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Fault-Resilient Lightweight Cryptographic Block Ciphers for Secure Embedded Systems

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Fault-Resilient Lightweight Cryptographic Block Ciphers for Secure Embedded Systems

by

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Electrical Engineering

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This graduate thesis is dedicated to my parents.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where specifically indicated in the text.

Kai Tian

2014

Abstract

The development of extremely-constrained environments having sensitive nodes such as RFID tags and nano-sensors necessitates the use of lightweight block ciphers. Indeed, lightweight block ciphers are essential for providing low-cost confidentiality to such applications. Nevertheless, providing the required security properties does not guarantee their reliability and hardware assurance when the architectures are prone to natural and malicious faults. In this thesis, considering false-alarm resistivity, error detection schemes for the lightweight block ciphers are proposed with the case study of XTEA (eXtended TEA). We note that lightweight block ciphers might be better suited for low-resource environments compared to the Advanced Encryption Standard, providing low complexity and power consumption. To the best of the author's knowledge, there has been no error detection scheme presented in the literature for the XTEA to date. Three different error detection approaches are presented and according to our fault-injection simulations for benchmarking the effectiveness of the proposed schemes, high error coverage is derived. Finally, field-programmable gate array (FPGA) implementations of these proposed error detection structures are presented to assess their efficiency and overhead. The proposed error detection architectures are capable of increasing the reliability of the implementations of this lightweight block cipher. The schemes presented can also be applied to lightweight hash functions with similar structures, making the presented schemes suitable for providing reliability to their lightweight security-constrained hardware implementations.

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Chapter 1

Introduction

1.1 Symmetric Key Cryptography Standard

Cryptography is a method that has been developed for transferring data securely. Cryptography now plays an increasingly important role in modern society, and it is essential to solve problems that involve secrecy, authentication, integrity, and dishonest entities. In digital communications, the data is sent through the wires or air and thus it is not protected from eavesdropping. Therefore, confidentiality of the transferring data is of extreme importance. Encryption is a process which transforms the data that is aimed to be sent to encrypted data using a key. The encryption process is not confidential but the key is only known to the sender and receiver of data. The receiver transforms the received data using the decryption process to obtain the original data.

Modern information theory concepts was first published by Claude Elmwood Shannon in 1948. There are two basic types of encryption, symmetric and asymmetric encryption. Asymmetric encryption uses public key and symmetric encryption uses shared private key.

- Asymmetric ciphers have two keys, a public (shared) key, and a mathematical-related private key [1].
- Symmetric key cryptography, which uses a shared key in both ends for encryption and decryption, has been utilized for secure communications for long period of time.

Symmetric key cryptography comprises two different methods for encryption and decryption. In the first method which is denoted as stream cipher, the bits of data are encrypted/decrypted one at a time. However, in the second method which is called block cipher, blocks of the input data which consist of a number of bits are encrypted/decrypted. The Data Encryption Standard (DES), triple DES (3DES), and the Advanced Encryption Standard (AES) are examples for the block cipher symmetric key cryptography. Block ciphers have played an increasing role in cryptology since the introduction of the data encryption standard (DES). Block ciphers are widely used to implement encryption of bulk data and are important elementary components in the design of many cryptographic protocols.

In 1997, the National Institute of Standards and Technology (NIST) initiated a process to select a symmetric-key encryption/decryption algorithm. In 1998, NIST announced the acceptance of fifteen candidate algorithms and requested the assistance of the cryptographic research community in analyzing the candidates. This analysis included an initial examination of the security and efficiency characteristics for each algorithm. NIST reviewed the results of this preliminary research and selected five final candidates: MARS, RC6, Rijndael, Serpent and Twofish. Finally, Rijndael algorithm was accepted among these finalists as the Advanced Encryption Standard. It is noted that before the acceptance of Rijndael algorithm, DES and its improved variant 3DES were used as symmetric key standards. DES has 16 rounds and encrypts and decrypts data in 64-bit blocks, using a 64-bit key. This can be compared to AES-128 which has 10 rounds where data is encrypted and decrypted in 128-bit blocks, using a 128-bit key. One can find a comparison between Rijndael and DES and triple DES in [2] and [3].

