Radboud University

A New Leakage Exploitation Framework and Its Application to Authenticated Encryption

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We contribute in this direction by:

- Building a new differential power analysis (DPA) framework.
- Applying this framework to NIST LWC (2018-2023) finalists.
- Showing how mode and primitive design impact leakage mitigation.

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- We demonstrate the applicability of the approach on ASCON.

Deploying:

- Using this framework, we study the SC properties of the finalists.

DPA in a nutshell

Assumption. $p_i \in_r \{0,1\}^w$ are known and $k \in \{0,1\}^w$ is unknown. For N tries, indexed by i, $f(p_i \oplus k)$ is computed, and the power trace is recorded as $\mathbf{T}_i$.

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Main SC observation. If $\mathbf{T}_i$ and $f(p_i \oplus k)$ are dependent, and f is "sufficiently" non-linear, then with enough $\{p_i, \mathbf{T}_i\}_{i=1}^{N}$, an attacker can recover k.

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- If $y_i = f(p_i \oplus k)$ is an intermediate variable, $\mathbf{T}_i$ has the required dependency.
- Usually, f is an S-box function.
- w is bit-width of the implementation, usually $w \in \{8, 32, 64\}$.
- Chunks of the target secret are processed similarly through f. This divide-and-conquer property is required for DPA attacks.

DPA challenges

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- In ISAP: inside the initialization, divide-and-conquer is thwarted.
- In Xoodyak: during encryption, if nonce uniqueness is preserved, N is bounded.

Relaxing the requirements. What happens if f is linear or identity function? Can we still recover k given enough $\{p_i, \mathbf{T}_i\}_{i=1}^{N}$?

