection.
- Every ℓ iterations: larger cost but earlier detection.
- At each iteration ($\ell = 1$): important cost but immediate detection and possible uniformization of behaviour.

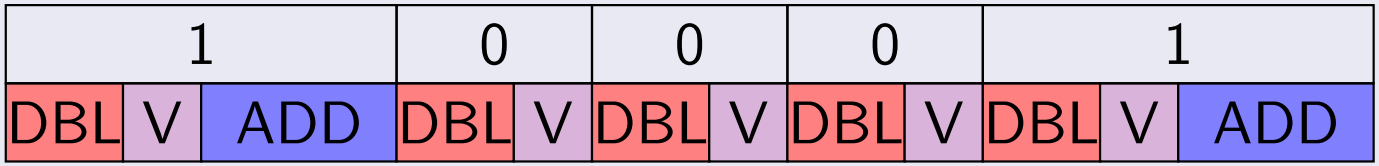
I. Biehl, B. Meyer, and V. Müller.
Differential Fault Attacks on Elliptic Curve Cryptosystems.
In *Proc. Advances in Cryptology - CRYPTO 2000.*

Software Implementation Result of Curve on 521 bits



Uniformization I

Uniformization:



Behaviour for ADD and for DBL V must be very close.

Example: Weierstrass curve - projective

Verification:

$$V : Y^2Z = X^3 + aXZ^2 + bZ^3$$

$\Rightarrow$ Cost: $4M + 3S + 5A + 1 \times b$

ADD	DBL	DBL+V
$11M + 6S + 18A$	$5M + 6S + 14A$	$9M + 8S + 19A + 1 \times b$

Uniformization II

Example: Weierstrass curve - projective

- New verification:

$$Y^3Z = X^3Y + aXYZ^2 + bYZ^3$$

$\Rightarrow$ Cost: $8M + 3S + 5A + 1 \times b$.

- Verification is included in DBL.
  $\Rightarrow$ Cost: $13M + 9S + 19A + 1 \times b$.
- Optimization using factorization.
  $\Rightarrow$ Cost: $11M + 6S + 18A + 1 \times b$.
- $1 \times b$ is added to ADD.

The costs for ADD and $DBL + V$ are equal.

Summary

Good points

- This protection is equivalent to *double and add always* but at for smaller cost.
- Bit flip detection in all field elements.

Weakness

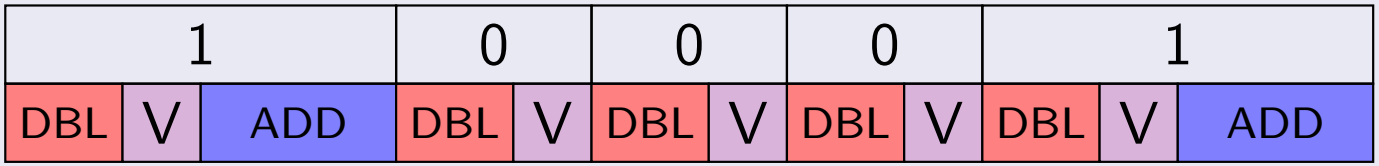
- Scalar is vulnerable to fault attacks.

Outline

Scalar Protection

Point verification does not protect the scalar from fault attack.

Example



Scalar Protection

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Example

1			0		0		0		1		
DBL	V	ADD	DBL	V	DBL	V	DBL	V	DBL	V	ADD

Scalar Protection

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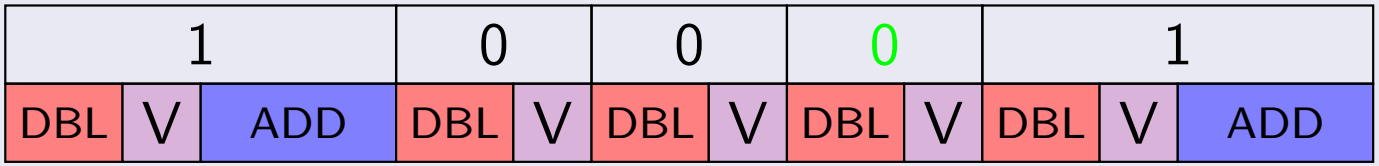
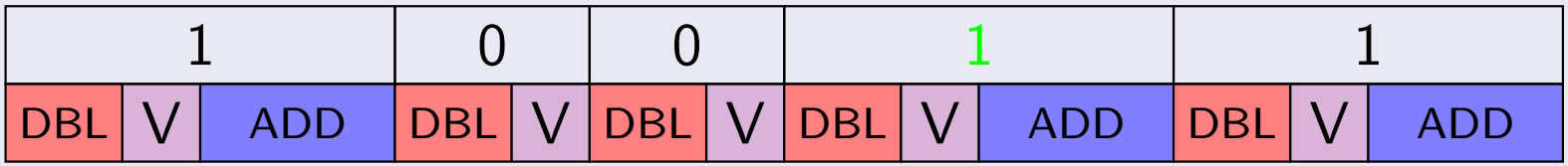
Example





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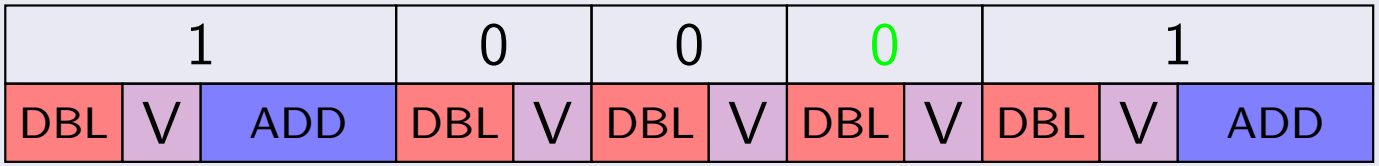