1.2 Lightweight Block Ciphers

With the development of resource-constrained and sensitive electronic and communication applications (and the advent of Internet of Things), one defining trend of this century's IT landscape will be the extensive deployment of tiny computing devices such as radio frequency identification (RFID) devices and wireless nano-sensor nodes. We note that such applications, for instance, the RFID technology, have been used in many aspects of our lives, such as access control, parking management, identification, and goods tracking. The sensitivity of such applications makes lightweight cryptography essential to reach acceptable confidentiality without adding much overhead to the constrained nodes [4]. These lightweight cryptographic solutions need to provide high security levels to counteract the malicious intents of adversaries, similar to those for the Advanced Encryption Standard (AES) [5].

Lightweight Cryptography is a relatively young scientific sub-field that is located at the intersection of electrical engineering, cryptography and computer science and focuses on new designs, adaptations or efficient implementations of cryptographic primitives and protocols. Due to the harsh cost constraints and a very strong attacker model—especially noteworthy is the possibility of physical attacks—there is an increasing need for lightweight security solutions that are tailored to the ubiquitous computing paradigm.

Every designer of lightweight cryptography has to cope with the trade-off between security, costs, and performance. For block ciphers, the key length provides a security-cost trade-off, while the amount of rounds provides a security-performance trade-off and the hardware architecture a cost-performance trade-off. Usually, any two of the three design goals – security and low costs, security and performance, or low costs and performance – can be easily optimized, whereas it is very difficult to optimize all three design goals at the same time. For example, a secure and high performance hardware implementation can be achieved by a pipelined architecture which also incorporates many countermeasures against side-channel attacks. The resulting design would have a high area requirement, which correlates with high costs. On the other hand it is possible to design a secure and low-cost hardware implementation with the drawback of limited performance.

A number of lightweight block ciphers have been proposed; for instance, TEA [6], DESL [7], HIGH [8], mCrypton [9], PRESENT [10], KATAN/KTANTAN [11], PRINCE [12], TWINE [13], TWIS [14], XTEA [15], and the like. The main differences between the lightweight block ciphers and the conventional block ciphers are centered on: the block size for a lightweight block cipher is generally 32, 48 or 64 bits and equal to 64 or 128 bits for a conventional block cipher. Lightweight block ciphers rely more on elementary operations such as binary AND, binary XOR, etc. which means lightweight block ciphers require more number of rounds. Lightweight block ciphers also simplify the key schedule extremely due to memory restriction [16].

- Tiny Encryption Algorithm (TEA) was presented by David Wheeler and Roger Needham [6], shortly after that several minor weaknesses were found [17] and after resolving them a new variant named as XTEA (for extended) was developed [15]. This algorithm is notable for its simplicity (it was originally proposed for software implementations, but simplicity makes it very suitable for hardware implementations) and is used widely in providing lightweight security to different applications including Texas Instruments microcontrollers.
- Lightweight variants of the DES cipher called DESL and DESXL [7] which is strong, compact and efficient for implementation. Due to its low area overhead, DESL is especially suited for tiny devices; it uses a single S-box repeated for eight times.
- Another lightweight block cipher HIGHT [8] is proposed by D. Hong et al. in 2006 for ultra-lightweight implementation.
- KLEIN is another lightweight block cipher which mainly focuses on software implementation; it also enjoys hardware efficiency resulting from its simple structure with an involutive S-box. The various key lengths of KLEIN offer flexibility and a moderate security level for ubiquitous applications.
- For resource-constrained tiny devices, cipher mCrypton is introduced in [9]. Its designed architecture like as Crypton but some simplification on component functions

has been introduced to enable much compact implementation in both hardware and software under restricted environments.

- Andrey Bogdanov et al. proposed a new family of ultra- lightweight block ciphers called PRESENT [10]. It offers a level of security and the hardware requirements which is comparable with today's leading compact stream ciphers.
- LBlock achieves good hardware performance and software efficiency on 8-bit micro-controller. It employs a variant of Feistel structure and the encryption algorithm is 4-bit oriented which can be implemented efficiently in both hardware and software. LBlock can achieve enough security margins against known attacks, such as differential cryptanalysis, linear cryptanalysis, impossible differential cryptanalysis and related-key attacks etc.
- KTANTAN & KATAN [11] are a family of block cipher composed of two sets having block sizes 32, 48, or 64-bit and key size 80-bit.
- LED mainly focuses on key schedule algorithm and protection against related-key attacks. The LED block cipher is simple to analyze and this allows us to precisely evaluate the necessary number of rounds to ensure proper security.
- Cipher PRINCE [12] uses the same optimal S-box for 16 times to get the lowest possible gate count without compromising security.

