FDTC 2010

Fault Diagnosis and Tolerance in Cryptography

PACA on AES

Passive and Active Combined Attacks

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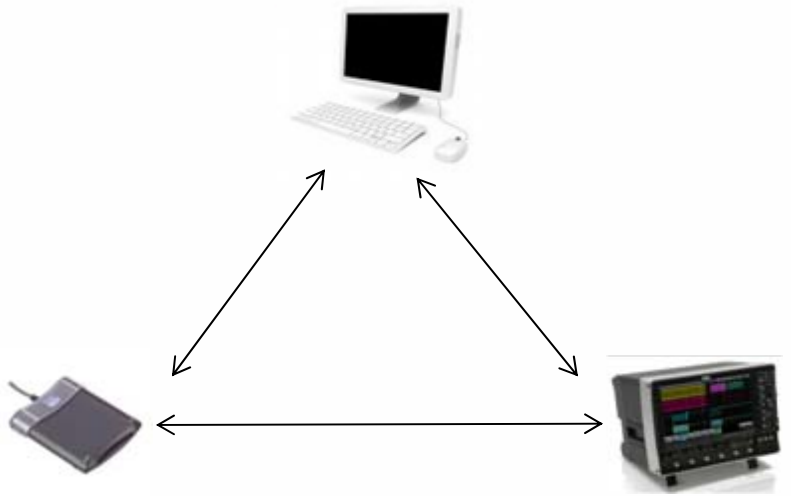
Saturday August, 21, Santa Barbara.

Outline

- Introduction
  - Passive Attacks: SPA, DPA, CPA
  - Active Attacks: DFA, CFA and IFA (Fail Safe Errors)
  - Previous PACA
- Targeted AES Implementation
- PACA on AES
  - CFA + CPA
  - IFA + CPA
- Conclusion

Passive Attacks Notions (some)

- When an IC makes a computation, several transistor are switching states depending on op-code or data manipulated.
- **Side Channel Analysis** exploits that relation
- **Simple Power Analysis**
  Analyze and recover secrets by “reading” curves
- **DPA** and **CPA**
  Usage of statistic Attacks to recover secrets



Passive Attacks

some previous results …

- P. C. Kocher. *Timing attacks on implementations of Diffie-Hellman, RSA, DSS, and other systems.* CRYPTO 1996.
- P. C. Kocher, J. Jaffe, and B. Jun. *Differential power analysis*. CRYPTO ’99,
- E. Brier, C. Clavier, and F. Olivier. *Correlation power analysis with a leakage model.* CHES 2004.
- P-A. Fouque and F. Valette. *The Doubling Attack - why upwards is better than downwards.* CHES 2003.
- S-M. Yen, W-C. Lien, S. Moon, and J. Ha. P*ower Analysis by Exploiting Chosen Message and Internal Collisions - Vulnerability of Checking Mechanism for RSA-Decryption.* Mycrypt 2005.
- S. Mangard, N. Pramstaller, and E. Oswald*. Successfully Attacking Masked AES Hardware Implementations.* CHES 2005
- F. Amiel, B. Feix, and K. Villegas. *Power Analysis for Secret Recovering and Reverse Engineering of Public Key Algorithms.* SAC 2007.
- F-X. Standaert, B. Gierlichs, and I. Verbauwhede. *Partition vs. Comparison Side- Channel Distinguishers: An Empirical Evaluation of Statistical Tests for Univariate Side-Channel Attacks against Two Unprotected CMOS Devices*. ICISC 2008.
- Not exhaustive …

Active Attacks Notions (some)

- **Voluntarily perturb the chip calculations:**
  - Erroneous results or computation can be used and exploited to recover secrets: DFA, CFA
  - Fault has an effect on the chip bits but the results remain correct: IFA, Safe Error
  - …
- **Can be done using glitches, light emission (laser) …**

