Feeding Three Birds With One Scone: A Generic Duplication Based Countermeasure To Fault Attacks

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***Abstract*—In the current world of the Internet-of-things and edge computing, computations are increasingly performed locally on small connected systems. As such, those devices are often vulnerable to adversarial physical access, enabling a plethora of physical attacks which is a challenge even if such devices are built for security.**

As cryptography is one of the cornerstones of secure communication among devices, the pertinence of fault attacks is becoming increasingly apparent in a setting where a device can be easily accessed in a physical manner. In particular, two recently proposed fault attacks, Statistical Ineffective Fault Attack (SIFA) and the Fault Template Attack (FTA) are shown to be formidable due to their capability to bypass the common duplication based countermeasures. Duplication based countermeasures, deployed to counter the Differential Fault Attack (DFA), work by duplicating the execution of the cipher followed by a comparison to sense the presence of any effective fault, followed by an appropriate recovery procedure. While a handful of countermeasures are proposed against SIFA, no such countermeasure is known to thwart FTA to date.

In this work, we propose a novel countermeasure based on duplication, which can protect against both SIFA and FTA. The proposal is also lightweight with only a marginally additional cost over simple duplication based countermeasures. Our countermeasure further protects against all known variants of DFA, including Selmke, Heyszl, Sigl's attack from FDTC 2016. It does not inherently leak side-channel information and is easily adaptable for any symmetric key primitive. The validation of our countermeasure has been done through gate-level fault simulation.

***Keywords*—**Fault Attack, Countermeasures, DFA, SIFA, FTA

I. Introduction

With the growth of highly constrained devices that perform cryptographic operations, the implementation related attacks are posing a serious threat. Such devices are deployed in what could be potentially hostile environment, thus allowing any malicious third party (henceforth denoted as, the *attacker*) to extract secret information by any means necessary. In particular, when the device is carrying out a cryptographic operation, the attacker may passively observe its physical footprint (such as power consumption) or actively alter its normal course of action (such as a voltage glitch that flips a particular bit). The former type of attack is known as *Side Channel Attack* (SCA) [1], and the latter as *Fault Attack* (FA) [2].

The focus of this work is fault attack and how to efficiently protect against such attacks in context of symmetric key cryptography. The first and one of the most commonly used models for fault attack is the so-called *Differential Fault Attack* (DFA) [3]. This fault model works by first injecting a non-zero difference δ in the processed data (typically near the end of the cipher execution). Then, the relationship between δ and resulting output difference Δ reveals the secret information. To resist against DFA, duplication based countermeasures have been widely proposed in the literature [2, Section 7]. Such a countermeasure can be broadly classified into *detective* and *infective* [4] classes. Overall, such a countermeasure compares two independent runs of the same cipher (which we call the *actual* and the *redundant* computations, following [4]), and checks if both are equal. If true, this output is returned; otherwise, a predefined recovery procedure (such as returning a garbage output) takes place.

While such a basic duplication based countermeasure works fine against DFA (except for the case where two identical faults are injected in the actual and the redundant computations; which is shown doable by Selmke, Heyszl and Sigl in FDTC'16 [5]). Moreover, the new types of fault attacks that are emerging over the last few years are capable of bypassing it. Of them, two notable attacks are of interest to this work, namely, the *Statistical Ineffective Fault Attack* (SIFA), reported in CHES'18 [6], and *Fault Template Attack* (FTA), reported more recently in Eurocrypt'20 [7]. These two fault models do not rely on the differential (δ, Δ) information, which requires knowledge of the faulty output. Instead, only the correct output from the cipher, or merely the information on whether or not the fault injection successfully altered the normal cipher flow would be sufficient. As a consequence, the basic duplication based countermeasure, which only blocks releasing of the faulty output, becomes vulnerable, revealing thereby the need for specialised countermeasures.