Experimenting with XOR

Assembly code snippet to test XOR leakage.

```
...        : r3 = k   r9 = p
8000aa8: bf00           nop
8000aaa: ea89 0903      eor.w  r9, r9, r3 ; r9 = r9 ⊕ r3
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Heading/trailing nops to filter out effects of neighboring operations.

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- Trace collection is synchronized at 7.37 MHz.

Processing tools:

- Correlation power analysis (CPA), linear regression (LR), combined with deep learning (DL) techniques.

Results:

- Attacks work with around 10K traces using 100K for profiling.

More on the attack tools

Leakage model. For some noise n and constant a, the leakage buried in the traces is described as $l = a\mathsf{HW}(k \oplus p) + n$.

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Byte by Byte CPA. To estimate byte j of the key, the attacker computes empirical correlation $\text{cor}(\text{HW}(k^* \oplus p[j]), \mathbf{T})$ for all values $0 \leq k^* \leq 255$, and sorts the key hypothesis based on the results.

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Drawback. In targeting each byte, the value of the other bytes is considered as noise. This increases the number of required traces for a successful attack.

More on the attack tools

Using LR for adjusting weights. Using the traces, leakage l of a variable v in terms of its bits can be estimated with LR as $l = \sum_{j=1}^{w} a_j v[j] + n$.

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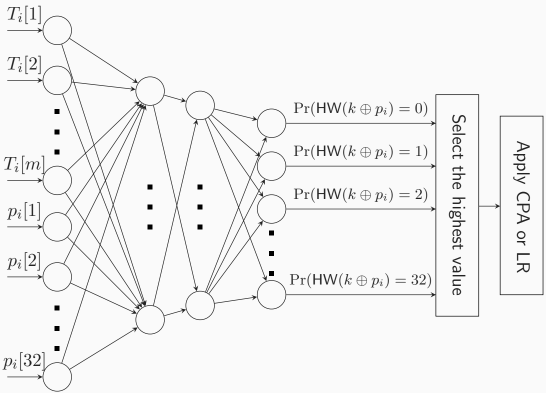
Using LR for the attack. If v is $k \oplus p$, output leakage of the XOR can be expressed in basis of bits of p as:

$$l = \sum_{j=1}^{w} a_j (k[j] \oplus p[j]) + n = \sum_{k[j]=0} a_j p[j] + \sum_{k[j]=1} a_j (1 - p[j]) + n$$
$$= \sum_{k[j]=0} a_j p[j] - \sum_{k[j]=1} a_j p[j] + b,$$

for some key-independent value b. The sign of coefficient of $p[j]$ reveals $k[j]$.

Combining CPA/LR with DL. To decrease the number of required traces, HW$(k \oplus p_i)$ can be estimated from $\{p_i, \mathbf{T}_i\}$ with DL. j in $T_i[j]$ and $p_i[j]$ denotes samples and bits, respectively.



Attack Results

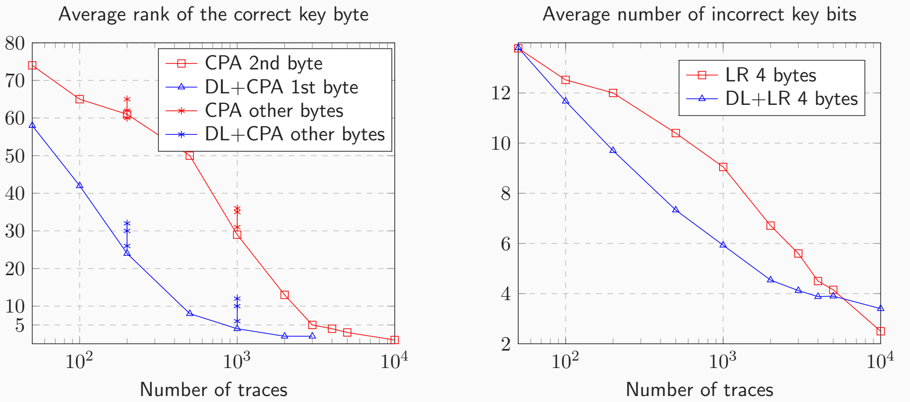


Figure: (Left) CPA with and without DL. The CPA attack for the 2nd byte produces slightly better results. DL+CPA in the used model worked better for the 1st byte. Results for other bytes are also shown. (Right) LR with and without DL.

Assumption. If w-bit chunks of an n-bit target secret are processed in $\frac{n}{w}$ separate XOR operations, each with a known random operand, the attacker can learn that secret.

Our framework

Assumption. If w-bit chunks of an n-bit target secret are processed in $\frac{n}{w}$ separate XOR operations, each with a known random operand, the attacker can learn that secret.

Application. We investigate the running assembly to find enough XOR instructions that are merging random (and known) operands with secret parameters.

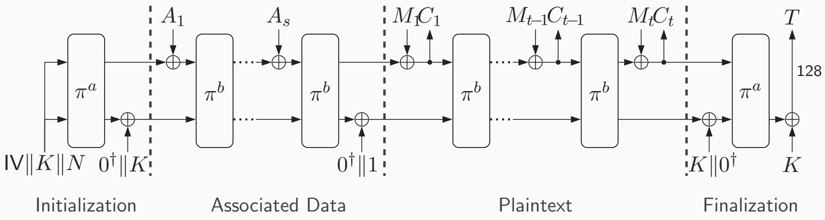


Figure: ASCON-Encryption. a and b denote the number of permutation rounds.

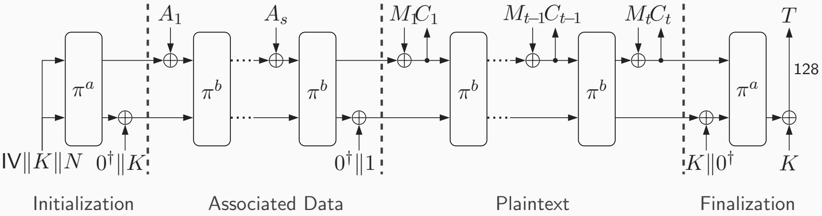
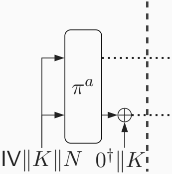


Figure: ASCON-Encryption. a and b denote the number of permutation rounds.

- K is used both in the initialization and finalization phases.
- State recovery in middle phases will not lead to key recovery or tag forgery.
- So, only the initialization and finalization need protection.
- This property is referred to as leveled masking.

Applying our framework. An optimized implementation of the initialization contains 4 32-bit XOR operations. .



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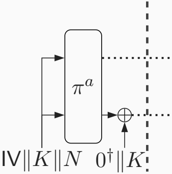

Initialization

```
... ; r0 contains address of parameters
10b60: e9d0 1205  ldrd r1, r2, [r0, #20]; r1 = K2, r2 = N1
10b64: e9d0 7601  ldrd r7, r6, [r0, #4] ; r7 = IV0, r6 = K1
10b68: e9d0 5403  ldrd r5, r4, [r0, #12]; r5 = K0, r4 = K3
... ; r1, r2, r4, r5, r6, r7 are not touched
10b7e: e9d0 ec08  ldrd lr, ip, [r0, #32]; lr = N3, ip = N2
10b82: 69c3       ldr  r3, [r0, #28] ; r3 = N0
10b84: f8d0 8000  ldr.w r8, [r0] ; r8 = IV1
10b88: f084 04f0  eor.w r4, r4, #240 ; K3 = K3 ⊕ 0xf0
10b8c: ea86 0904  eor.w r9, r6, r4 ; r9 = K1 ⊕ K3
10b90: ea88 0a0e  eor.w sl, r8, lr ; sl = IV1 ⊕ N3
10b94: ea82 0b0e  eor.w fp, r2, lr ; fp = N1 ⊕ N3
10b98: ea62 0e0e  orn  lr, r2, lr ; lr = N1|(~ N3)
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10ba0: ea82 0206  eor.w r2, r2, r6 ; r2 = N1 ⊕ K1
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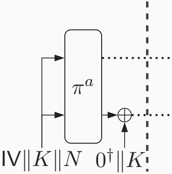

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A profiling phase is required to identify the sample index of target instructions.