Active Attacks some previous work …

- E. Biham and A. Shamir. *Differential Fault Analysis of Secret Key Cryptosystems*, CRYPTO 97.
- D. Boneh, R. A. DeMillo, and R. J. Lipton. *On the importance of checking cryptographic protocols for faults.* EUROCRYPT 1997,
- S. P. Skorobogatov and R. J. Anderson. *Optical fault induction attacks*, CHES 2002.
- C. Giraud and H. Thiebeauld. *A survey on fault attacks*. CARDIS 2004.
- G. Piret and J-J. Quisquater . *A Differential Fault Attack Technique against SPN Structures, with Application to the AES and KHAZAD.* CHES 2003.
- S-M. Yen and M. Joye. *The Montgomery Power Ladder.* CHES 2002.
- H. Choukri and M. Tunstall.,*Round Reduction Using Faults.* FDTC 2005
- Blomer and J-P. Seifert . *Fault Based Cryptanalysis of the Advanced Encryption Standard (AES).* FC 2003.
- F. Amiel, C. Clavier and M. Tunstall - Fault Analysis of DPA-Resistant Algorithms – FDTC 2006
- C. Clavier: *Secret External Encodings Do Not Prevent Transient Fault Analysis*. CHES 2007
- J-S. Coron, A. Joux, I. Kizhvatov, D. Naccache, P. Paillier. *Fault Attacks on RSA Signatures with Partially Unknown Messages.* CHES 2009
- Not exhaustive …

Some Previous Work similar to PACA

- **Sergeï Skorobogatov.**
  Optically Enhanced Position-Locked Power Analysis CHES 2006
  Use a focused laser to enhance the power consumption of a sensitive part in a chip.

- **F. Amiel, B. Feix, L. Marcel and K. Villegas.**
  PACA on RSA FDTC 2007
  Use fault injection to perturb message operand settings to create SPA leakage in exponentiation

- **J. Di-Battista, J-C. Courrege, B. Rouzeyre, Li. Torres and P. Perdu.**
  When Failure Analysis Meets Side-Channel Attacks CHES 2010

- … Not exhaustive …

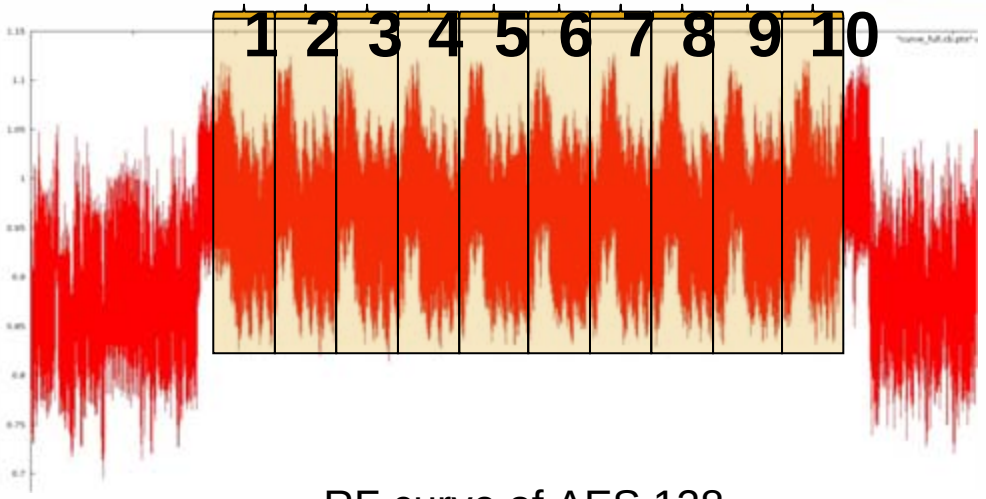
Reminder on AES

- **Advanced Encryption Standard**
  - 128-bit input message blocks
  - 128, 192 or 256 bits key
  - Based on SPN scheme.

