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Taylor Expansion of Maximum Likelihood Attacks

Nicolas Bruneau[1,2], Sylvain Guilley[1,3], Annelie Heuser[1], Olivier Rioul[1], François-Xavier Standaert[4], Yannick Teglia[5]

[1] Télécom-ParisTech, Crypto & ComNum Group, Paris, FRANCE
[2] STMicroelectronics, AST division, Rousset, FRANCE
[3] Secure-IC S.A.S., Rennes, FRANCE
[4] Université Catholique de Louvain, Louvain-la-Neuve, BELGIQUE
[5] Gemalto, La Ciotat, FRANCE

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Nicolas Bruneau, Sylvain Guilley,
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Outline

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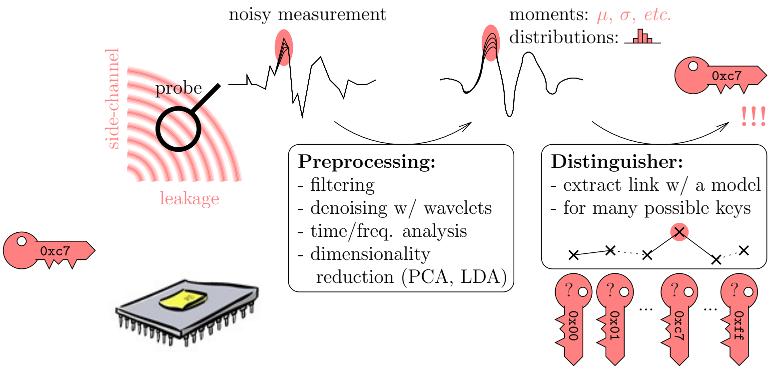
Side-Channel Analysis on Embedded Systems



$(\Omega - 1)$th-Order Masking: Principle

Aim

The sensitive variable Z is randomly split into Ω shares:
$\Rightarrow$ need random masks M_i , $0 < i < \Omega$

$$Z$$

$$Z \perp M_1 \perp \ldots \perp M_{\Omega-1} \qquad M_1 \qquad \cdots \qquad M_{\Omega-1}$$

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$$
\begin{tikzcd}
 & Z \arrow[dl] \arrow[d] \arrow[dr] \arrow[drr] & & \\
Z \perp M_1 \perp \ldots \perp M_{\Omega-1} & M_1 & \cdots & M_{\Omega-1}
\end{tikzcd}
$$

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$$Z$$

$$Z \perp M_1 \perp \ldots \perp M_{\Omega-1} \qquad M_1 \qquad \cdots \qquad M_{\Omega-1}$$

Consequence

Increases the minimum key-dependent statistical moment.

Shuffling: Principle

Aim

Randomize the order of execution
$\Rightarrow$ need a random permutation π

$\boxed{Z_1}$

Shuffling: Principle

Aim

Randomize the order of execution
$\Rightarrow$ need a random permutation π

$$Z_1 \longrightarrow Z_2$$

Shuffling: Principle

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$$Z_1 \longrightarrow Z_2 \longrightarrow Z_3$$

Shuffling: Principle

Aim

Randomize the order of execution

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$$Z_1 \longrightarrow Z_2 \longrightarrow Z_3 \longrightarrow Z_4$$

Shuffling: Principle

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Z_3

Shuffling: Principle

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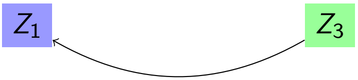

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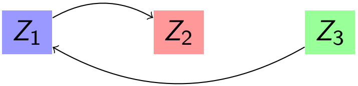

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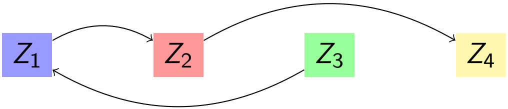

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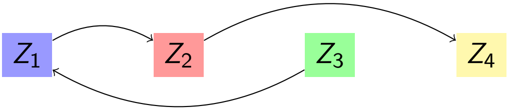

Consequences

The attacks are applied on the sum of the variables $\Rightarrow$ increases the algorithmic noise.

Protection Parameters

The security level of the protections depends on these parameters:

Masking

- Ω: the number of shares ($\Omega - 1$ masks);
- O: the order (i.e. the minimal key-dependent statistical moment).

Perfect masking scheme $\Leftrightarrow O = \Omega$.

Shuffling

- Π the size of the permutation.

