Practical Algebraic Side-Channel Attacks against ACORN

Alexandre Adomnicai^{1,2}   Laurent Masson¹   Jacques J.A. Fournier³

¹Trusted Objects

²Mines Saint-Étienne

³Univ. Grenoble Alpes, CEA-Leti

21th International Conference on Information Security & Cryptology

Seoul, November 30th 2018

Competition for Authenticated Encryption: Security, Applicability, and Robustness (CAESAR)

- ▷ New authenticated encryption schemes that offer advantages over AES-GCM
- ▷ At the end, a multiple-algorithm portfolio
- ▷ 57 candidates for the first round (March 2014)
- ▷ 7 finalists (March 2018)

**Lightweight
applications**

ACORN [Wu14]
Ascon

**High-performance
applications**

AEGIS
MORUS
OCB

**Nonce misuse
resistance**

COLM
Deoxys-II

Lightweight Applications Criteria

- ▷ Fits into small hardware area and/or small code for 8-bit CPUs
- ▷ **Natural ability to protect against side-channel attacks (SCA)**
- ▷ Good performance in both software and hardware (especially energy/bit)
- ▷ Low overhead for short messages (e.g. 16 bytes)

Side-Channel Attacks (SCA)

- ▶ Cryptographic primitives are designed to be finally executed on a **physical system**
- ▶ **The physical characteristics** of the computing platform produce **side effects** depending on the processed data
  - Power consumption
  - Electromagnetic emanations (EM)
  - Time execution ...
- ▶ One can **measure** these side effects to get information on the processed values during **sensitive operations**
- ▶ Using an appropriate **leakage model**, one can recover the **secrets** involved in calculations

Susceptibility of ACORN Towards SCA

- ▶ No conditional branch or use of look-up table $\Rightarrow$ **intrinsic constant-time implementation**
- ▶ 2 previous works regarding power/EM side-channels
  - 1 – Leakage detection on hardware implementation using t-test [DAF⁺18]
  - 2 – Theoretical attack using differential power analysis (DPA) [AFM18]
- ▶ Assessment leakage methodologies can be insufficient to guarantee the security level of an implementation $\Rightarrow$ need to run additional tests
- ▶ **No practical DPA against ACORN published to date** $\Rightarrow$ how hard is it to put into practice?

Previous Work (Leakage Detection)

Our Contribution

- ▷ Put into practice the theoretical attack described in [AFM18]
- ▷ Explicit definition of all selection functions required to mount the attack
- ▷ Proposition of 2 different optimizations of the reference attack
  - 1 – Maximize the practical efficiency
  - 2 – Minimize the number of IV bits to consider

ACORN in a nutshell

- ▶ Authenticated stream cipher introduced by Hongjun Wu in 2014
- ▶ 128-bit key, 128-bit IV, 128-bit tag
- ▶ Based on the concatenation of 6 LFSRs (+ a 4-bit register)
- ▶ Encryption and authentication share the same state (293-bit long)
- ▶ Feedback bit f and keystream ks are computed in a nonlinear manner

StateUpdate(S, m)

$$\begin{aligned}
 S_{289} &\leftarrow S_{289} \oplus S_{235} \oplus S_{230} \\
 S_{230} &\leftarrow S_{230} \oplus S_{196} \oplus S_{193} \\
 S_{193} &\leftarrow S_{193} \oplus S_{160} \oplus S_{154} \\
 S_{154} &\leftarrow S_{154} \oplus S_{111} \oplus S_{107} \\
 S_{107} &\leftarrow S_{107} \oplus S_{66} \oplus S_{61} \\
 S_{61} &\leftarrow S_{61} \oplus S_{23} \oplus S_0 \\
 ks &\leftarrow \kappa(S) \\
 c &\leftarrow ks \oplus m \\
 f &\leftarrow \phi(S, ks) \\
 \text{for } i \text{ from } 0 \text{ to } 291 \text{ do} \\
 &S_i \leftarrow S_{i+1} \\
 S_{292} &\leftarrow f \oplus m
 \end{aligned}$$