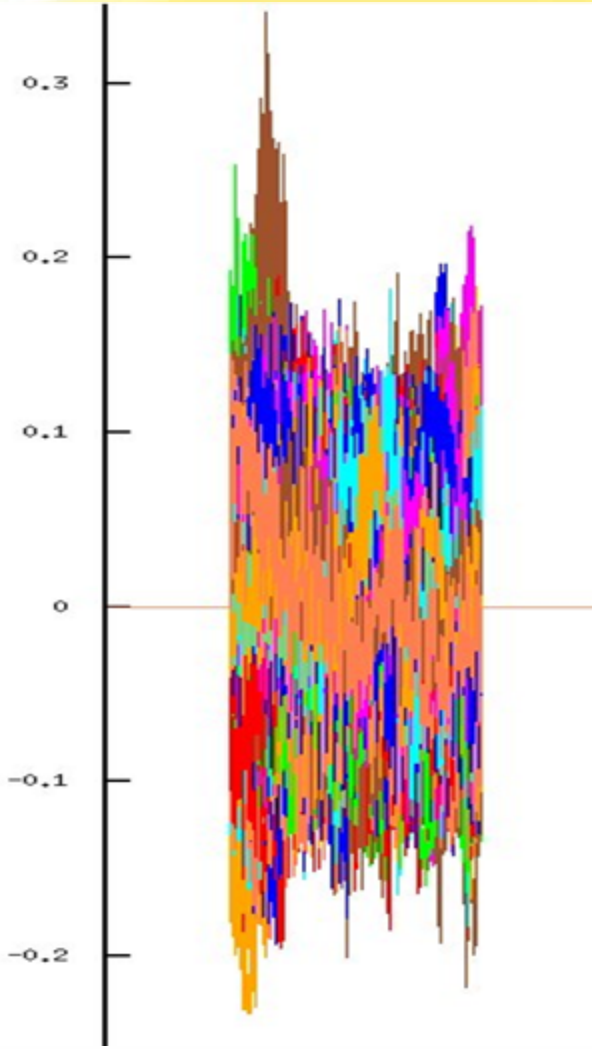
- We choose here AES 128 but our results can be applied to AES 192 and AES 256.

- **Schoolbook implementation not resistant to**
  - Active Attacks
  - Passive Attacks

Correlation on AES



RF curve of AES 128



CPA Sample

Secure AES implementation targeted

- Implementation using an 8-bit architecture core
- **Targeted** to resist classical practical Second Order Power Analysis attacks

  [1] M.-L. Akkar, R. Bevan, and L. Goubin. *Two Power Analysis Attacks against One-Mask Methods*

  [17] S. Mangard, N. Pramstaller, and E. Oswald. *Successfully Attacking Masked AES Hardware Implementations.*

- Computing the inversion with Oswald et al. FSE 2005 trick

  [19] E. Oswald, S. Mangard, N. Pramstaller, and V. Rijmen. A Side-Channel Analysis Resistant Description of the AES S-Box.

  → We use different mask per byte values for intermediate data and between the different rounds

- Such an implementation is resistant to the CFA presented by Amiel et al. at FDTC 2006 as it only applies to single mask protected AES.
  - The attack could not occur when mask uses 16 different bytes.
- We improve here their analysis when intermediate data bytes and key bytes are masked with different bytes …
  - Based on the **same fault model**
  - Using **less fault** injections
  - But adding **power analysis** …

