WDDL is Protected Against Setup Time Violation Attacks

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***Abstract*—In order to protect crypto-systems against side channel attacks various countermeasures have been implemented such as dual-rail logic or masking. Faults attacks are a powerful tool to break some implementations of robust cryptographic algorithms such as AES and DES. Various kind of fault attacks scenarios have been published. However, very few publications available in the public literature detail the practical realization of such attacks. In this paper we present the result of a practical fault attack on AES in WDDL and its comparison with its non-protected equivalent. The practical faults on an FPGA running an AES encryptor are realized by under-powering it and further exploited using Piret's attack. The results show that WDDL is protected against setup violation attacks by construction because a faulty bit is replaced by a null bit in the ciphertext. Therefore, the fault leaks no exploitable information. We also give a theoretical model for the above results. Other references have already studied the potential of fault protection of the resynchronizing gates (delay-insensitive). In this paper, we show that non-resynchronizing gates (hence combinatorial DPL such as WDDL) are natively immune to setup time violation attacks.**

***Keywords*-AES; FPGA; Setup violation fault attacks; WDDL; Protection against faults.**

I. INTRODUCTION

Side channel analysis or attacks (SCA) are attacks based on the analysis of the secret information (generally the encryption key) leaked from the physical implementation of the cryptographic system. The leakage is passively observed via timing information, power consumption, electromagnetic radiations, *etc*. Protection against side channel attacks is important because the attacks can be implemented quickly and at a low cost. Differential power analysis (DPA) [1] and its derivatives such as correlation power analysis (CPA) [2] correlate the leakages with an internal power model, which depends on the cryptographic key.

Several countermeasures have been devised to avoid SCA. Dual-rail with precharge logic (DPL) is one of the state-of-the-art countermeasure against SCA. In DPL, the idea is to make the power consumption of the device uniform, thus hiding the crucial information it conceals. Each signal is replaced by true and false representations. $Precharge$ & $Evaluation$ phases are alternated to ensure exactly one switching event per cycle. Wave Dynamic Differential Logic (WDDL) [3] is one of the commonly used DPL. Unlike Sense Amplifier based Logic (SABL) [4], WDDL uses standard CMOS cells. Owing to this property, WDDL can be used with any design as no special library is required. Due to the same reason it can be used in FPGAs [5], [6]. It is interesting to note that WDDL is prone to the "early evaluation" vulnerability [7], corrected from instance in SecLib [8], [9]. Despite this second-order issue, WDDL is relatively secure for a reasonable overhead. Hereafter we present our work with respect to WDDL designs.

Differential fault attacks (DFA) [10], [11], [12] also referred to as active attacks alter the functional behavior of the attacked device by injecting one or several faults. Several techniques are available to inject faults: variations of the supply voltage or clock frequency, temperature variation or irradiation by a laser beam which leads to a wrong computation result that can be exploited to perform DFA. Some countermeasures for DFA have been introduced. These countermeasures are generally based on temporal [13] or spatial [14], [15] redundancy, either in a generic manner or taking advantage of some peculiarity of the algorithm.

Here in this paper we analyze the security of WDDL against setup violation fault attacks. We implemented AES ($Singlerail$ & $WDDL$). Singlerail refers to simple version of AES and WDDL the DPL version. The sbox of the AES is implemented by calculations in composite field GF(2^4) as described in [16].

The results presented in this article are obtained with an EP1S25 Altera Stratix FPGA soldered on a Parallax evaluation board. As described in [17], [18], faults can practically be induced in an FPGA by under-powering the circuit. When we drive the FPGA at a voltage less than the nominal voltage, the propagation time of the signal increases as illustrated in figure 1. Such attacks are non-invasive in nature as the attacker does not need access to the silicon die and are therefore easy to implement. We recall that there is no straightforward mechanism to monitor either the power supply level or the frequency in commodity FPGAs. The permanent under-powering causes a phenomenon called "setup time violation" on one of the timing path of the design causing a faulty byte. We call this fault as a "byte-flip" fault, which is obtained by flipping of one or more bits in a byte. The number of bits flipped during a byte-flip is called the Hamming weight of the fault. Since cryptography involves highly complex computations it is very likely that the critical path is in the cryptographic part [19]. Such faults can be exploited using various known attacks [20], [21], [22]. Here we use Piret's attack to exploit the faults and retrieve the secret key using the method described in [20].

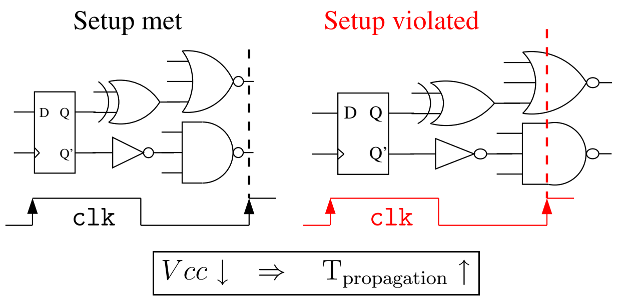
Setup met
Setup violated
D Q
Q'
clk
clk
$Vcc \downarrow \Rightarrow T_{\text{propagation}} \uparrow$

Figure 1. Setup violation.

The rest of the paper is organized as follows. In section II, we explain the WDDL rationale and the design flow to implement it. Section III describes the attack setup and the faults analysis procedure. Section IV presents the comparison of a fault acquisition campaign on single-rail and WDDL version of AES, in terms of spatio-temporal localization of faults. Section V is devoted to the theoretical demonstration of the intrinsic immunity of WDDL against setup violation attack on AES. Finally, the section VI concludes the paper and opens perspectives for better protecting sensitive cryptographic implementations.