1.3 Fault Detection

Fault is a problem that results in a complete failure of a piece of equipment, or even involves specific hardware. A problem in digital system can be defined as a bit inversion in digital hardware, i.e., 0 to 1 or 1 to 0. As technology becomes scaled, manufacturing large defect-free integrated circuits becomes difficult. There is also the issue of device degradation over large periods of time. ASICs and FPGAs are primarily affected by these degradation issues which make them less reliable over time. Future FPGAs, beyond the 45nm technology, will have low reliability such that fault tolerance or other recovery methods will be unavoidable in large FPGAs. This section provides some insight on some common faults and degradation. FPGAs are highly reconfigurable; this provides interesting opportunities for fault detection and tolerance.

1.3.1 Faults and Degradation

Digital circuits incur degradation in many ways [18], some of the leading ways are as follows:

- The *hot-carrier* effect leads to a buildup of trapped charges in the gate-channel interface region [19]. This leads to degradation in electron mobility and increased threshold voltage in CMOS transistors. This in turn leads to reduced switching speeds and hence leads to increased delays. This phenomenon is also caused as a result of negative-bias temperature instability, which exhibits a similar behavior [20].
- *Electromigration* is a phenomenon in which metal ions migrate, which leads to a lack of holes and voids in interconnect. Eventually these can cause faults by creation of shorted circuits or open circuits [21].
- *Time-Dependent Dielectric Breakdown* causes an increase in leakage current by affecting the transistor gates, eventually this leads to a short circuit. The reason for this is charge trap creation within the gate dielectrics which diminishes the potential barrier if forms [22, 23]

There are a couple of other faults that can affect FPGAs. These are highly relevant to this thesis because the proposed techniques uses these fault models.

- Manufacturing defects can affect circuit nodes which cause a stuck-at-0 or 1 or they may switch slowly and cause a timing issue. Interconnect networks can also be affected, leading to short or open circuits and open or closed transistors [24].
- The most common type of fault in FPGAs comprises of Single Event Upsets (SEUs) and Single Event Transient (SETs) caused by certain types of radiation. These types of faults primarily affect circuits in aviation, space applications and nuclear research where devices are subjected to higher levels of radiation. Another most common and frequently occurring type of fault is in SRAM cells, where particular cells maybe flipped. This error remains in the memory until a refresh occurs; this process is known as scrubbing. Scrubbing may not be relevant during permanent faults but is highly useful during transient faults.

1.3.2 Fault Detection Techniques

Fault detection primarily has two purposes; alerting the supervising process that action needs to be taken for the system to remain operational and secondly, the defective components are identified so that it can be repaired. Usually, these two stages are covered simultaneously or it can have more than one stage comprising of different strategies. Fault detection strategies can be categorized into three types:

- *Redundant/concurrent error detection*: This technique uses additional circuitry to detect a potential fault/error. The most frequently used techniques are parity detection and hardware redundancy.
- *Off-line test methods*: This methodology uses external circuitry to detect faults in an FPGA/ASIC when it is not in operation. Some examples of off-line test circuits are Built-In-Self-Test (BIST) and Automated-Test-Pattern-Generator (ATPG).
- *Roving test methods*: These techniques take a complicated approach but are useful in pinpointing a faulty location in a FPGA circuit. Roving performs a scan of

the entire FPGA structure and checks for defects by replacing them with a test function.

Concurrent Error Detection Error detection of this kind is mainly used to detect errors due to SEUs and SETs. These detection methods as mentioned before involve adding logic to the original module to implement the detection mechanism. In the event of an error, there is a disagreement between the included logic and the original module, over which a particular calculation is processed and this is indicated by some sort of error detection mechanism, usually a comparator. One of the simplest and most used methods is *modular redundancy*. A functional block is replicated, usually two or three times. The outputs of these replicated modules are compared; any differences in the results trigger the error mechanism. *Concurrent Error Detection* (CED) allows a more area efficient design compared to modular redundancy. The data lines and registers are widened to store error coding algorithms such as parity. Error validation algorithms are included at the outputs of these lines or registers to detect faults (parity check registers).

