On the Impact of Aging on Power Analysis Attacks Targeting Power-Equalized Cryptographic Circuits

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Cryptographic Circuits

- ❑ Preserving data confidentiality via cryptographic circuits

- ❑ The physical implementation can be compromised
 - Observing dynamic circuit emanations

- ❑ **Side Channel Attacks: Analyzing the physical leakage**
 - Running time
 - Electromagnetic radiation
 - Power consumption

Power Analysis Attacks

- ❑ Revealing a cryptographic device's key by analyzing its power consumption
- ❑ The key is retrieved based on the dependency of:
 - Power leakage and the data being processed
 - Power leakage and the operation being performed
- ❑ Countermeasure:
 - **Hiding**: Decreasing Signal-to-Noise ratio (SNR)
 - **Masking**: Randomizing the intermediate values
- ❑ Hiding Schemes mainly **equalize the power consumption** regardless of the data being processed
 - **Dual-Rail Pre-Charge (DRP)**:
 - Complementary Counterpart
 - Fed with the primary inputs & their complements
 - Generates the outputs & their complement

Source: Power analysis, Wikipedia,
https://en.wikipedia.org/wiki/Power_analysis

Sense Amplifier Based Logic (SABL)

- ❑ One of the main Dual-Rail Pre-Charge (DRP) circuitries
- ❑ Complementary signals:
 - **Input:** in and $\overline{in}$
 - **Output:** out and $\overline{out}$
- ❑ Operating Phases:
 - **Pre-charge:** All signal goes to LOW (0)
 - Internal nodes and capacitances all are pre-discharged
 - **Evaluation:** One rail stays at "0" and its dual goes to "1"
- ❑ Need a full custom design
 - **Differential Pull Down Network**
- ❑ Twice area & power and half clock frequency
- ✓ Avoiding glitches
- ✓ Power $\rightarrow$ independent of the data being processed
- ✓ **Significantly hinders PA attacks**

Overall-view of an SABL gate

SABL AND/NAND gate

Source: Power Analysis Attacks, Revealing the Secrets of Smart Cards, S. Mangard, E. Oswald and T. Popp

Device Aging

- ❑ Device aging is an important failure mechanism in nanoscale designs that jeopardizes the **reliability and/or security** of electronic devices
- ❑ Performance of nanoscale CMOS circuits degrades over their lifetime.

Ultimate Failure

- ❑ **Circuit aging mechanisms:**
 - Bias Temperature-Instability (BTI)
 - Hot Carrier Injection (HCI)
 - Time dependent dielectric Breakdown (TDDB)
 - Electromigration (EM)

Aging Mechanisms

□ Negative Bias Temperature Instability (NBTI)

- **Cause:** Holes creating traps between Si-SiO₂ and substrate
- **Impact:** V_{th} increase, especially for PMOS transistors

□ Hot Carrier Injection (HCI)

- **Cause:** Electrons colliding with the gate oxide (rather than going only to the conduction channel between source and drain)
- **Impact:** V_{th} increase, especially for NMOS transistors

NBTI

HCI

Impact of Aging on V_{th} of MOSFETs

- ❑ The threshold voltage of a MOSFET can be used as a parameter to regulate the trade-off between its propagation delay and its leakage current.
- ❑ Devices with a high threshold voltage are slower and can be used where timing is not critical in order to reduce the leakage current.
- ❑ By aging a CMOS circuit, the threshold voltage of its transistors increases, and the design fails to meet the timing requirements.
- ❑ The aging process can be accelerated by increasing the supply voltage and operating temperature.

Aging-induced Delay Change

- ❑ Fed with the input values that results in maximum NBTI aging
- ❑ Unprotected and SABL circuits experience different amount of delay change
 - Related to their transistor level topology
- ❑ Each path in a cryptographic device may degrade with a different rate based on:
 - Type of its underlying gates
 - The input values feeding it
- ❖ Aging can result in imbalances in the power consumption of SABL circuits.
- ❖ These imbalances can increase the success of the PA attacks on such protected devices.

Need to investigate the effect of device aging on the resiliency of SABL-Protected Circuits against Power Analysis Attacks.