A handful of countermeasures against SIFA have been proposed in the literature [2, Section 7.6]. In order to avoid the pitfall of basic duplication, all those countermeasures save for [8] rely on some form of triplication of the cipher execution, followed by an error correction procedure. Assuming the attacker can only target at most one execution at a time,

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those countermeasures block the attacker from gaining any exploitable knowledge. The countermeasure proposed in [8], on the other hand, relies on a randomised duplication based approach. Based on a random coin toss (λ), it is decided whether the cipher will be run as-is in both the circuits, or the *inverted* cipher will be run. The inverted[1] cipher essentially maps 0 to 1 and vice-versa. A final comparison takes place to sense any fault, before taking appropriate procedure. In this way, the exploitable information in SIFA, which manifests in the form of a statistical bias, is removed.

Contribution

Our work combines the concepts of SIFA and FTA protection together with the DFA protection, all in one countermeasure scheme. Our idea is built on top of [8], i.e., relying on randomised duplication. While other SIFA countermeasures [2, Section 7.6] protect against SIFA as well as FTA, one has to note that all the countermeasures depend on some form of error correction (hence triplication, at minimum). Our proposal, on the other hand, has an overhead closer to that of duplication. The DFA protection covers all known types of DFA, such as the algebraic [9], impossible differential [10], collision fault attack [11], [12]. At the same time, it protects against the DFA model reported in [5], which works by injecting identical faults to the actual and redundant computations so that the countermeasure senses it as the case of no fault and thus passes the faulty output to the attacker. Moreover, to the best of our knowledge, no countermeasure has been proposed against FTA in the literature; thereby making our FTA protection probably the first-of-its-kind.

II. Background: Attack Models

Based on the presumed power of the attacker, the attack models can be classified into two broad categories with respect to our analysis. In the first, referred to as the *classical attack*, the attacker only has access to the cipher as a black-box. Thus, the attacker is only allowed to provide inputs to the cipher and receive the corresponding outputs. In the *gray box* category, the attacker is given additional access like power consumption or electromagnetic radiation information (i.e., physical side channel attacks), or the ability to alter the normal flow of operation (i.e., fault attack).

The classical attacks (i.e., the black box model) are protected by the virtue of the cipher design. However, the situation with the gray box model is different. To protect against side channel attack and/or fault attack, specialised countermeasure would be needed.

A. Differential Fault Attack (DFA)

DFA is the first fault attack proposed in the context of symmetric key cryptography [3], and probably the most common attack model. Most, if not all, major ciphers are vulnerable to it (unless any protection mechanism is in place). The attacker needs both the faulty and non-faulty outputs to compute the difference, which is used to find the information on the secret key. This attack targets regions near the end of the cipher execution, which results in a weakened version of the classical *Differential Attack* [13].

B. Statistical Ineffective Fault Attack (SIFA)

The recently proposed fault model, SIFA [6] uses the bias in the fault injection. Say, in a particular set-up, the probability of flipping 0 to 1 of a bit is more than the probability of the bit to stay at 0. Stated differently, the probability that the output will change or not depends on the actual content of the bit. Thus, SIFA works only when there is a bias in the fault (i.e., the probability of a bit set is not the same as a bit reset). This assumption on bias is shown practical in [6]. In this way, SIFA can work only with the cases where the faults do not alter the normal course of execution (i.e., non-faulty). Since both the non-faulty and faulty outputs are required for DFA, SIFA works in a relatively restricted environment. On the flip-side, SIFA needs more faults (typically in the order of thousands) compared to DFA (which can work with only one fault).

C. Fault Template Attack (FTA)

The fault template attack is a recent inclusion in the family of fault attacks [7]. This attack is capable of overcoming the existing fault countermeasures, does not require the faulty output (only the information on whether or not the output has changed is sufficient), and also can target at an arbitrary time during execution of the cipher (thus overcoming the limitation of DFA, which can only work by targeting regions near the end of the cipher execution). The main observation that leads to FTA is that, flipping one input line of the AND gate (while keeping the other at a constant) will make the output flip only if the other input line is 1. Thus, the attack can successively recover all the input lines to each non-linear operation, leading to the secret key. In some sense, FTA can be thought of a generalization of DFA and SIFA, as it is capable of using both the differential and statistical information. To the best of our knowledge, no countermeasure against FTA has been proposed till date.