The major drawback of modular redundancy is the additional overhead required for its implementation, which can be three times in case of TMR [25] or more in NMR. In addition to this, it provides very limited resolution for the identification of the faulty component. The fault detection can only be limited to a particular block which implements modular redundancy. This can be overcome by breaking down the circuit and adding additional error detection logic, with the expense of area. In CED, the efficiency of error coverage comes at the expense of additional area. These methods do not provide coverage of multiple SEUs or SETs.

Error coverage through redundancy does not have to be restricted to circuit area. It is possible to detect errors with the trade-off with latency/throughput. [26], [27] proposes a method where operations are carried out twice. During the second run the operations are encoded in a different way so that they yield a different output. The output of both runs are passed through a suitable decoder and then compared at the output. In certain cases, data-checking (parity) and redundant systems are incorporated into an FPGA configuration. [28] implements a FPGA system with built in redundancy.

Off-Line Fault Detection One of the most widely used techniques for fault detection is off-line fault detection. This is usually used to identify manufacturing defects in FPGAs. Any circuit which does this without the help of an external circuit, i.e., built into the FPGA but not a part of the original design. These techniques work by loading one or more test patterns into the FPGA. The entire system consists of a test pattern generator, an output response analyzer and between them the device under test. To include full coverage the system will have to test not only the logic and interconnect, but also the configuration network. Many recent consumer grade FPGAs have this built into the development boards. This eliminates the need of a large number of different test configurations. Compared to ASICs, FPGAs have the advantage of a fixed reconfigurable structure, which removes the need of dedicated test structures to be built into the circuit. As FPGAs are reconfigurable, test patterns should be optimized so that they can be used for various designs. The major advantage of BIST is that it does not interfere with normal operation of the FPGA. It also covers complicated systems such as PLLs and clock networks. The major drawback of BIST is that it can detect faults only when the circuit is not operational, i.e., only when a dedicated test mode is run, it can detect faults. This is usually done at system startup or when an error event triggers the BIST check.

Recent trends use BIST to test individual LUT [29–31] properties like timing and stuck-at-faults. [32] uses a BIST system to test interconnects which reduces time through a large degree. In [24] and [33] a hierarchical approach is used to locate stuck-at faults, short circuits and open circuits with high accuracy.

Roving Fault Detection This technique exploits run-time configuration to adapt BIST techniques on-line, with minimum area overhead. In roving detection, the FPGA is split equally into a certain number of regions. One of the regions is subjected to BIST testing while the rest carry out the desired operation. Over time the region under test is switched with the operational region, in this order the entire FPGA array is scanned for faults. This method is very popular in partial reconfiguration. Roving techniques have lower area compared to modular techniques; the overhead comprises of just one self-test

region and a controller to manage the reconfigurable (swapping) process and better than off-line methods because the circuit can be operational. The speed, while better than off-line testing methods, it is not comparable to redundancy techniques. The detection speed of a roving technique depends on the speed of the roving cycle and the operation time. The best roving tests are reported to have latency of less than one second [34].

In roving tests, performance is impacted in two ways. Firstly, the connections between adjacent functional areas are stretched as the test region is moved through the FPGA, resulting in longer signal delays which in turn affect the system clock speed, in the range of 2.5% to 15% [35]. Secondly, in current FPGAs the functional blocks are halted as they are swapped. It is reported that a 250 μs pause is required between swaps. Most of the initial testing in the field of roving test has been carried out by Emmert, Stroud and Abramovici [34, 35]. The system called Roving STARS uses two test sections one for rows and other for columns. Another variation of roving test was proposed in [36] which uses buses rather than segmented interconnects. Though, this system has no impact on system clock, it limits the application base.

1.4 Reconfigurable Hardware

Hardware modules containing a large number of switching-circuit components are called reconfigurable hardware modules. The modules in general are called field programmable gate arrays (FPGAs), general FPGAs contain an array of simple logic cells, some storage, and interconnection path in each cell that can be configured to perform specific functions by loading a predetermined bit pattern. The predetermined bit patterns are loaded into a layer called a configurable logic block (CLB) which rests below the logic layer. This layer is responsible for the connection pattern between different components in the FPGA. Once the bit pattern is loaded into the CLB, the actual customization is very fast compared to the standard process of producing custom ICs. This allows the user to use the same hardware for different implementations. Even though, the designs presented in this material are suitable for ASIC, FPGAs have gained popularity in recent years, hence this is an attractive option to implement the proposed designs.