Fault Model

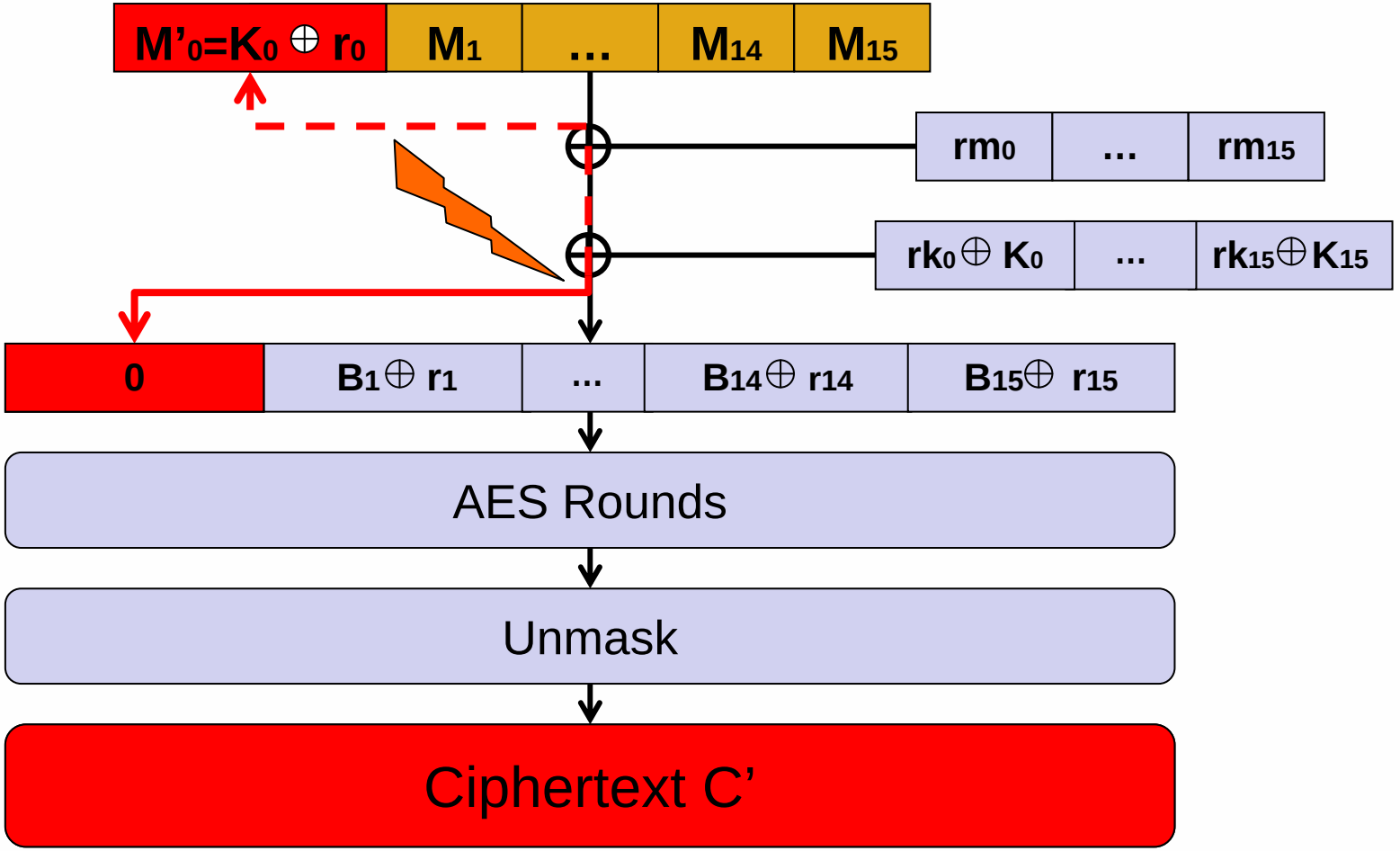
- An instruction can be bypassed
  - For instance by modifying an op-code to a NOP (NOP = 00 in JAVA)
- A loop counter can be modified
  - Reducing the number of byte key additions
- Corruption of Read or Write operations on RAM
- ALU process can be perturbed
  - XOR result can be set to 0 or to a constant value

Combining CPA with CFA

to counterfeit an

Differential SCA Protected AES

PACA on AES


M'0=K0 ⊕ r0
M1
…
M14
M15
rm0
…
rm15
rk0 ⊕ K0
…
rk15⊕K15
0
B1⊕ r1
…
B14⊕ r14
B15⊕ r15
AES Rounds
Unmask
Ciphertext C'

PACA on AES

- Effect: a differential δ has been introduced in the calculation
  - Indeed fault effect is the same as if we introduced a modification on M0
  - *For cst = 0*

$$AES_{\substack{faulted \\ sec\ ure}}(M) = AES_{sec\ ure}(M_0 \oplus \delta, M_1, ..., M_{15}) = C'$$

$$\delta = M_0 \oplus K_0 \oplus rm_0 \oplus rk_0 = M_0 \oplus K_0 \oplus r_0$$

$$AES_{\substack{faulted \\ sec\ ure}}(M) = AES_{sec\ ure}(K_0 \oplus r_0, M_1, ..., M_{15}) = C'$$