II. Wave Dynamic Differential Logic

Power consumption of a standard CMOS cell is dependent on the transition of its input. Thus for a DPA-resistant design, a possible solution could be to introduce a family of DPA resistant cells. In a WDDL cell [3], one transition per cycle is observed, which is favourable for a DPA resistant logic style.

WDDL uses true and false representations of each signal (I/O of each cell). To make the power consumption fairly uncorrelated to the processed data, it is necessary that there should be the same number of transition every cycle. This condition is fulfilled by alternate cycles of precharge and evaluation. In the precharge phase all the signals are charged to the same level (*e.g.* 0 in WDDL) and during evaluation exactly one of the two complementary outputs is evaluated (=1). Figure 2 shows the timing diagram of WDDL AND gate. We can see that during precharge all signals are put to logic 0. During evaluation, exactly one of the two complementary inputs and outputs evaluates to 1.

In DPL, glitches make the design vulnerable to attacks [23]. Indeed, without special attention, if the inputs arrive at different moments, glitches can be observed. To avoid glitches it is necessary that all the gates in the design

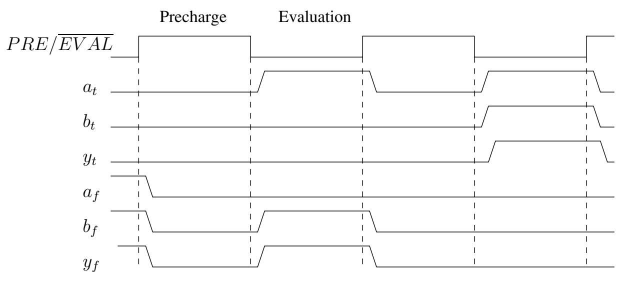

Figure 2. Timing diagram for a WDDL AND gate.

should be positive in nature. To ensure this in WDDL, the design is synthesized with a library consisting of only positive gates (like AND, OR) [24]. As shown in figure 3, a WDDL AND gate consists of an AND gate (G) and a complementary OR gate (G^*, satisfying $G^*(x) \doteq \overline{G(\overline{x})}$). For sequential circuits, each flip-flop is replaced by a pair a flip-flops. This double flip-flop allows the precharge wave to propagate through the whole design as all the gates are positive. It has to be noted that inverters in WDDL are implemented by crossing the true and false signals of the same variable.

A point worth noting in figure 3 is that one flip-flop in the single-rail design is replaced by four flip-flops in the WDDL design. This is explained as follows. During the precharge phase, the combinatorial part of the circuit will be discharged to 0 and this 0 is stored to the first of the two flip-flops. The second flip-flop will store the result of the last computation. In the evaluation phase, the value stored in the second flip-flop serves as input and the output is stored in the first flip-flop. In the mean while, the zero stored in the first flip-flop is shifted to the second flip-flop to allow proper precharge of the circuit ahead in the next cycle. This phenomenon happens in both true and false rail. Thus the number of flip-flops is quadrupled in the WDDL design.

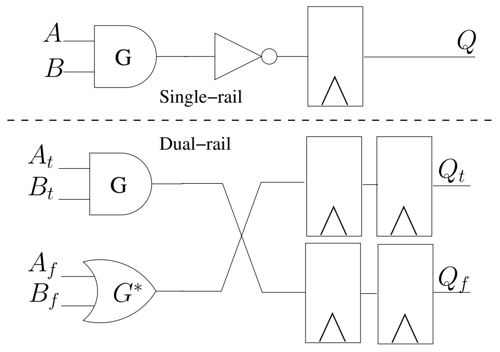

Figure 3. WDDL building block.

In our implementation, we use a different way to ensure all positive logic. Instead of using positive gates, we use a library containing all look-up tables (LUTs) which implement a positive function. This technique is called WDDL+ in [25].

A. Design Flow for WDDL Implementation

As every digital system, cryptographic coprocessors can be separated into control and datapath parts. As the secret key is used only in the datapath part, leakage from the control part is not crucial. Thus to assure security of the design it is sufficient to implement only the datapath in WDDL. This will also save area as WDDL takes more area on the FPGA than a single-rail design. The design flow to implement a cryptographic coprocessor on an FPGA is shown in figure 4. The datapath is first synthesized using an ASIC synthesizer taking advantage of a library with only positive LUTs (the FPGA synthesis tool does not provide enough options to limit the library therefore we use an ASIC synthesizer). Then the output netlist is processed using a custom tool (called vDuplicate in figure 4) which converts a single-rail netlist into a WDDL netlist. The controller is then connected to the WDDL datapath using a wrapper. The FPGA vendor tool does synthesis, mapping, placing & routing for the whole design on the FPGA.

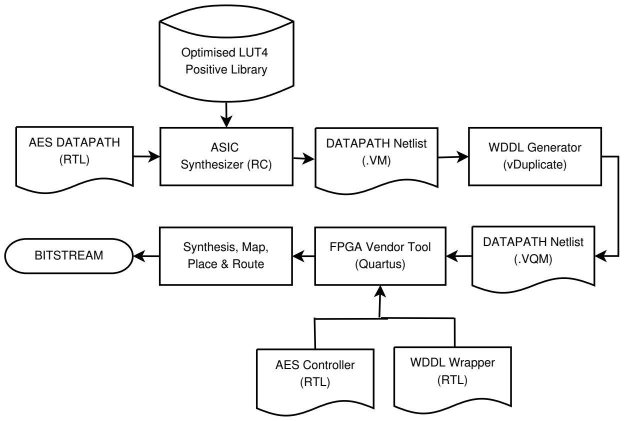

Figure 4. WDDL design flow.

B. Dualization of single-rail design

As mentioned earlier, the controller of the cryptoprocessor is not converted to WDDL technology. To make the same controller work with the WDDL version of the datapath, there is a need to introduce an extra input to the controller. As the WDDL datapath will precharge in one cycle and evaluate in the next cycle, we require the controller to work every alternate cycle (evaluation) and freeze during the precharge phase. A enable signal driven at half the clock frequency is introduced to provide this functionality.