Some notable FPGA implementations: Girau and Tisserand [37] implemented multilayer perceptron back-propagation algorithms. Tisserand and Dimmler [38] designed real-time digital controllers. Tenca and Ercegovic [39] designed a variable long-precision arithmetic unit. Tisserand, Marchal, and Piguet [40] developed an on-line arithmetic based FPGA architecture for low power custom computing. Mosanya and Sanchez [41] implemented a generalized profile search. Lau, et. al [42] implemented signal processing algorithms for Fast Fourier Transform and Discrete Cosine Transform.

1.5 Objectives

To date, many research works have analyzed lightweight block ciphers such as the recent one on SIMON [43]. As one of the fastest and most efficient block ciphers in existence, XTEA is used for some real-life cryptographic applications. This block cipher only uses simple addition, XOR, and shift functions, and has a very small code size. This makes XTEA an excellent candidate to provide confidentiality for nodes having limited memory and computational power.

In [44], the authors show an impossible differential attack on 23-round variant. In [45], a three-subset meet-in-the-middle attack is applied against 25 rounds of the algorithm with 9 known plaintexts and $2^{120.4}$ computations. However, the recommended 32 round version is still considered to be secure.

In this thesis, using this algorithm as the case study and considering the insights for false-alarm resilience, reliability and fault resilience of lightweight crypto-architectures are assessed. We note that this choice does not confine the proposed methods for other lightweight cryptographic algorithms (such as SIMON) and, thus, insights are presented for applying such approaches to smart infrastructures. Technically, an attacker may not be able to inject a single-bit fault because of the technological constraints. Therefore, in practice, multiple faults occur and this is considered in the fault model assessed throughout this thesis.

Both natural faults and malicious faults can be modeled by the stuck-at fault model (single or multiple bits). Thus, this fault model is utilized to model these two kinds of faults in the proposed schemes of this thesis. To the best of the author's knowledge, this thesis is the first to present the fault-resilient architectures for this lightweight block cipher. As such, efficient error detection schemes are proposed to increase the reliability of the hardware architectures. The ratios of the errors detected are different depending on the error detection methods taken. The high error coverage of the presented schemes would meaningfully increase the difficulty for potential fault attackers.

The contributions of this are summarized as follows:

- We propose fault diagnosis approaches for the presented XTEA block cipher con-

sidering the reliability, resiliency, and performance metrics objectives. Unified and combined fault resilience approaches are used in conjunction with performance boost modifications to achieve high throughput and frequency architectures while maintaining high error coverage.

- Through simulations for this fault model, we benchmark the error detection capabilities of the proposed schemes. The results of these simulations show acceptable error detection capabilities which ensures reliability and hardware assurance of the proposed approaches.
- Finally, we implement the proposed error detection architectures on Kintex FPGA device xc7k70tlfbg676-2L [46]. Our results show that the proposed efficient error detection architectures can be feasibly utilized for reliable architectures of the presented complex division structures making them suitable for the required performance, reliability, and implementation metrics to achieve for constrained applications.

1.6 Thesis Outline

The structure of the thesis is as follows:

- **CHAPTER 2:** This chapter explains briefly preliminaries related to Tiny Encryption Algorithm (TEA) and eXtended TEA (XTEA) block cipher. In this chapter, the algorithms of TEA and XTEA are presented. In addition, the block diagram of XTEA is also presented. This is followed by the proposed error detection approaches. The two error detection approaches presented in this thesis are based on signatures and RERO. This chapter also discusses False-Alarm Explorations.
- **CHAPTER 3:** In this chapter the results of the fault-injection simulations are presented. Describes the fault model used for testing the proposed designs. The chapter also discusses the error coverage results of the two architectures.
- **CHAPTER 4:** In this chapter the overheads are benchmarked through FPGA implementations for the proposed architectures.
- **CHAPTER 5:** This chapter presents the “insights” and “discussions”.
- **CHAPTER 6:** Conclusions and possible future work are described in this chapter.