Present Architecture

Targeted Circuit

- Nibble-serial PRESENT implementation with single Sbox instance:

- Design:

- Area-optimized
- Data paths are serialized to 4-bit words (one nibble)
- Requires 563 clock

- Simulation:

- RTL converted to SABL- Dual Rail
- Transistor level simulation
- Includes:
 - NMOS: 21,980
 - PMOS: 13,838

Experimental Setup

- ❑ Technology:
 - 45-nm NANGATE library
- ❑ Simulation Voltage and Temperature
 - V_{dd} : 1.2V
 - Temperature: 80°C
- ❑ Aging Evaluation:
 - Deploying Synopsys HSpice MOSRA Level 3 model
 - Assessing NBTI and HCI aging effects
 - Aging effects were assessed for 8 weeks of operations (1-week steps)
- ❑ Attack Setup:
 - Present Cipher (S-Box module) operated at 300 MHz
 - Randomly generated plaintexts and a fixed key
 - Targeting first Round: 22 Clock Cycles
 - 1665 sample points in each clock cycle

Power Change: Unprotected circuit

Experimental Results

- ❑ Five current traces corresponding to
 - Five different plaintexts
 - But the same key
- ❑ Traces extracted when one S-Box operation is performed.
- ❑ Current traces are deviating from each other in different points of time.
- ❑ The deviations can be exploited by the adversary to recover the key.

Unprotected circuit (Age=0)

Aging-induced Power Change

Experimental Results

❑ SABL Protected (Age = 0):

- The current traces are highly balanced
- This makes the device compromising highly difficult (if not impossible).

SABL Protected circuit (Age = 0)

❑ SABL Protected (Age = 8 Weeks):

- Deviates from equalized power consumption
- Deviations can be exploited by the adversary to extract the key.

SABL Protected circuit (Age = 8 Weeks)

Aging-induced Variance change

Experimental Results

- Corresponding variance of several traces for

- New circuit: Week 0
- aged circuit: Week 8

- With aging, the variance is increased

- Increase of leakage with aging

Figure: Variance traces of the SABL-protected circuit.

Aging-induced Dynamic Power Change

Experimental Results

- ❑ Dynamic power change during the computation of an S-Box
- ❑ One randomly generated plaintext
- ❑ Power traces for week 0 to 8
- ❑ **Observations:**
 - Magnitudes of the current trace changes during the device lifetime.

Current traces during the computation of an S-Box for the same input in different aging conditions

Mutual Information

Experimental Results

- MI reveals how much noise is required to avoid the exploitability of leakages.

- Observations:**

- MI drops with a higher amount of noise when the circuit is aged
- Information leakage is increased by aging in SABL circuits

SABL-Protected

Figure: Mutual Information curves associated to an S-Box input for different aging conditions.

Power Analysis Attacks

Experimental Results

- ❑ Side-channel leakage was analyzed with Correlation Power Analysis (CPA)
 - Hypothetical model to an intermediate value that depends on
 - ❖ Known input as well as (part of) the unknown key

❑ Attack Setup:

- Traces without Noise: 90
- Added noise: 100 times

9,000 noisy traces

- Repeated each attack and evaluation 50 times to remove randomness
- Power Model: Hamming weight (HW)

Suits best as the signals are set to 0 in pre-charge phase of SABL, then evaluation phase starts

PA Attacks: CPA Results

Experimental Results

Age = 0

Age = 2 Weeks

Age = 5 Weeks

Age = 8 Weeks

❖ Due to Aging: SABL-protected circuit experiences imbalances

Aged circuits Need less traces for a successful attacks

PA Attacks: Success Rate

Experimental Results

- ❑ CPA attack with HW model
 - ❑ Average success rate of the attack targeting all key nibbles
 - ❑ Success Rate:
 - Week 0: $\approx 81.4\%$
 - Week 1: $\approx 86.4\%$
 - ❑ Confirming that device aging makes the attack easier on SABL circuits.
- ↓
- ❑ Necessity of revisiting the security of power-equalized cryptographic devices with respect to aging

Figure: Attack success rate in different aging conditions

Conclusion and Future Directions

- ❑ Investigated the impact of transistor aging on the success of power analysis attacks launched on the SABL-protected PRESENT cipher.
- ❑ Device aging defeats the purpose of the SABL countermeasure, and results in power consumption imbalances originated from the change of transistors' threshold voltage over time.
- ❑ For the first time, we illustrated that such deviation of transistors specification over time can ease the attacks launched on SABL protected circuits.
- ❑ Success rate increased over 6.1% (from 81.4% to 86.4%) when targeting a 1-week-old device.
- ❑ This observation calls for proper secure implementations of cryptographic circuits that are resilient against power analysis attack over the circuit lifetime regardless of its age.

❖ Future Directions:

- ❑ Investigating the impact of device aging on the success of the attacks that exploit static power in SABL circuits
- ❑ Validating our findings on real silicon.
- ❑ Designing an aging-resilient SABL-Based circuitry to provide lifelong security for cryptographic devices

Thanks for your attention.
Any questions?