One more modification is required in the design. The I/Os of the WDDL datapath are dual-rail, while the signals from controller to datapath and the global I/Os are single-rail. Therefore we need to create a wrapper which will make the single-rail and the WDDL parts compatible. As shown in figure 5, all the inputs to the datapath (I & C) are transformed into dual-rail (true and false) signals using inverters. A signal phase is introduced to make the datapath inputs compatible with precharge and evaluation phases. When phase is precharge, both the true and false inputs are discharged to 0. During the evaluation phase, exactly one of the complementary input charges to 1. For the output (O) as shown in figure 5, the true output is `AND`ed with the inverted false output. Only taking the true output while leaving false output unconnected is also an option. The reason for using both the outputs is to make sure that the FPGA vendor tool doesn't remove the unconnected false output during optimization in placement and routing steps, as the optimization will create an unbalanced design. After the wrapper has integrated the WDDL datapath and the controller, it seems to work as a single-rail design from the top. Therefore now the design could be simulated, synthesized or tested as a single-rail design using the same softwares. In this way, if the results are same for single-rail and WDDL, we are ensured that the two designs are functionally equivalent.

When both the designs are synthesized, the single-rail design works at a frequency of 54.5 MHz using 10% of the FPGA logic. On the other hand, the WDDL design as expected works at a frequency of 22.01 MHz which is less than the half of the single-rail frequency due to two phase operation in WDDL. The WDDL design uses 51% of the logic blocks i.e. 5 times more than the single-rail design. The overhead of 5 times is due to the fact that 20 instantiations of sbox is used and each sbox is replaced by a true and false sbox which makes the design huge.

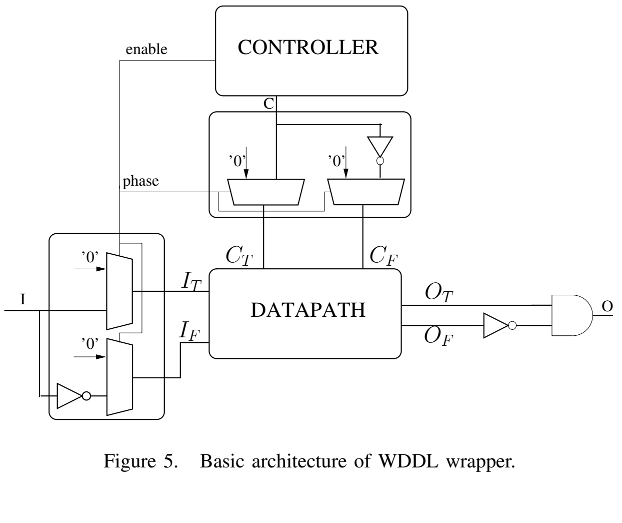

Figure 5. Basic architecture of WDDL wrapper.

III. Setup for fault attacks on FPGAs

In order to induce faults during the execution of the algorithm we drive the core of the FPGA at a non-nominal continuous voltage Vcc. The power supply is remotely controlled using GPIB cable.This feature allows us to test various values of input voltage successively. For each value of Vcc, the triples $\{$message, key, ciphertext$\}$ are recorded for 1,000 encryptions at each 100 values of Vcc. Figure 6 sketches the experimental setup. The testing platform is a stratix FPGA soldered on a parallax board. The FPGA is powered by the progarammable power supply. The rest of the board is powered by a 5V constant supply.

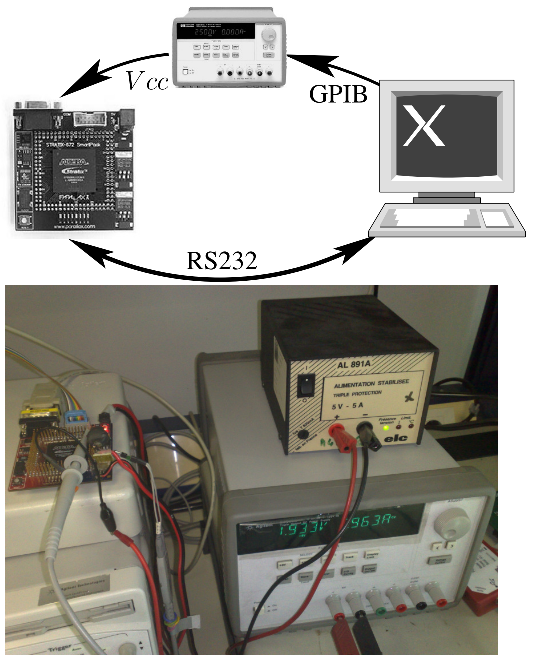

Figure 6. Experimental platform.

Once acquisition is done, we use a software for an offline analysis of the collected ciphertext in order to detect single byte errors that occur during the encryption. A modified RTL description of AES where faults can be injected at any byte of the ten rounds is used to generate a dynamic database. The database consists of all possible ciphertexts generated only by single faults for each key, message pair. Then we test if the faulty ciphertext matches an entry in the database. If so, the fault is said "covered" otherwise the fault is said "uncovered" and the ciphertext is affected by multiple byte faults. If a fault is covered, the software provides the location, the value of the faulty byte, its corresponding correct byte and the Hamming weight of the fault. The purpose of this implementation is to identify the typology of single faults that occurs in the FPGA.

If the fault is "covered" then we can identify the round and the sbox affected by the fault. This concludes that the voltage reduction generates random single faults that most differential attack models are based on. In this experiment we use a global non-invasive fault injection technique. The propagation time increases with the decrease of the power supply and faults are caused by an early latching of a combinatorial function as shown in figure 1.