Chapter 2

Proposed Error Detection Schemes

This chapter presents the proposed fault diagnosis method in this thesis. This work has been accepted in the journal of "IEEE Embedded Systems Letter" and to be published in Dec. 2014.

2.1 Tiny Encryption Algorithm (TEA)

British researchers from Cambridge University proposed extremely simple encryption algorithm, the TEA (Tiny Encryption Algorithm). It based on an alternative application of a large number of iterations with XORs and additions, rather than on preset tables. Therefore, it can achieve better performance with smaller code size and less complexity than standard encryption algorithms. TEA is three times faster than popular encryption algorithms such as DES.

The TEA encrypts 64 data bits at a time using a 128-bit key, which is a strongest encryption. The TEA uses a 128-bit master key $K[0..3]$ and derived subkeys. The Key schedule is simple. Odd rounds use $K[0,1]$ as the round subkey, and even rounds use $K[2,3]$. Originally designed for 64 bit plaintext blocks, later the TEA was extended for larger block sizes, in which the iterative times and key scheduling are slightly changed.

In SPINS, the authors implemented encryption on resource-constrained devices using RC5 encryption algorithm. However, the TEA is much more efficient in terms of static size and running time consumption. Its extra-ordinary simplicity and efficiency are very

important features for potentially miniaturized hardware. Moreover, the size of message packets in specific sensors is often fixed, so it is more acceptable to view each message packet as data chunk and use the Block TEA algorithm to encrypt the packet.

Two minor weaknesses of TEA were pointed out. The mixing portion of TEA seems unbroken but related key attacks are possible even though the construction of 2^{32} texts under two related keys seems impractical. The second weakness, that the effective length of the keys is 126 bits not 128 does affect certain potential applications but not the simple cipher decipher mode.

2.2 Side-Channel Analysis Attacks

Natural fault detection is the concentration of a number of previous works. An important reason leading to natural faults in the very-large-scale integration (VLSI) implementations is hardware failures, for instance, natural VLSI single event upsets and external radiations or electromagnetic waves. In cryptographic hardware and embedded systems, the adverse effects of such faults are amplified considering not only the sensitivity of such structures but the possibility of mounting active side-channel analysis attacks, commonly referred to as fault attacks.

2.2.1 Side-Channel Analysis

In the real world, an adversary can go beyond the mathematical concept and attack the implementation rather than the specification. Obviously, the real world offers many possibilities for attacks, which cannot be modeled or prevented by mathematics. When electronic devices are used, they must obey the laws of physics. The device requires a certain amount of time and a certain amount of energy, the electronic circuits emit a certain amount of radiation, energy, and even sound, and they may be affected by their environment. These additional sources of information are referred to as side-channels in Figure 2.1. It has been shown by various authors that lots of these side-channels provide information, which reveals important and compromising details about secret data.

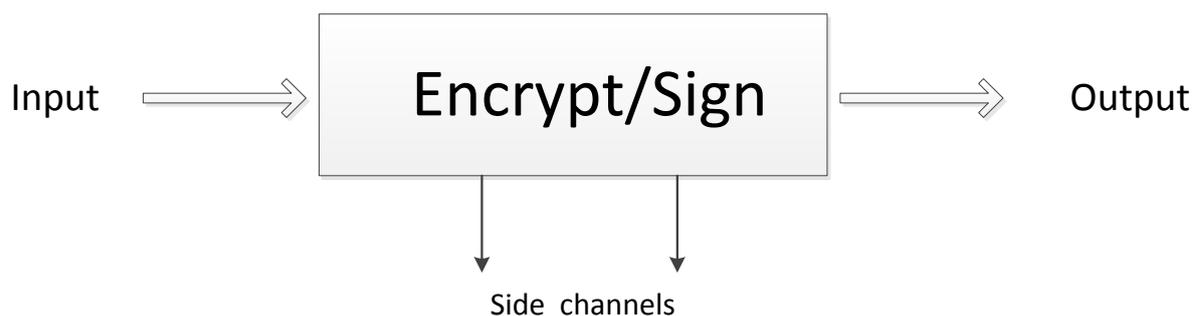


Figure 2.1: Side-channel leakage.

The various side-channels include timing measurements [47], power consumption and the power profile [48], electromagnetic emissions [49–51], sound [52], presence and abuse of testing circuitry [53, 54] and data gathered by probing circuitry or bus lines [55].