Differential Power Analysis (DPA)

- ▷ Power consumption of an operation varies with the operand values $\Rightarrow$ **intermediate values leak**
- ▷ Variations are relatively small, not directly observable $\Rightarrow$ **use of statistical tools over several measurements**
- ▷ Targeted intermediate values are defined by **selection functions** $y = \varphi(m, k)$
- ▷ It is assumed that m varies over measurements and is known by the attacker

Built from **key** bits

Built from **input** bits

Built from **key** and **input** bits

Theoretical DPA against ACORN

- DPAs against stream ciphers usually focus on the **initialization phase**
- IV bits do not directly interact with key bits** but with feedback bits
- The theoretical attack targets intermediate bits $y_i = f_{128+i} \oplus IV_i$

AcornInit(S, K, IV)

$(S_0, \dots, S_{292}) \leftarrow (0, \dots, 0)$

for i from 0 to 127 **do**

$S \leftarrow \text{StateUpdate}(S, K_i)$

for i from 0 to 127 **do**

$S \leftarrow \text{StateUpdate}(S, IV_i)$

$S \leftarrow \text{StateUpdate}(S, K_0 \oplus 1)$

for i from 1 to 1535 **do**

$S \leftarrow \text{StateUpdate}(S, K_{i \bmod 128})$

Theoretical DPA against ACORN

- ▷ f_{128+i} are defined by key bit combinations: $f_{128} = (\neg K_{70} \oplus K_{11} \oplus K_{16}) \wedge \neg K_{28} \oplus K_{31}$
- ▷ Returns a system of equations $\mathcal{F}$ to solve $\Rightarrow$ **algebraic side-channel attack!**
- ▷ Bad news: from $i = 177$, f_i are not only key-dependent anymore
- ▷ $\mathcal{F}_{[0,48]}$ has 49 equations for 128 unknowns $\Rightarrow$ too many solutions...

$$\begin{aligned} f_{177} = & \neg((\neg((\neg K_{70} \oplus K_{11} \oplus K_{16}) \wedge \neg K_{28}) \oplus \neg K_{31} \oplus IV_0 \oplus K_{69} \oplus K_{10} \oplus K_{15} \oplus K_{74} \\ & \oplus K_{15} \oplus K_{20}) \wedge (\neg K_{44} \oplus K_7 \oplus K_{10} \oplus K_5 \oplus K_{11})) \oplus (\neg((\neg K_{61} \oplus K_2 \oplus K_7) \\ & \wedge \neg K_{19}) \oplus \neg K_{22} \oplus K_{119} \oplus K_{60} \oplus K_1 \oplus K_{65} \oplus K_{11}) \wedge (K_{76} \oplus K_{17} \oplus K_{22} \oplus K_{40} \\ & \oplus K_3 \oplus K_{43} \oplus K_9 \oplus K_{38} \oplus K_1 \oplus K_4 \oplus K_5 \oplus K_{44} \oplus K_7 \oplus K_8 \oplus K_5 \oplus K_{11}) \\ & \oplus \neg K_{38} \oplus K_1 \oplus K_4 \oplus K_5 \oplus K_{80} \oplus K_{21} \oplus K_{26} \oplus K_{43} \oplus K_6 \oplus K_{46} \oplus K_{12} \end{aligned}$$

Distributive property of AND over XOR to the rescue!