IV. Experimental Results

In this section, the fault analysis is used to find the occurrence of a single byte fault that affects the state matrix of AES. Both single-rail and WDDL versions are tested against setup violation faults. Faults detected are those occurring only in the datapath, while the key schedule is assumed here to be fault-free. Indeed, in our design, the key schedule block is not critical in timing.

Figure 7a shows the occurrence of faults in single-rail implementation. We can see that the graph of single faults has a bell-shaped distribution. As we decrease the voltage beyond a certain threshold, setup time is violated on multiple paths and faults become multiple (uncovered). The maximum percentage of single faults is 39% at a voltage of 1.256 V as shown in figure 7a. All single faults are analyzed in terms of spatio-temporal locality: Figure 8a and figure 9a. 26% of single faults occur in round 8 and 12% of them occur in round 9 (refer figure 8a). Such faults are exploitable using Piret's Attack. Thus the single-rail implementation of AES with SBOX in LUT is not protected against "setup violation" attacks.

For the WDDL version of AES, the results are shown in the figure 7b. Since we use only positive LUTs to implement WDDL, there are no glitches in the circuit. When we run the fault attack campaign on WDDL design, less than 2% of the detected faults are single and all of them fall in the last round of AES as shown in figure 8b. These faults are not exploitable and thus the key cannot be retrieved using Piret attack. The software for fault analysis allows us to see faulted bytes and its corresponding correct value (value of byte if not faulted). We find that everytime a fault occurs, the faulted value C^* is less than its corresponding correct value C, in a bitwise sense: $C \,\&\, C^* = C^*$. This comes down to using the partial order $\preceq$, defined bit by bit in the following truth table:

C	C^*	$C^* \preceq C$
0	0	1
0	1	0
1	0	1
1	1	1

This means that all the faults are caused when an expected '1' takes a value equal to '0'.

The reason why all the faults are seen in the last round is as follows. When an XOR gate is implemented using positive logic, it is a combination of AND, OR gates and inverters (for inverted inputs). These inverters yield a mixture of true and false part of the design as per the definition of XOR. Thus a fault occurring in a true part is further corrupted by mixing with the false part and vice versa. The MixColumns operation involves a lot of XOR operations. Therefore a MixColumns operation after a fault will corrupt the fault which cannot be detected. Since the last round does not have MixColumns, the faults are detected but not exploitable. One interesting observation was that every time a byte is affected by a fault, a null byte in the ciphertext was reflected at its expected place. This means that even after successfully injecting the fault during encryption and precisely knowing the location of the fault, the output does not give any information which can be acted upon to retrieve the hidden secrets. The results observed are easily reproducible. This means that for a particular voltage lower than the nominal voltage, if the ciphertext and input message are constant, the fault is often in the same sbox. This feature gives us better flexibility for complete analysis of these faults. Therefore, a WDDL design is naturally secure against setup violation faults. This has been further explained in the section V-A.

V. Theoretical Fault Analysis

The purpose of this section is to show that the fault model corresponding to a setup violation time has the consequence that all DFAs on AES in WDDL are impractical.

A. Fault Analysis on AES in WDDL with SubBytes in LUTs

1) Fault Model: In an under-powering or overclocking attack, faults arise from a setup time violation [17], [18]. Authors of paper [26] argue that the effect of a glitch on the power supply increases the propagation times of all the signals, which makes this disturbance similar in effect to the global chip under-powering. As the WDDL protocol with a (0, 0) spacer starts in evaluation step with all the nodes voltage equal to zero, the evaluation consists in propagating rising transitions along exactly half of the wires. If by any means, an attacker manages to trigger a setup time violation, the consequence is an asymmetric bit flip: only 1 to 0 errors are considered. Therefore, the consequence of the fault is to leave (at least) one dual-rail signal in its (0, 0) precharge state, while the others couples of wire are in legal (0, 1) or (1, 0) evaluation state.

As already discussed in Sec. IV, the error is likely to happen for a few dual-rail signals if the stress level is low. This invalid data representation will then propagate through the next round logic. Four cases are possible:

1) the protocol error can turn into functional errors on the data or not, and
2) the protocol errors can vanish while flowing through the combinatorial logic (self protocol healing), or, at the opposite, be amplified.

Table I
Modified functionality of an AND gate in the presence of erasure faults.

Correct computation								
a	b	a_t	a_f	b_t	b_f	c_t	c_f	c
0	0	0	1	0	1	0	1	0
0	1	0	1	1	0	0	1	0
1	0	1	0	0	1	0	1	0
1	1	1	0	1	0	1	0	1

Faulted computation								
a	b	a_t	a_f	b_t	b_f	c_t	c_f	c
NULL	0	0	0	0	1	0	1	0
NULL	1	0	0	1	0	0	0	NULL

Table II
Modified functionality of an XOR gate in the presence of erasure faults.

Faulted computation								
a	b	a_t	a_f	b_t	b_f	c_t	c_f	c
NULL	0	0	0	0	1	0	0	NULL
NULL	1	0	0	1	0	0	0	NULL

The next section shows that functional errors occur, corresponding to bits erasure. In addition, the erasure rate increases: one single error at the entrance of a round will trigger many invalid precharge bits to be generated, and we show that in a reasonable cryptographic algorithm (no computation is done uselessly), the erasure rate increases. The consequence is that, after some percolation in the combinatorial logic, most of the values are erased.

2) Propagation of Faults: We start this analysis by the example of two representative gates: the AND and the XOR functions each having two inputs that we note a and b. We assume in this study that the fault occurs on input a. In evaluation, instead of having $(a_t, a_f) = (0, 1)$ when $a = 0$ and $(a_t, a_f) = (1, 0)$ otherwise, we simply have $a_t = a_f = 0$, which can also be expressed as a=NULL. The logic that implements the AND gate is $(c_t, c_f) = (a_t \cdot b_t, a_f + b_f)$. When a is faulty, the Tab. I function degenerates to AND$(a^*, b) = 0$ if $b = 0$, and NULL otherwise.