Template Attacks

Template attacks are the most powerful in a information-theoretic sense [Chari et al., 2002].

Offline Profiling

The leakage model is learned:

- non-parametric methods (e.g. histogram, kernel methods...);
- parametric methods (e.g. mixture models).

Online Attack

Recover the key using the models by applying a maximum likelihood (ML) attack.

Parametric or Non-Parametric ?

Parametric

The only random part is the noise with known distribution.

- easy to estimate;
- shuffle and mask are known;
- many templates are learned.

Non-Parametric

Shuffle and masks are part of the noise.

- can be hard to estimate $\Rightarrow$ curse of dimensionality;
- shuffle and mask are unknown.

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Notations for the Online attack

The attacks are applied on:

- Q queries (i.e. the traces).
- D dimension (i.e. the number of leakage samples);

A leakage measurement is $X = y(t, k^*, R) + N$ where:

- $y(t, k^*, R)$ is the deterministic part of the model;
- the secret key k^* and the plaintext t are n-bit words;
- R is the random countermeasure;
- N is a random Gaussian noise of variance σ^2.

Maximum Likelihood Attacks

Theorem (Maximum Likelihood [Bruneau et al., 2014])

When the model is known the optimal distinguisher (OPT) consists in maximizing the sum over all traces $q = 1, \ldots, Q$ of the log-likelihood:

$$\mathrm{LL} = \sum_{q=1}^{Q} \log \mathbb{E} \exp \frac{-\|x^{(q)} - y(t^{(q)}, k, R)\|^2}{2\sigma^2} \quad ,$$

where expectation $\mathbb{E}$ is applied to the random variable $R \in \mathcal{R}$ and $\|\cdot\|$ is the Euclidean norm on $\mathbb{R}^D$.

For convenience we let $\gamma = \frac{1}{2\sigma^2}$ be the SNR parameter.

Complexity in presence of Masking and Shuffling

$$\mathcal{O}\left(Q \cdot D \cdot (2^n)^{\Omega-1} \cdot \Pi! \right)$$

- number of traces
- dimension of the attack
- number of possible share values
- number of possible permutations

Complexity in presence of Masking and Shuffling

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Not computable for large Π !

Outline

Taylor Expansion of Optimal Attacks in Gaussian Noise

The optimal attack consists in maximizing the sum over all traces $q = 1, \ldots, Q$ of the log-likelihood:

$$\mathrm{LL} = \sum_{q=1}^{Q} \log \mathbb{E} \exp \frac{-\|x^{(q)} - y(t^{(q)}, k, R)\|^2}{2\sigma^2} \quad .$$

It can be rewritten using the cumulant generating function:

$$\mathrm{LL} = \sum_{q=1}^{Q} \sum_{\ell=1}^{+\infty} \frac{\kappa_\ell^{(q)}}{\ell!} (-\gamma)^\ell \quad ,$$

where $\kappa_\ell^{(q)}$ is the ℓth-order cumulant of $\|x^{(q)} - y(t^{(q)}, k, R)\|^2$.

High order Cumulants

The ℓth-order cumulant of $\|x - y(t,k,R)\|^2$ is given by:

$$\kappa_\ell = \mu_\ell - \sum_{\ell'=1}^{\ell-1} \binom{\ell-1}{\ell'-1} \kappa_{\ell'} \mu_{\ell-\ell'} \qquad (\ell \geq 1),$$

where μ_ℓ is the corresponding moment:

$$\mu_\ell = \mathbb{E}_R\left(\|x - y(t,k,R)\|^{2\ell}\right) \ .$$

Rounded Optimal Attack

Rounded Optimal Attack (ROPT_L)

The rounded optimal *Lth-degree attack* consists in maximizing the sum over all traces of the Lth-order Taylor expansion LL_L in the SNR of the log-likelihood :

$$\mathrm{LL}_L = \sum_{q=1}^{Q} \sum_{\ell=1}^{L} (-1)^\ell \kappa_\ell^{(q)} \frac{\gamma^\ell}{\ell!} \quad ,$$

and we have

$$\boxed{\mathrm{LL} = \mathrm{LL}_L + o(\gamma^L)} \quad .$$

Complexity Gain

- number of possible share values
- number of traces

$$\mathcal{O}\left(Q \cdot L \cdot \binom{D+L-1}{L} \cdot 2^{(\Omega-1)n} \cdot \binom{\Pi}{\min(\lceil \frac{\Pi}{2} \rceil, L)} \right)$$

- Factorial terms
  - dimension of the attack
  - degree of the Taylor Expansion
  - size of the permutation

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- Factorial terms
  - dimension of the attack
  - degree of the Taylor Expansion
  - size of the permutation

Reduces to small constants when $L \ll D$

Outline

Implementation of Masking Schemes

In masking schemes, while the implementation of the linear parts is obvious, that of the non linear parts is more difficult.