$$\begin{aligned}
 f_{177} = & (\neg((\neg((\neg K_{70} \oplus K_{11} \oplus K_{16}) \wedge \neg K_{28}) \oplus \neg K_{31} \oplus K_{69} \oplus K_{10} \oplus K_{15} \oplus K_{74} \\
 & \oplus K_{15} \oplus K_{20}) \wedge (\neg K_{44} \oplus K_7 \oplus K_{10} \oplus K_5 \oplus K_{11})) \oplus (\neg((\neg K_{61} \oplus K_2 \oplus K_7) \\
 & \wedge \neg K_{19}) \oplus \neg K_{22} \oplus K_{119} \oplus K_{60} \oplus K_1 \oplus K_{65} \oplus K_{11}) \wedge (K_{76} \oplus K_{17} \oplus K_{22} \oplus K_{40} \\
 & \oplus K_3 \oplus K_{43} \oplus K_9 \oplus K_{38} \oplus K_1 \oplus K_4 \oplus K_5 \oplus K_{44} \oplus K_7 \oplus K_8 \oplus K_5 \oplus K_{11}) \\
 & \oplus \underbrace{\neg K_{38} \oplus K_1 \oplus K_4 \oplus K_5 \oplus K_{80} \oplus K_{21} \oplus K_{26} \oplus K_{43} \oplus K_6 \oplus K_{46} \oplus K_{12}}_{f'_{177}} \\
 & \oplus IV_0 \wedge \underbrace{(\neg K_{44} \oplus K_7 \oplus K_{10} \oplus K_5 \oplus K_{11})}_{S_{160}^{177}}
 \end{aligned}$$

- ▶ Attacking $y_{49} = f_{177} \oplus IV_{49}$ requires 2 hypotheses: $y_{49} = f'_{177} \oplus IV_0 \wedge S_{160}^{177} \oplus IV_{49}$
- ▶ The more the state is updated, the more IV bits interfere in f_i
- ▶ Still possible to isolate key-dependent variables but increases exponentially the attack complexity

Selection Functions φ_i

▷ Attacking φ_i for $i \geq 82$ is sufficient to recover the entire key [AFM18]

$\mathcal{I}$	$\varphi_{i \in \mathcal{I}}$
[0, 48]	$f_{128+i} \oplus IV_i$
[49, 57]	$f'_{128+i} \oplus (S_{160}^{128+i} \wedge IV_{i-49}) \oplus IV_i$
[58, 62]	$f'_{128+i} \oplus (S_{160}^{128+i} \wedge IV_{i-49}) \oplus (S_{193}^{128+i} \wedge IV_{i-58}) \oplus IV_i$
[63, 96]	$f'_{128+i} \oplus (S_{160}^{128+i} \wedge IV_{i-49}) \oplus (S_{193}^{128+i} \wedge IV_{i-58}) \oplus (S_{111}^{128+i} \wedge IV_{i-63}) \oplus IV_i$

Resulting Boolean System to Solve

$$\mathcal{F}_{[0,81]} = \left\{ \begin{array}{ll} (\neg K_{70} \oplus K_{11} \oplus K_{16}) \wedge \neg K_{28} \oplus K_{31} & = f_{128} \\ \vdots & \vdots \\ (\neg (K_{69} \oplus K_{10} \oplus K_{15}) \wedge \neg K_{27} \oplus K_{30} \oplus K_{127} \oplus K_{68} \oplus K_9 \oplus K_{73} \oplus K_{19}) \wedge \dots & = f_{176} \\ (f_{128} \oplus K_{69} \oplus K_{10} \oplus K_{74} \oplus K_{20}) \wedge S_{160}^{177} \oplus \neg (K_{61} \oplus K_2 \oplus K_7) \wedge \neg K_{19} \oplus \dots & = f'_{177} \\ \vdots & \vdots \\ (f_{160} \oplus (\neg K_{44} \wedge \neg K_2) \oplus K_5 \oplus K_{102} \oplus K_{43} \oplus K_{48}) \wedge (\neg K_{60} \oplus K_1 \oplus K_6 \oplus \dots) \oplus \dots & = f'_{209} \\ \neg K_{44} \oplus K_7 \oplus K_{10} \oplus K_5 \oplus K_{11} & = S_{160}^{177} \\ \vdots & \vdots \\ K_{76} \oplus K_{17} \oplus K_{22} \oplus K_{39} \oplus K_2 \oplus K_{42} \oplus K_8 \oplus K_{37} \oplus K_0 \oplus K_3 \oplus K_4 \oplus K_{43} \oplus \dots & = S_{160}^{209} \\ \neg K_{86} \oplus K_{27} \oplus K_{32} \oplus K_{49} \oplus K_{12} \oplus K_{14} \oplus K_{52} \oplus K_{15} \oplus K_{18} & = S_{193}^{186} \\ \vdots & \vdots \\ (\neg K_{51} \wedge \neg K_9) \oplus K_{21} \oplus K_{109} \oplus K_{50} \oplus K_{55} \oplus K_1 \oplus K_{72} \oplus K_{13} \oplus K_{18} \oplus \dots & = S_{193}^{209} \\ \neg K_9 & = S_{111}^{191} \\ \vdots & \vdots \\ \vdots & \vdots \\ \neg K_{27} & = S_{111}^{209} \end{array} \right.$$