The same analysis can be carried out for the WDDL XOR gate in figure 10. The logic that implements the WDDL XOR gate is $(c_t, c_f) = (a_t \cdot b_f + a_f \cdot b_t, (a_f + b_t) \cdot (a_t + b_f))$. This equation shows that if we have a faulty input $(a_t = a_f = 0)$ then the output will be NULL $(c_t = c_f = 0)$. Thus the XOR gate has a maximum error propagation since the error is propagated for any value of b as shown in table II.

Now, for any function f, we have this property:

Definition Let f be a positive Boolean function with inputs

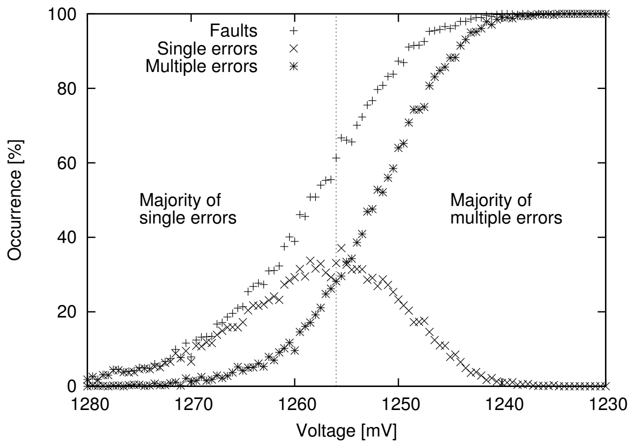

Figure 7a. Occurrence of Fault — Singlerail.

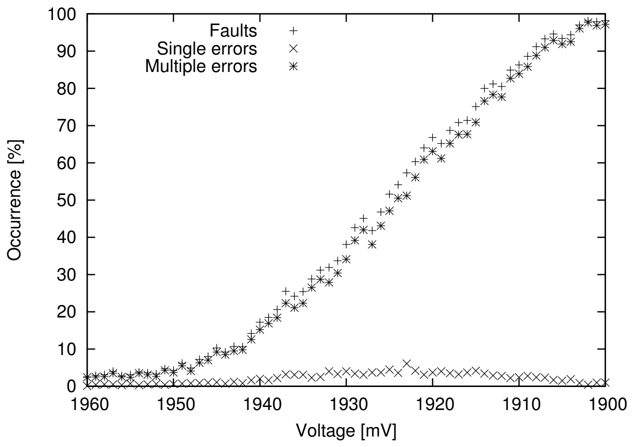

Figure 7b. Occurrence of fault — WDDL.

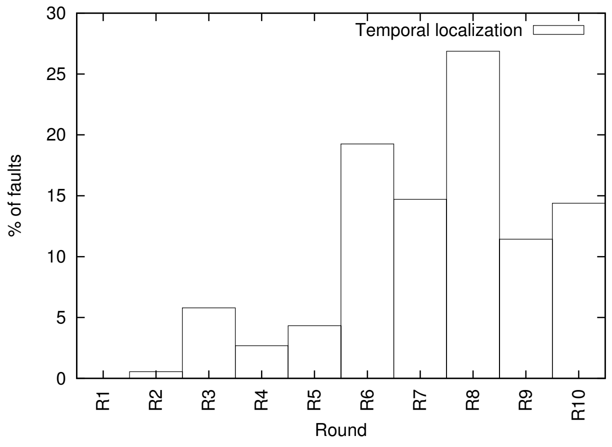

Figure 8a. Temporal localisation — Singlerail.

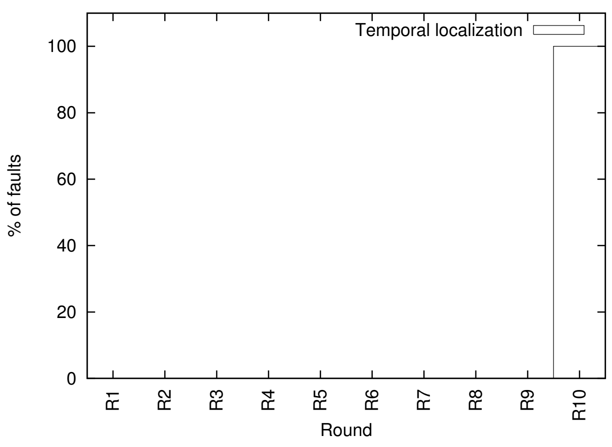

Figure 8b. Temporal localization of fault — WDDL.

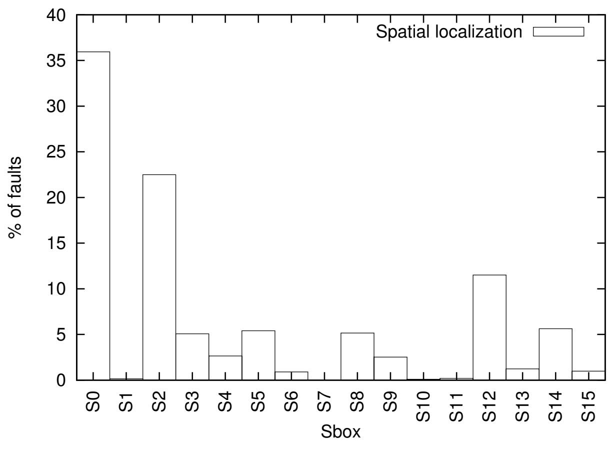

Figure 9a. Spatial localisation — Singlerail.