- For sake of simplicity use *M = (0 … 0)*
- Search *M'=(M'0 |0 |… | 0)* which collides with *C'*
  - s.t. *AES(M') = C'*
  - *only 256 possible values to test for M'0.*
- We obtain a simple relation between key byte and random byte

$$M'_0 = K_0 \oplus r_0$$

  - We store the power curve W0 of the faulted AES

PACA on AES

- By repeating it we obtain many relations and power curves:

$$\begin{aligned} M'_{0,0} &= K_0 \oplus r_{0,0} & W_0 \\ M'_{0,1} &= K_0 \oplus r_{0,1} & W_1 \\ &\ldots & \ldots \\ M'_{0,k-1} &= K_0 \oplus r_{0,k-1} & W_{k-1} \end{aligned}$$

- We obtain the relations set :

$$SK_0 = \left\{ M'_{0,0} \oplus K_0 = r_{0,0}, M'_{0,1} \oplus K_0 = r_{0,1}, \ldots, M'_{0,k-1} \oplus K_0 = r_{0,k-1} \right\}$$

- Correlation then occurs between the two following sets:

$$SK_0$$

$$W = \left\{ W_0, W_1, \ldots, W_{k-1} \right\}$$

… as random values are generated and manipulated in W_i.

PACA on AES

- A guess *g* on K_0 can then be validated if correlation occurs between the two following sets:

$$Sg = \{ M'_{0,0} \oplus g, M'_{0,1} \oplus g, ..., M'_{0,k-1} \oplus g \}$$

$$W = \{ W_0, W_1, ..., W_{k-1} \}$$

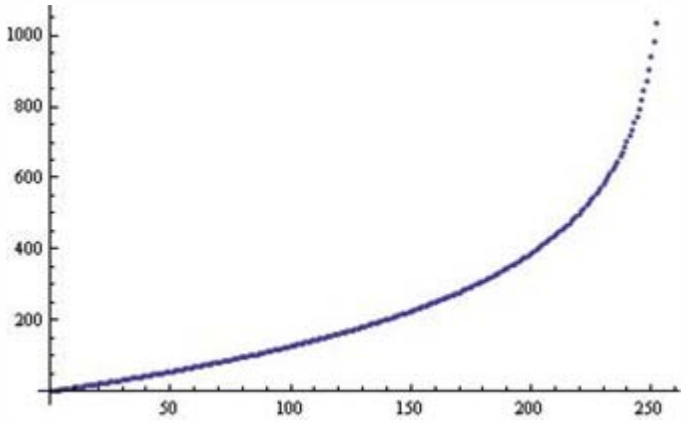
- Try the 256 possible values and when correlation is high we know $K_0 = g$.

- Reproduce same analysis for other key bytes.

PACA on AES

- Expected faults to obtain k relations:

Fault injections



Delta relations

Delta Values	Faults needed
50	56
100	126
150	226
200	388
256	1568

Phase 1: dictionnary precomputation

$M = (M_0, \ldots, M_{15}) \leftarrow (0, \ldots, 0)$
for $u = 0$ to 255 **do**
  $C_u \leftarrow AES(M|M_n = u)$