III. Our Three-in-one Solution

Despite the supposed contrast among the three major fault attack models (i.e., DFA, SIFA and FTA), we observe that a general duplication based countermeasure can be devised that can protect against those. As noted earlier, this observation follows from the duplication based SIFA countermeasure proposed in [8]. However, this countermeasure does not protect against the identical faults in the two computations in a DFA model as proposed in [5]. Therefore, our work extends the functionality of the SIFA countermeasure to cover the FTA model as well as the DFA variant of [5] without any extra overhead.

To protect against SIFA, the authors propose a novel concept of randomised duplication in [8]. Here a random bit

[1]Note: The inverted cipher is different from the inverse of the cipher. The inverted cipher changes the encoding of the bits while performing the same mathematical operation as the underlying cipher, while the inverse of the cipher computes the mathematical inverse of the cipher.

λ ($\lambda \xleftarrow{\$} \{0,1\}$) determines the encoding of the bits. The bits are unchanged or inverted, each with probability $\frac{1}{2}$. When run over multiple test cases, the statistical bias is removed from the output. The random bit, λ, is generated at each invocation of the cipher, and is not known to the attacker. We denote the actual computation by E_K^1 and the redundant (denoted by E_K^2) where E denotes the cipher and K is the secret key, and the corresponding outputs are denoted by C' and C''. If $\lambda = 1$, the inverted logic is employed; where 0 is encoded as 1, and 1 is encoded as 0. Finally, the output is released only if the actual and the redundant computations match. If not, an appropriate recovery procedure takes place, such as an returning a random output or suppressing the output altogether. Note that the check on whether or not the actual and the redundant computations match can be done with an explicit or implicit check (as described in [4]). The authors substantiate the claim by using the same fault simulation tool as [14].

Overview of Our Three-in-one Countermeasure: With the same set-up from [8], we now describe the FTA and identical DFA protection. It may be noted that it enjoys all the benefits as its predecessor. Figure 1 shows the overview. Here, an on-chip *True Random Number Generator* (TRNG) is presumed as the source of entropy.

We briefly describe how the situation for $\lambda = 1$ (i.e., the inverted cipher) is implemented (which is also termed as the inverted cipher). The basic idea is to encode each logic 0 to logic 1 and vice-versa. To see how it can be done, we start with the state where all the bits are flipped, thereafter, we change the XOR and AND operations to $\overline{\text{XOR}}$ and $\overline{\text{AND}}$, as per [8, Table 1].

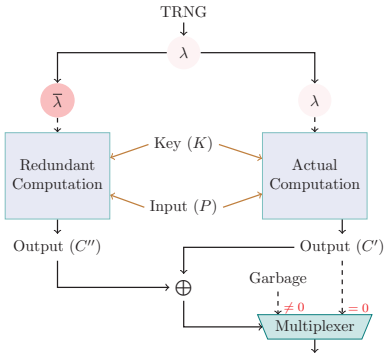


Fig. 1: Schematic for our three-in-one protection

IV. Evaluation

The proposed countermeasure has been validated through simulation of the technology mapped gate level net-list corresponding to the cipher designs in the presence of fault injections introduced during simulation. We do this through a modified version of VerFI [15][2] (which is also used in [8], [14]). In particular, we simulate two following designs — `PRESENT-80` encryption [16] protected with naïve duplication countermeasure, `PRESENT-80` encryption protected with the proposed countermeasure. The designs are synthesised targeting the open 45nm Nangate PDK v13 with appropriate constraints (e.g., ensuring the redundant paths are not optimised away). Each design is simulated (i.e., 1 encryption run) a number of times; with the same key used for all runs, but the plaintext and λ are changed at every invocation; and the output consists of the plaintext-ciphertext pair, and whether the injected fault was ineffective or was detected. The model allows to inject a single fault anywhere in the design (excluding inconsequential locations, such as the key register) during any clock cycle/round, and use the same fault location and fault type across all subsequent simulation runs. As the results for the earlier rounds would be similar, we only show the result with the last round attack without losing generality in Figure 2. The data shown in each of Figure 2(a) (naïve duplication) and Figure 2(b) (our countermeasure) are collected over a simulation of 80k random runs for `PRESENT-80`. It may be noted from Figure 2(a) that a stuck-at 0 fault is active at the second MSB of the SBox 13 for the actual and the redundant computations, but its effect is nullified in our countermeasure which is shown in Figure 2(b).