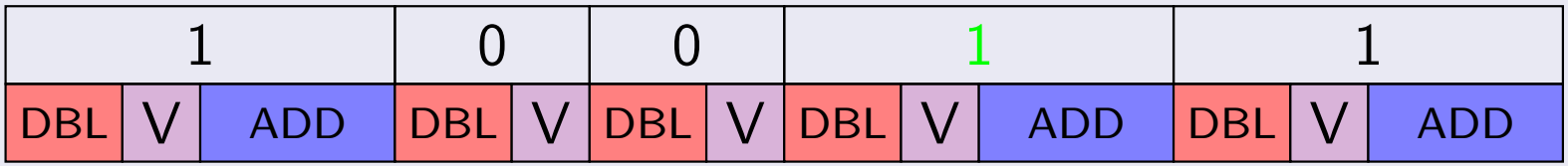

- Attack is not detected: current point is on curve but is wrong result.
- Proposed countermeasure: *Iteration Counter*.

Scalar Protection - Iteration Counter

Aim: Verify if the operation sequence is equivalent to key k.

Scalar Protection - Iteration Counter

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First idea, naive idea:

- Count the number of *ADDs* during computations.
  - Use a *cmp* register and a *ref* reference value.
  - If $k_i = 1$, add 1 to register.
- No detection in case of 2 bit flips at different indexes.

Scalar Protection - Iteration Counter

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- Count the number of *ADDs* during computations.
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Second idea:

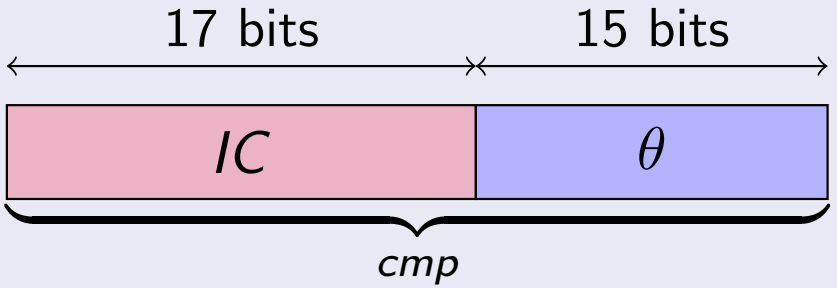
- Count the number of *ADDs* combined with a weight.
  - This weight is the iteration index.
  - If $k_i = 1$, add i to register.
- Problem: if $k_i = 0$, no electric activity.

Scalar Protection - Iteration Counter

Last idea:

Divide the register in 2 parts.

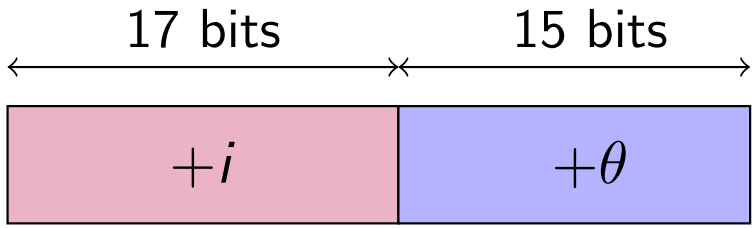
- First part: counter IC.
- Second part: noise θ.



- If $k_i = 1$, add iteration index i to IC.
- If $k_i = 0$, add random number to θ.
- At the end: comparison between IC and the reference counter ref.
- (17, 15) parameters has been selected for first implementation (work in progress).

Example - Double and Add

Require: P, $k = (k_{n-1}, \ldots, k_0)_2$. Data: ref.
Ensure: $Q = k \cdot P$
  for $i = n - 1$ **to** 0 **do**
    $Q = 2 \cdot Q$
    $\theta =$ random number
    if $k_i = 1$ **then**
      $Q \leftarrow Q + P$
      $cmp \leftarrow cmp + i \cdot 2^{15}$
    else
      $cmp \leftarrow cmp + \theta$
  $IC \leftarrow cmp >> 15$
  if $IC \neq ref$ **then**
    return *Fault detected*



Summary

Good points

- Cost: n small integer additions + small random number generator.
- Bit flip detection on the scalar.

Weakness

- Late detection.
- Stuck-at fault not detected $\Rightarrow$ safe error vulnerability.

Future work

- Key recoding.

Outline

Evaluation of Two Protections I

What is implemented

- 3 curves:
  - Weierstrass, Edwards and Tripling-oriented Doche–Icart–Kohel (TDIK).
- 4 coordinates:
  - affine, projective, jacobian, standard.
- 4 algorithms:
  - double and add, Montgomery ladder, NAF, w-NAF ($w = 3, 4$).
- 3 point *verification* methods:
  - at the very end;
  - every ℓ iterations;
  - at each iteration ($\ell = 1$).

Evaluation of Two Protections II

Implementation target

- C language with GMP library.
- Intel core i7-5600U CPU @ 2.60GHz

Algorithms	Coordinates		
	Affine	Jacobian	Projective
Double and add	5.7%	25.3%	18.8%
Montgomery ladder	6.0%	26.2%	19.0%
NAF	6.1%	25.5%	18.1%
3-NAF	7.2%	29.8%	24.7%

Computation overheads in the worst case for Weierstrass curves.

Outline

Conclusion

What is done

- Bit flip attack detection.
  - on all field elements, on the scalar.
  - low cost.
  - adaptable for many curves.
- SPA resistant.

Future works

- Stuck-at fault and safe error.
- Implementation on small processors (32, 16 bits).

Thank you for your attention.

Questions?