From Theory to Practice – Experimental Setup

- ▷ 32-bit assembly implementation on an ARM Cortex-M3 (32 steps at once)
- ▷ Fixed hard-coded 128-bit key K = “Encryption Key K”
- ▷ Electromagnetic emanations recorded using an industrial near-field probe
- ▷ **Correlation coefficient** as statistical distinguisher and **Hamming weight** as leakage model
- ▷ 5 000 encryptions using random IVs

From Theory to Practice - Successful Results

(a) φ_0 returns $f_{128} = 1$

(b) φ_{49} returns $f_{177} \parallel S_{160}^{177} = (10)_2$

(c) φ_{58} returns $f_{186} \parallel S_{160}^{186} \parallel S_{193}^{186} = (100)_2$

(d) φ_{63} returns $f_{191} \parallel S_{160}^{191} \parallel S_{193}^{191} \parallel S_{111}^{191} = (0110)_2$

Maximizing the Practical Efficiency (Opt. 1)

$$\varphi_{i \in [63, 96]}(x, y, z, t) = x \oplus (y \wedge IV_{i-49}) \oplus (z \wedge IV_{i-58}) \oplus (t \wedge IV_{i-63}) \oplus IV_i$$

- ▶ **Nonlinearity ensures a good distinguishability** between correct and incorrect key guesses
- ▶ Additional IV bits interact with hypotheses through **bitwise AND**
- ▶ The more IV bits involved the more efficient the selection function is $\Rightarrow \varphi_{i \in [63, 96]}$ **requires less acquisitions for the correct hypothesis to stand out**

Minimizing the Knowledge of Initial Vectors (Opt. 2)

$$\varphi_{i \in [0,48]}(x) = x \oplus IV_i$$

- Knowledge of full plaintexts/IVs is sometime unrealistic in practice $\Rightarrow$ interests in attack paths given the fewer bits to consider
- ACORN defined by the concatenation of 6 LFSRs $\Rightarrow \varphi_{i \in [0,48]}$ can be used to recover up to 7 intermediate values ($f_{128+i}^1, f_{128+i}^2, \dots, f_{128+i}^6$)
- Knowledge of a single IV bit allow to recover up to 7 key bit combinations**

Summary & Comparison of our Practical Experiments

- ▷ Boolean systems were given as input to the SAT solver CryptoMiniSat 5.0 [SNC09]

	Ref.	Opt. 1	Opt. 2
IV bits to consider	$IV_{i \in [0,78]}$	$IV_{i \in [0,95]}$	$IV_{i \in [0,18]}$
# of required acquisitions	$\geq 4\,000$	$\geq \mathbf{2\,000}$	$\geq 4\,000$
# of attacked bits	79	32	$19 \times 6 = 114$
# of equations	148	128	114
# of CNF clauses	2165	1804	4251
Solving time (i5-6200U CPU)	0.05sec	0.04sec	87min17sec

Conclusion & Perspectives

- ▷ Practical full key recovery against ACORN using EM side-channels
- ▷ Open the way for evaluations of its implementations on embedded devices
- ▷ Introduced 2 optimizations regarding the reference attack
- ▷ Some selection functions require to clearly identify point-of-interests (i.e. leakages in time) $\Rightarrow$ **desynchronization countermeasures could be of great interest for this algorithm**

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Thank you for your attention

경청해 주셔서 감사합니다