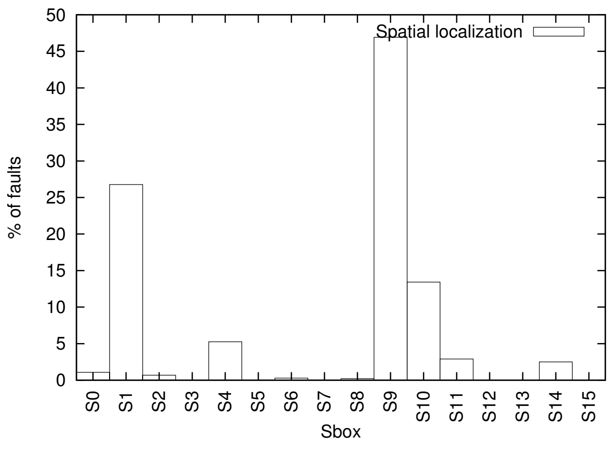

Figure 9b. Spatial localization of fault — WDDL.

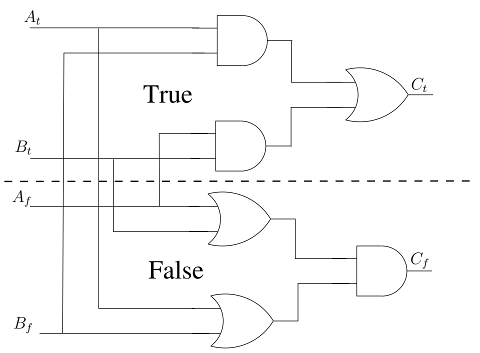

Figure 10. WDDL implementation of the XOR gate.

(a, b) then its WDDL equivalent F can be defined as:

$$\begin{cases} F_t(a_t, b_t) & = & \underline{f(a_t, b_t)}\,, \\ F_f(a_f, b_f) & = & \overline{f(\overline{a_f}, \overline{b_f})}\,. \end{cases}$$

The output of f is correct when f does not depend on the faulty input, and erased otherwise.

The proof is straightforward. If the output does not depend on the faulty input, the computation is correct for both the true and the false outputs, because the protocol violation does not impact the result. On the contrary, for the configuration of non-faulty inputs b such as F depends on the faulty input bit, then we have four cases:

1) $F_t = F_f = 1$: impossible since F is positive and the inputs are lower than a legal value, that is either (1, 0) or (0, 1),
2) $F_t = 1$ and $F_f = 0$. In this case, $1 = f(0, b)$ [equation for F_t] and $0 = \overline{f(\overline{0}, \overline{\overline{b}})} = \overline{f(1, b)}$ [equation for F_f] , *i.e.* $1 = f(1, b)$. Therefore $f(0, b) = f(1, b)$. However, we assumed that F does depend on the first faulty input, hence a contradiction.
3) $F_t = 0$ and $F_f = 1$: for the same reason, this case is incompatible with the input configuration such that F does depend on the faulty input.
4) Consequently, the only possibility is that $F_t = F_f = 0$, hence a NULL propagation.

Let us now study a random function, modeling the byte substitution table (SubBytes) of the AES. If there is a NULL fault at the input, then:

- for one half of the input data, a specific output bit will depend on this input, and
- for the other half, the targeted output bit does not depend on the input.

Therefore, statistically, one half of the output bits are erased to NULL. Notice that this result is independent of the exact functional decomposition in a positive dual gates netlist. Similarly, if two inputs are erased, then 3/4 of the outputs will also be NULL. And of course, when seven or eight errors are presented at the input, all the output bits become NULL.

Table III
EQUATIONS FOR THE BYTES TRANSFORMATIONS $\times 01$, $\times 02$ AND $\times 03$.

a'	$a \times 01$	$a \times 02$	$a \times 03$
a'_7	a_7	a_6	$a_7 \oplus a_6$
a'_6	a_6	a_5	$a_6 \oplus a_5$
a'_5	a_5	a_4	$a_5 \oplus a_4$
a'_4	a_4	$a_3 \oplus a_7$	$a_4 \oplus a_3 \oplus a_7$
a'_3	a_3	$a_2 \oplus a_7$	$a_3 \oplus a_2 \oplus a_7$
a'_2	a_2	a_1	$a_2 \oplus a_1$
a'_1	a_1	$a_0 \oplus a_7$	$a_1 \oplus a_0 \oplus a_7$
a'_0	a_0	a_7	$a_0 \oplus a_7$

Table IV
TRUTH TABLE FOR THE UNIVERSAL GATE AND.

AND	**'0'**	**'1'**	**'U'**
'0'	'0'	'0'	'0'
'1'	'0'	'1'	'U'
'U'	'0'	'U'	'U'

We have already shown in section V-A2 that with XOR gates the fault propagation is maximal. The MixColumns transformation is a multiplication of a polynomial over $GF(2^8)$ with the fixed polynomial $a(x)$[1], reduced modulo $x^4 + 1$.

$$a(x) = (\texttt{0x03})x^3 + (\texttt{0x01})x^2 + (\texttt{0x01})x + (\texttt{0x02}) \quad (1)$$

The equations for the byte multiplications involved in this multiplication are written down in Tab. III. Hence we see that the MixColumns operation is implemented as a tree of XOR gates. This ensures a maximum propagation of NULL.

In an SPN (substitution permutation network) like AES, the fault number can only grow at each step. Indeed, for every block f, if a fault is stopped, then: $f(\texttt{'U'}, x)$ is certain, for a given input x. Now, this means that $f(\texttt{'0'}, x) = f(\texttt{'1'}, x)$, and this implies that f is not bijective. Therefore, differential attacks become difficult as the attacker observes an erased value, and cannot backtrack from the faulty ciphertext. The best case being when all the output bits are erased and thus no information that can be useful to generate the key is available.