- algebraic methods [Blömer et al., 2004];
- global look-up table method [Prouff and Rivain, 2007];
- table recomputation methods which precompute a masked S-box stored in a table [Chari et al., 1999].

In [Coron, 2014] a table recomputation scheme secure at order $\Omega - 1$ was presented.

Table Recomputation Algorithm

input : t, one byte of plaintext, and k, one byte of key
output: The application of AddRoundKey and SubBytes on t, i.e., $S(t \oplus k)$

$m \leftarrow_{\mathcal{R}} \mathbb{F}_2^n$, $m' \leftarrow_{\mathcal{R}} \mathbb{F}_2^n$ `// Draw of random input and output masks`
for $\omega \in \{0, 1, \ldots, 2^n - 1\}$ **do** `// Sbox masking`
  $z \leftarrow \omega \oplus m$ `// Masked input`
  $z' \leftarrow S[\omega] \oplus m'$ `// Masked output`
  $S'[z] \leftarrow z'$ `// Creating the masked Sbox entry`
end
$t \leftarrow t \oplus m$ `// Plaintext masking`
$t \leftarrow t \oplus k$ `// Masked AddRoundKey`
$t \leftarrow S'[t]$ `// Masked SubBytes`
$t \leftarrow t \oplus m'$ `// Demasking`
return t

- usual 2-variate 2nd-order attack;
- 2-stage CPA attack [Pan et al., 2009];
- improved $(2^n + 1)$-variate 2nd-order attack on the input [Bruneau et al., 2014].

Protected Table Recomputation Algorithm

input : t, one byte of plaintext, and k, one byte of key
output: The application of AddRoundKey and SubBytes on t

$m \leftarrow_{\mathcal{R}} \mathbb{F}_2^n$, $m' \leftarrow_{\mathcal{R}} \mathbb{F}_2^n$ `// Draw of random input and output masks`
$\varphi \leftarrow_{\mathcal{R}} \mathbb{F}_2^n \to \mathbb{F}_2^n$ `// Draw of random permutation of` $\mathbb{F}_2^n$
for $\varphi(\omega) \in \{\varphi(0), \varphi(1), \ldots, \varphi(2^n - 1)\}$ **do** `// S-box masking`
    $z \leftarrow \varphi(\omega) \oplus m$ `// Masked input`
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Make the index of the loop unknown, use some random permutation φ.

Leakages

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- second-order Correlation Power Analysis 2O-CPA;
- OPTimal distinguisher OPT;
  - Rounded OPTimal Distinguisher ROPT_2, ROPT_4

Bi-Variate Attacks

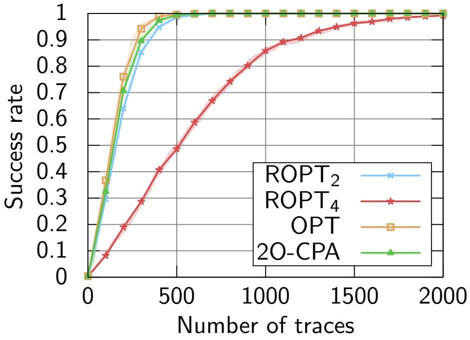

Figure: $\sigma = 1$

Bi-Variate Attacks

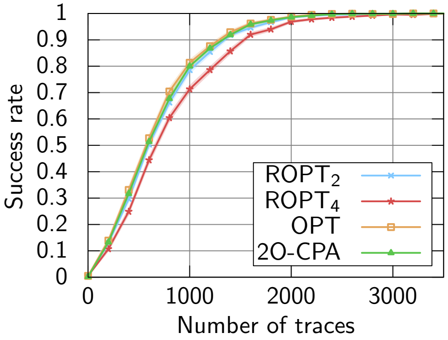

Figure: $\sigma = 2$

Leakages, with Table Recomputation

input : t, one byte of plaintext, and k, one byte of key
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input : t, one byte of plaintext, and k, one byte of key
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- optimal distinguisher NOT computable due to the term 2^n!