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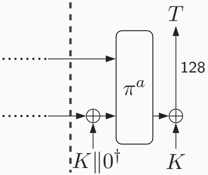

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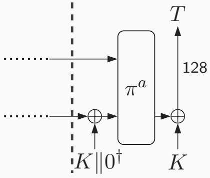

Finalization

... ; `r4` *address of state, r5 address of key*
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109b2: 69a2 **ldr r2**, [**r4**, #24] ; $\texttt{r2} = S0$
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109b6: 4050 **eors r0**, **r2** ; $\texttt{r0} = K0 \oplus S0$ $(T0 = r0)$
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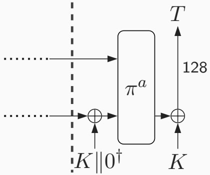

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K is also XORed with the state before the final permutation. However, there is no known data associated with this instruction. These operations can be targeted with a second-order DPA.

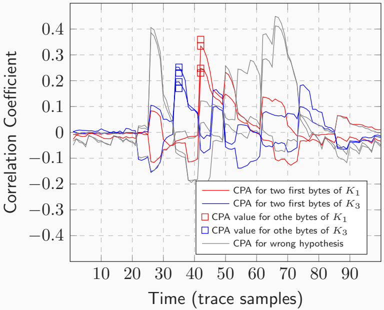
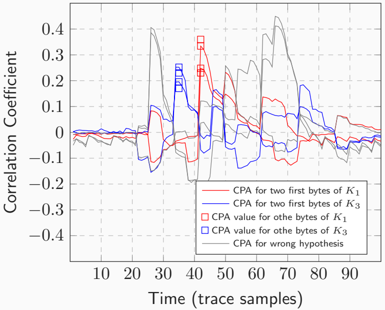


Figure: CPA results for attacking the initialization phase of ASCON.

Application to ASCON



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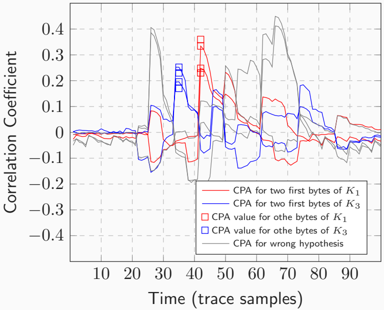

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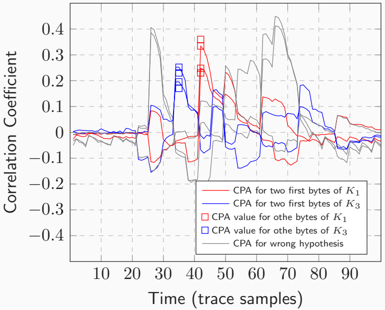

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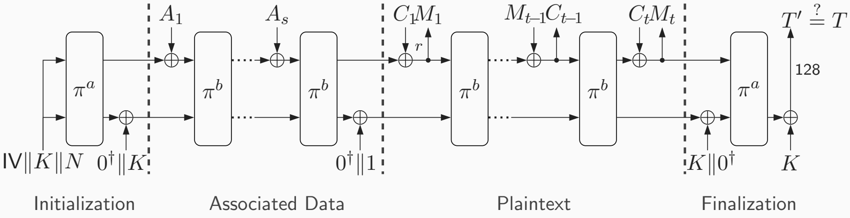
- The interval for $K1$ is one instruction after that of $K3$.
- Peaks should be compared only in their target interval.
- The attack at the finalization works, but peaks are negative.

DPA for plaintext recovery. To decrypt C_1^* (without knowing a valid tag), an attacker can ask for decryption of random C_1 using the same (N^*, A^*) and perform DPA over the XOR defined by $M_1^* = C_1^* \oplus \text{Trunc}(S^*, r)$.



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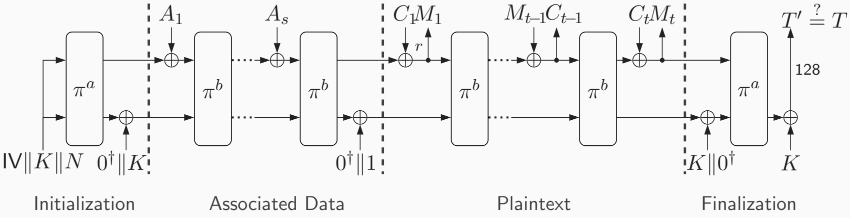

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Encrypt-then-MAC construction can prevent plaintext recovery attacks.