Unlike byte-flips induced by a laser, the setup time violation on WDDL causes no computation to be wrong. Instead, when an input is partially NULL, the logic evaluates the bits that can be correct for sure, but answers NULL if it cannot decide. Therefore, the propagation model is that of `'U'` in VHDL [27]. The logic tries to evaluate bits that would not be wrong if any correct value (`'0'` or `'1'`) were used instead of `'U'`. We recall in Tab. IV the extended truth table of the universal gate `AND` over $\{\texttt{'0'}, \texttt{'1'}, \texttt{'U'}\}^2$.

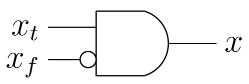

Figure 11. Dual-to-single rail circuitry usable in the case of a NULL0 spacer.

As shown in Fig. 11, the conversion of the dual-rail signals to single-rail turns a NULL into a `'0'`. This circuit makes use of both true and false signal halves, so as to prevent the CAD tool from simplifying half of the logic and balance the true and false networks. Therefore, if a fault occurs during the computation, it can be observed. This difference could be exploited by an attack, as done in the attack of Gilles Piret. However, the computed differential will not disclose any information about the last round key, since the XOR function used to mix it propagates a NULL.

All the considerations detailed regarding WDDL rely on the fact the gates are positive. Indeed, the gates will stick to zero unless valid values are produced. This is not true for delay insensitive gates which stay in a zero state and jam the computation. Notice that in WDDL the results are independent of the type of spacer used. It can be $NULL0 \doteq (0,0)$, $NULL1 \doteq (1,1)$, used as constants or interleaved alternatively or randomly.

3) Generalization to Arbitrary Fault Models: We consider two categories of faults:

1) **Asymmetric faults**, where bits can only be flipped from 1 to 0. This type of faults is typical encountered in WDDL circuits stressed by a global perturbation, such as under-voltage or over-clocking. Glitch attacks can lead to the same symptom, because it manifests in adding a delay globally to all wires. Flash of white light have been reported in [28, §12, page 163] to zero selectively the output of some operations. Equally, laser shots on SRAM-based FPGAs tend to favor $1 \to 0$ bit-flips over $0 \to 1$ [29]. Notice that in DPL with a (1, 1) spacer, the opposite transition occurs when trying non-invasive attacks. We do not detail this situation as it is the exact opposite of the 1 to 0 case.
2) **Symmetric faults**, where bits are susceptible of toggling in both directions. Laser shots can trigger both 1 to 0 and 0 to 1 transitions. This fault is thus semi-invasive, as opposed to the previous ones. Therefore, it models a more powerful attacker, at least able to chemically prepare the sample to attack.

In the context of asymmetric faults, DPL circuits are natively protected as such. In this respect, it is interesting to compare the pros and the cons of synchronous and asynchronous circuits. When exposed to under-voltage, asynchronous circuits will continue to work, down to a voltage value where the gates will not be supplied enough to produce a strong one. Below this threshold, errors of type "stuck at zero" will manifest, exactly as in the case of synchronous circuits. Overclocking is not an attack that applies to asynchronous circuits that are, by definition, clockless. However, we have noticed that this perturbation is ineffective is exposing secrets. Therefore, a synchronous circuit will be less reliable in the presence of non-invasive faults, but as secure as an asynchronous circuit. A trade-off between the two approaches can be reached by considering synchronous circuits with jitter on the clock. The jitter can have a large variance, since even if it conducts to a setup time violation, the secrets remain safe. Therefore, with DPL, it is secure when used in addition with aggressive clock jitter.

If the attacker has the means to inject symmetric faults, then three types of protections must be considered:

1) When the fault induction is gentle, single bit flips is the most likely fault model. In this case, even if the fault is a 0 to 1 transition occurring during the evaluation stage, the only risk is to create a (1, 1), also called NULL1. However, in a dual way of the case study of the propagation of NULL0 values, we can show that the propagation of NULL1 consist in an erasure of the data, so that the syndrome does not convey any single bit of information about the faulty circuit internal state. DPL style thus forces the attacker to be less furtive.
2) With a more intense stress, the attacker will start to induce multiple faults with low multiplicity. In this case, a DPL gate can output completely false values. For instance, an AND gate for which the inputs are NULL0 and NULL1 evaluates to the correct value 0 (with respect to WDDL valid states), even if the two unfaulty inputs were both equal to 1. To protect the implementation against those attacks, additional detection hardware must be added so as to cross-check the computation. A little gain can however be obtained: As the DPL style is protected against single faults, a datapath of n bits can be checked with code words of only $n-1$ bits without risking to weaken the security level. A protection method at the technological level such as the one presented in [30] could be extended from SRAM points to DFFs and combinatorial gates. By using high-VT P transistors (those that compute the `'1'`) and low-VT N transistors (those that compute the `'0'`), the designer could make the faults $1 \to 0$ much more likely than the opposite $0 \to 1$.
3) When the stress is very strong, then we expect the faults to be very frequent. Hence the recommendation to use physical captors spread on the chip surface.

Now, if we consider only asymmetric faults, we could think that power analysis could be made possible by the fault injection. Indeed, if DFA does not expose the key, it at least indicate to the attacker that a fault has happened. More precisely, we could imagine to correlate the amount of detected faults to a side-channel, in a view to establish correlations. Indeed, in nominal operation conditions, the activity is constant: half of the gates commute in each clock cycle. When a fault is injected, the activity will become lower:

- in a fault position dependent fashion (for sure), as illustrated in Fig. 12,
- but perhaps also in a data dependent fashion.