Moreover, the hardware performance of our countermeasure is given in Table I with the same set-up. Similar to [4], [8], we do not consider the cost for generating randomness.

TABLE I: Area overheads of our countermeasure

`PRESENT-80` Encryption	Gate Equivalents (45nm Nangate PDK)		
	Combinational	Non-combinational	Total
Naïve Duplication	1289	1807	3096 (1.00×)
Our Countermeasure	2290	1807	4097 (1.32×)

While with naïve duplication as well as with our countermeasure, the linear components of the cipher will increase proportionately, the same for the non-linear components (i.e., SBoxes) are not straightforward. In this regard, we show the overhead of protecting one layer of SBoxes by both the countermeasures in Table II with respect to `PRESENT` (sixteen 4×4 SBoxes) and `AES` (sixteen 8×8 SBoxes).

TABLE II: Area overhead for `PRESENT` and `AES` SBoxes

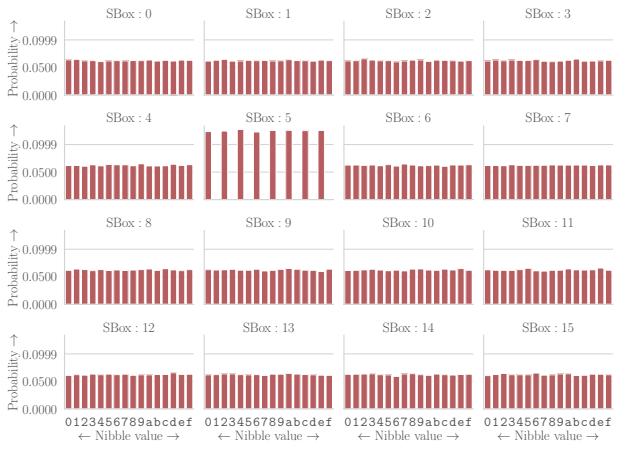
Countermeasure	Gate Equivalents (45nm Nangate PDK)	
	`PRESENT` SBoxes	`AES` SBoxes
Naïve Duplication	605 (1.0×)	8363 (1.0×)
Our Countermeasure	1397 (2.3×)	15327 (1.8×)

Following [8], we remark that the software performance will be similar to the underlying cipher in terms of code size (possibly marginally increased) and the required number of clock periods would be essentially the same.

V. Conclusion

A randomised duplication based approach is presented in this work, which is able to thwart against three major models of fault attacks. More precisely, our countermeasure protects against the differential fault attack (DFA) [3], the statistical ineffective fault attack (SIFA) [6], and the most recent member in the fault

[2]Our source codes can be found at https://github.com/vinayby/VerFI.



(a) Naïve duplication

(b) Our countermeasure

Fig. 2: Results for gate level simulation

attack family, the fault template attack (FTA) [7]. The basic idea follows from that of the SIFA countermeasure proposed recently in [8]. To prevent the attacker from getting any usable information, previous countermeasures to SIFA use a form of error correction. In the work of [8], the authors propose to use random encoding in a duplicated setting, so as to remove the statistical bias which is the source of usable information to the attacker. We note that originally this countermeasure does not protect against the attacker who is able to apply identical fault mask to both the computations, a DFA model which is shown practical in [5]. With our amendments to this countermeasure, we show how it is possible to achieve protection against this DFA model as well as the FTA model. To the best of our knowledge, our work serves as the first FTA countermeasure.

We hope our work will encourage more research in fault/side channel attacks as well as efficient countermeasures against those. In particular, one may be interested in a combined side channel and fault countermeasure. Also, a cipher can be constructed so that its inversion can be implemented with relatively low overhead, thereby reducing the overall cost.

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