Application to Xoodyak

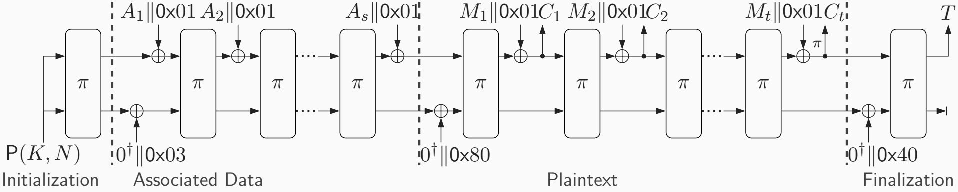

Figure: Xoodyak-Encryption, with P$(K,N) = K\|N\|$0x80$\|$0x01$\|0^\dagger\|$0x02.

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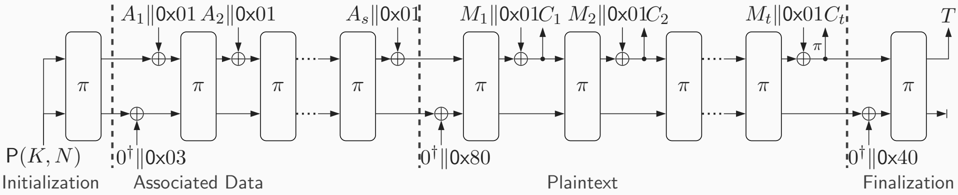

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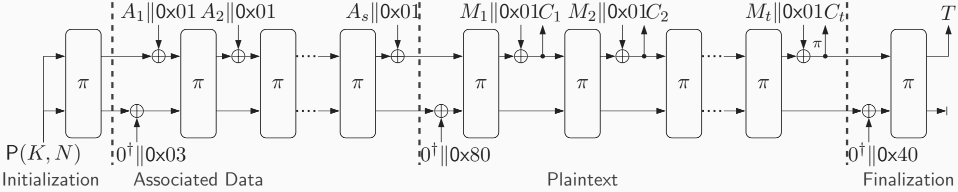
- We skip the initialization and focus on the associated data absorption phase.



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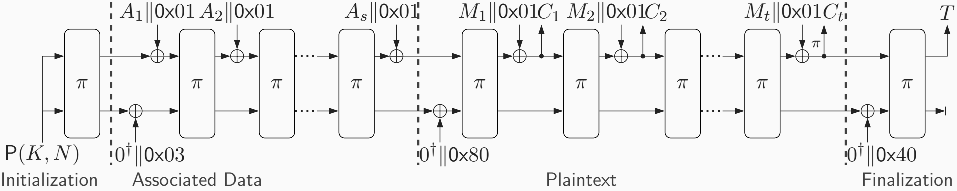
- We skip the initialization and focus on the associated data absorption phase.
- Associated data is absorbed with rate $r = 44 \cdot 8$ and state size is $48 \cdot 8$.

Application to Xoodyak



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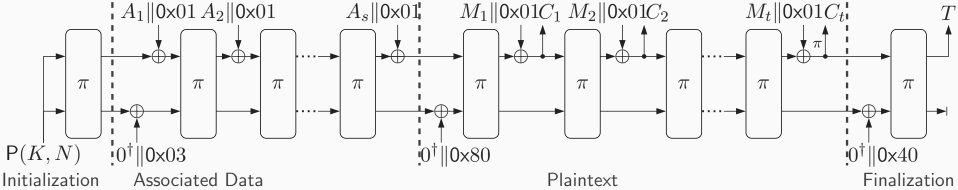

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- If the attacker is allowed to repeat the nonce, SC attack can recover the state.
- The permutation chain upgrades a state recovery attack to a key recovery attack.

Application to the other finalists

Cipher	(A)	(B)	(C)	(D)	(E)	(F)	(G)
ASCON	✓			32 bit	✓	×	
Elephant	✓			8 bit	×	✓	
GIFT-COFB	✓			32 bit	×	×	
Grain128-AEAD	×	×	✓	1 bit	✓	×	
ISAP	×	×	×	32 bit	✓	✓	✓
TinyJambu	✓			32 bit	×	×	
Xoodyak	×	✓		8 bit	×	×	×

- (A) is checked if there is a first-order DPA key recovery attack.
- (B) is checked if there is a first-order DPA key recovery attack in the fixed nonce setting.
- (C) is checked if there is only a second-order DPA key recovery attack.
- (D) shows the bit-width of the studied assembly implementation.
- (E) is checked if leveled masking is possible.
- (F) is checked if DPA for plaintext recovery is not possible.
- (G) is checked if there is an SCA-aware version that is not computationally heavier.

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Thank you for your attention!