Phase 2: collision search

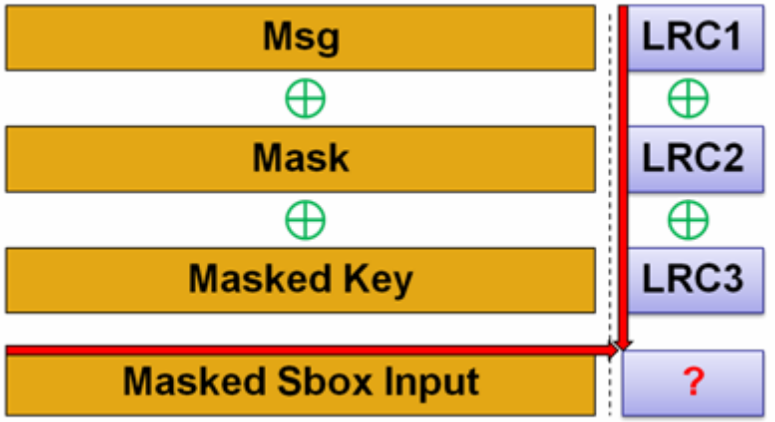
$\Gamma = \varnothing$
$i \leftarrow 1$
while $(i < k)$ **do**
  $C^i = AES^i(M)$
  if $C^i \notin \Gamma$ **do**
    $\delta_i \leftarrow u$ such that $C^i = C_u$ with $u \in \{0, \ldots, 255\}$
    $W_i \leftarrow$ power curve of the faulted execution
    $\Gamma \leftarrow \Gamma \cup \{C^i\}$
    $i \leftarrow i + 1$

Phase 3: correlation

for $g = 0$ to 255 **do**
  for $i = 1$ to k **do**
    $r_{n,i} \leftarrow \delta_i \oplus g$
  $\rho_g \leftarrow$ correlation trace between $\{r_{n,1}, \ldots, r_{n,k}\}$ and $\{W_1, \ldots, W_k\}$
$K_n \leftarrow g$ which gives the highest correlation peak

Countermeasures

- Standard inverse computation
- Duplicated rounds
  - Alternative to full inverse computation
  - Not efficient when both encryption and decryption are both available
- Integrity verifications between calculations