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return t

- third order attack MVA_{TR} [Bruneau et al., 2015];
- Rounded Optimal Distinguisher ROPT_3.

Complexity of the Case Study

Attack	Time (seconds)	Computational Complexity
2O-CPA	39	$\mathcal{O}(Q)$
MVA_{TR}	130	$\mathcal{O}(Q \cdot 2^n)$
ROPT_3	2495	$\mathcal{O}\left(Q \cdot 2^{2n}\right)$
OPT_{2O}	9473	$\mathcal{O}(Q \cdot 2^n)$
OPT	Not computable	$\mathcal{O}\left(Q \cdot 2^n \cdot 2^n! \cdot \left(2^{n+1} + 2\right)\right)$

The time of execution have been computed on a Intel Xeon X5660.

$(2^{n+1}+2)$-Variate Attacks on Shuffled Table Recomputation

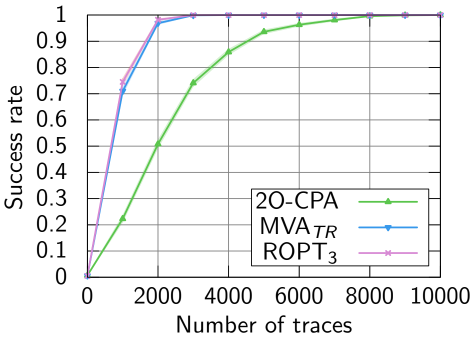

Figure: $\sigma = 3$

$(2^{n+1}+2)$-Variate Attacks on Shuffled Table Recomputation

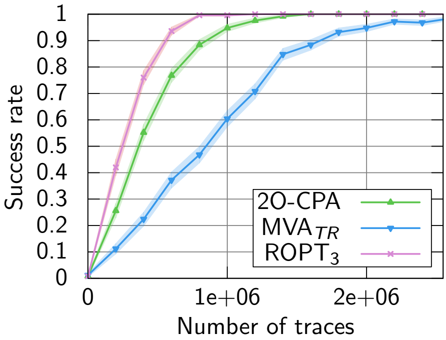

Figure: $\sigma = 12$

$(2^{n+1}+2)$-Variate Attacks on Shuffled Table Recomputation

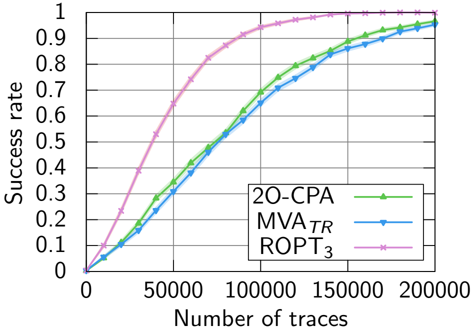

Figure: $\sigma = 8$

$(2^{n+1}+2)$-Variate Attacks on Shuffled Table Recomputation

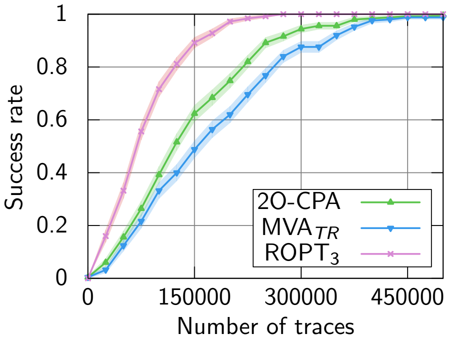

Figure: $\sigma = 9$

$(2^{n+1}+2)$-Variate Attacks on Shuffled Table Recomputation

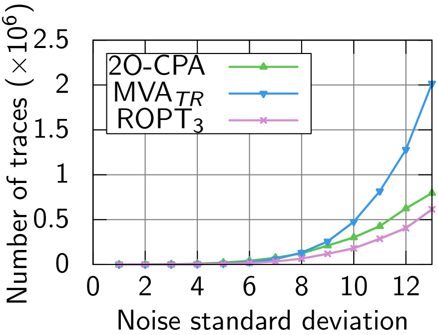

Figure: Number of traces to reach 80% of success

Conclusion

Results

We have presented a practical, truncated version of the theoretical, optimal distinguisher:

- becomes efficient;
- remains effective.

Perspective

How to quantify the accuracy of the approximation?

Conclusion

Results

We have presented a practical, truncated version of the theoretical, optimal distinguisher:

- becomes efficient;
- remains effective.

Perspective

How to choose the degree of the Taylor Expansion?

Thank you for your attention.

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