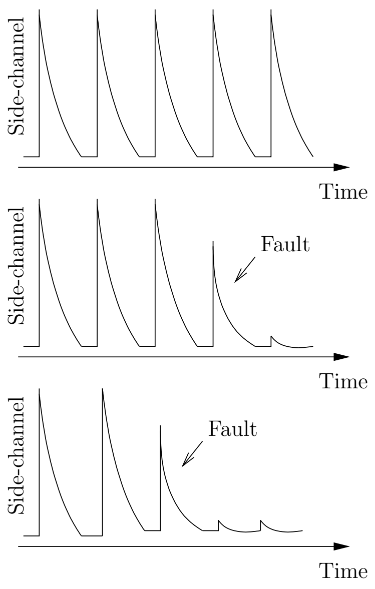

Figure 12. Power dependence of a WDDL circuit in the faults.

However, such an attack cannot be mounted, since if a sensible variable is faulty, irrespectively of its value, the fault will generate a NULL0. Therefore, after the fault, the system has forgotten its value, and computation (in terms of number of toggles) will continue in similar ways. This argument is confirmed by the practical observation of power consumption of WDDL AES as shown in figure 13. We can see that the power consumption of the device is abruptly reduced as soon as the fault occurs approximately at time 2130 ps. The power consumption further reduces after two cycles and remains constant till the end of encryption. It takes exactly 2 cycles (1 ShiftRows and 2 MixColumns) for NULL0 to diffuse through the whole design. This holds even if the DPA protection has a second order flaw, such as early evaluation. The only way to take advantage of such a flaw is to exploit it without faults. Indeed, to rephrase why DFA does not help the DPA, with faults, the distinctions of power curves at second order simply disappear. We cannot show any experimental curve to illustrate this point since we have no mean to deduce the bit concerned with the fault based on the sole knowledge of the ciphertext.

Finally, we attract the reader's attention to the fact that vulnerability analysis of WDDL against faults exploitation

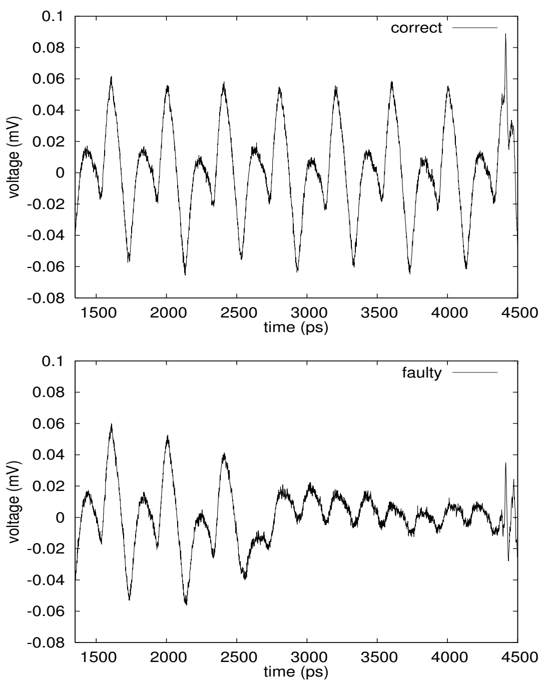

Figure 13. Practical power consumption of a WDDL circuit in the faults.

or DPA in the presence of faults has been argued in the precharge to evaluation step. However, it can be transposed without any change to the case of evaluation to precharge step. Indeed, the circuit's behavior is unchanged, except that $0 \rightarrow 1$ transitions are replaced with $1 \rightarrow 0$. And the attacker has less insight, since he cannot observe the faults occurring in the precharge stage, that are filtered out by the WDDL circuit wrapper described in Sec. II-B.

B. Counter-Measures against Non-Invasive Attacks

A straightforward countermeasure against non-invasive attacks on various circuits (not only DPL) consists in inserting into the circuit some logic in charge of detecting abnormal situations before the critical parts of the designs become faulty. For instance, in Fig. 14, a setup consisting of an even number of inverters between two registers is presented. The source register invert its value every cycle and the combinatorial chain of even number of inverters computes always the same value. At the end of the chain, a destination register checks that the value computed by the chain. The setup time of the invertor chain is violated if the monitored (output) value is different than the input. Hopefully, if the chain is designed to be longer than the critical path, an alarm is raised before the cryptographic parts of the design become faulty.

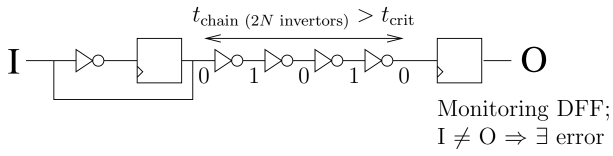
$t_{\text{chain }(2N\text{ invertors})} > t_{\text{crit}}$
I
0
1
0
1
0
O
Monitoring DFF;
I $\neq$ O $\Rightarrow \exists$ error

Figure 14. Counter-measure based on the insertion of a monitoring logic with a propagation time larger than the critical path of the rest of the circuit.

VI. Conclusion

Information masking and hiding are two concurrent protection techniques against side-channel attacks. Last year at FDTC, Arnaud BOSCHER and Helena HANDSCHUH showed that masking does not protect against fault attacks [31]. On the contrary, we have demonstrated theoretically and shown practically that information hiding (such as DPL) makes it difficult to mount fault attacks, since faulty outputs reveal no information about the keys. Unlike the "differential behavioral attack" (DBA), where a simultaneous observation of the faulty message and of the power curve empowers an attacker into mounting an attack, in the case of WDDL the attacker cannot learn anything from power curve corresponding to a faulty encryption.

We show, for the first time, that asymmetric fault attacks in general being not a threat for DPL circuits. As a perspective, we can study whether or not more traditional faults model (such as the byte-flip caused by a laser spot) also leads to unsuccessful attacks. Provided this analysis turns out to be correct, all previously proposed countermeasures against DFA for WDDL would be useless: for instance, the alarm (namely the `('1', '1')` state) propagation scheme presented in [32] warns of a possible attack against which the circuit is already natively immune.

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