- Resistant HODPA implementation

M. Rivain and E. Prouff. Provably Secure Higher-Order Masking of AES CHES 2010

Combining CPA with IFA / Safe Errors

to counterfeit an

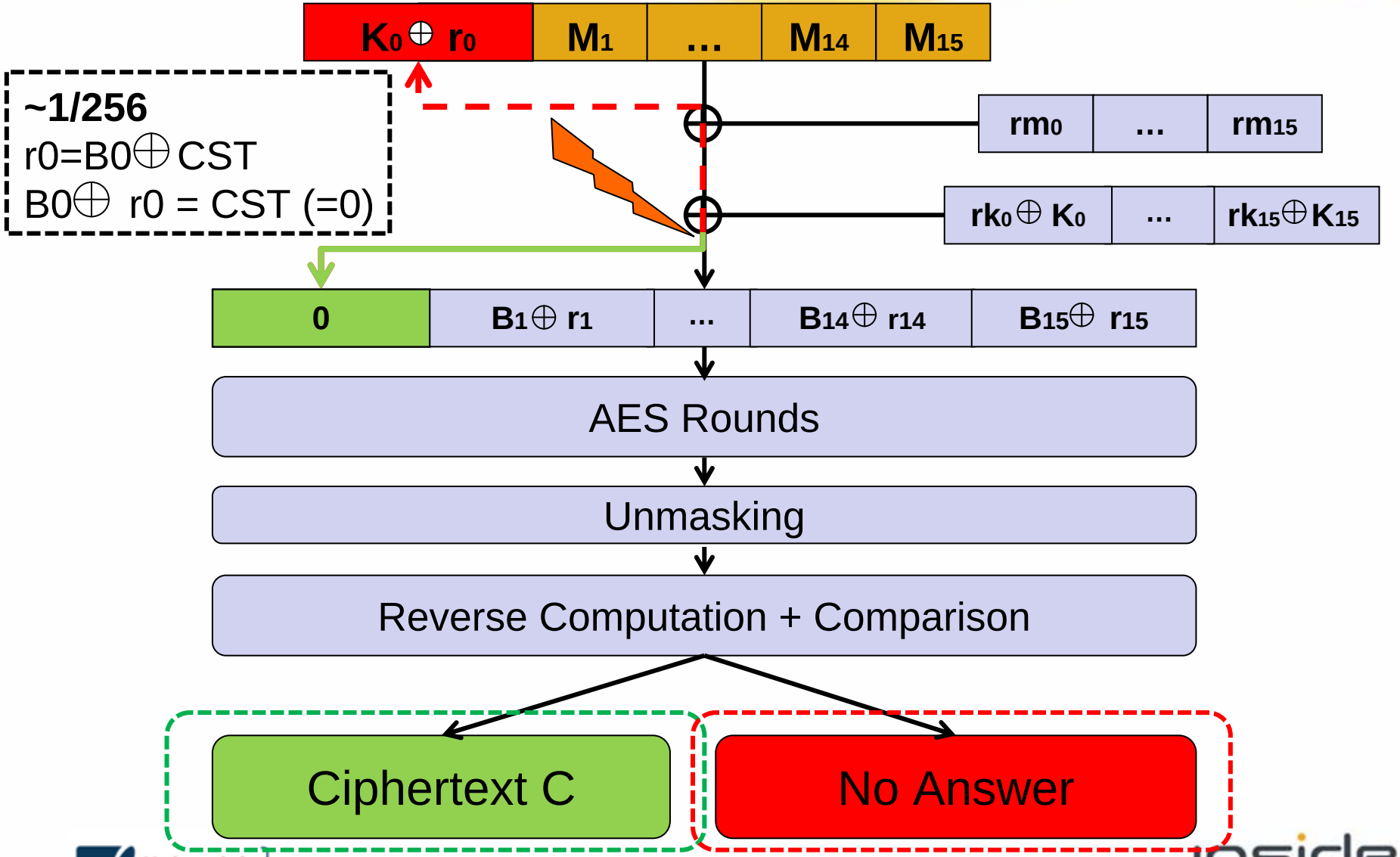
DPA and DFA/CFA Protected AES

PACA with IFA

- We consider the previous Differential SCA resistant AES with a reverse AES computation done at the end to prevent DFA.
- In that case the previous PACA cannot apply as the fault injection will be detected.

  EXCEPT when *delta = 0*
- As previously the KEY addition is faulted to a constant value
- **Repeat fault process until the card returns a Ciphertext rather than "No answer"**

IFA on AES-AES^{-1}



PACA on AES-AES$_{inverse}$

- Assuming Cst=0, We get the relations:

$$AES_{\substack{faulted \\ secure}}(M) = AES(M)$$

$$AES(K_0 \oplus r_0, M_1, ..., M_{15}) = AES(M)$$

$$M_0 = K_0 \oplus r_0$$

- The attack works as previously described
- Hard to tell whether the fault perturbed the IC or not
  - Fault injection system must be very reliable
- More fault injections are needed
- Known message attack is possible while in the first attack it was a chosen message attack.

Countermeasures

- Previous countermeasures like inverse computation doesn't work anymore.
- Improving the difficulty
  - Hardware countermeasures improve the feasibility
    - Clock jitter
    - Fault detectors
  - Code execution randomized
- Lock the card when too many faults have been detected.
- Resistant HODPA implementation

  M. Rivain and E. Prouff. Provably Secure Higher-Order Masking of AES CHES 2010

Attacks Comparison

CFA+CPA

- Can verify fault effect with collision
- Easy to setup

- Obvious countermeasures
- Doesn't Work on Fault protected Implementations

IFA+CPA

- **Works on implementations protected against DPA/Fault**
- **Known message Attack**
- Hard to protect against

- Fault injection system must be very reliable
- Hard to setup with desynchronization
- Requires more faults injection

Conclusion

- **New attack combining FA and SCA** can be used to break DPA resistant implementations in few fault injections combined with classical CPA.
- **Combined with IFA it can bypass full security countermeasures**
  - Very difficult to mount in practice
  - Realistic only if the fault effect is very reliable
- **Not limited to AES...**

Erratum

- Some errors are present in the proceedings paper
  - Minor typos in final scheme AES on masks notations
  - Number of AES rounds to protect is 5 and not 3
  - Our implementation seems to be threatened by some kind of Second Order DPA

- **Corrected and extended version of the paper will be soon published on IACR e-print.**

Thank you for your attention !

Questions ?

Countermeasures