2.2.2 Fault Attacks

One specific side-channel is faults. An adversary may inject faults into a device, while it executes a certain program, and then the adversary observes the reaction. This kind of attacks is denoted as fault attacks, and it is different from other side-channel attacks. Other side-channel attacks are passive attacks, which just listen to some side-channel without interfering with the computation. Fault attack is a variant of side-channel analysis which is active, where an adversary has to tamper with an attacked device in order to create faults, thereby opening the desired side-channel.

Dan Boneh, Richard DeMillo, and Richard Lipton from Bellcore Labs [56] in 1997 first introduced how to recover secret keys of the Rivest-Shamir-Adleman (RSA) and the Discrete-Logarithm-Based crypto-systems through fault analysis attacks by injecting faults during computations and using the erroneous outputs to deduce information on the secret key stored in the secure components. In the following, several authors extended the ideas from Boneh, DeMillo, and Lipton to other cryptosystems, using other fault models and different means of physical attacks. Fault attacks are a practical scenario. Fault attacks have been used to break security mechanisms even before the cryptographic community became aware of them. Pay TV card hackers used rapid transient changes in

the clock signal, called clock glitches, to access pay TV channels before 1996. Since the threat of fault attacks is real, both customers and hardware manufacturers are looking for secure devices.

For cryptographic architectures such as the AES, much research has been carried out to achieve fault-immune structures, see, for instance, [57–68] (also, refer to [69] for reliable architectures for lightweight cryptography). Moreover, concerning the finite field arithmetic architectures, various concurrent error detection (CED) multipliers have been proposed [70, 71] to provide reliability mechanisms for crypto-systems.

2.3 eXtended TEA (XTEA)

The lightweight block cipher XTEA accepts a cryptographic key of 128 bits and a 64-bit block size. Input block is separated into two halves X and Y . These are applied to a Feistel network for N cycles and N is normally 32. Feistel networks usually use the XOR operation as a reversible function to apply the result of a mixing function to one half of the input data. XTEA also uses additions during encryption and subtractions during decryption for the same reason.

Algorithm 2.1 shows the process through which this algorithm derives the outputs. The algorithm includes two parts. The first part is the encryption routine and the second is the decryption routine. Within XTEA, all additions and subtractions are modulo 2^{32} . Logical left shifts by 4 bits are denoted as $\ll 4$ and logical right shift by 5 bits are denoted as $\gg 5$. The XOR function is denoted as " \oplus " in this algorithm.

The first part of the algorithm is a permutation function and the second part is a subkey generation function. The 128-bit user key can be split into 4 blocks. Each block is a 32-bit subkey. The function $key[sum]$ chooses one block out of the four subkey depending on bits 1st and 0th (bits 12th and 11th in the second half cycle) of sum . The XOR function is applied to the result of the permutation function and the subkey generation function and, then, this result is applied to x and y by addition when encrypting or subtraction when decrypting.

Algorithm 2.1 The XTEA lightweight block cipher algorithm.

Inputs: 64-bit data: $v[0]$ - $v[1]$, 128-bit key: $key[0]$ - $key[3]$.

Initialize (encryption): $v_0 = v[0]$, $v_1 = v[1]$, $sum = 0$, $delta = 0x9E3779B9$, n : number of rounds.

1. for $i = 0$ to $n - 1$ do
2. $v_0 \leftarrow v_0 + (((v_1 \ll 4) \oplus (v_1 \gg 5)) + v_1) \oplus (sum + key[sum \& 3])$.
3. $sum \leftarrow sum + delta$.
4. $v_1 \leftarrow v_1 + (((v_0 \ll 4) \oplus (v_0 \gg 5)) + v_0) \oplus (sum + key[sum \gg 11 \& 3])$.
5. end for.

Initialize (decryption): $sum = delta \times n$,

1. for $i = 0$ to $n - 1$ do
 2. $v_1 \leftarrow v_1 - (((v_0 \ll 4) \oplus (v_0 \gg 5)) + v_0) \oplus (sum + key[sum \gg 11 \& 3])$.
 3. $sum \leftarrow sum - delta$.
 4. $v_0 \leftarrow v_0 - (((v_1 \ll 4) \oplus (v_1 \gg 5)) + v_1) \oplus (sum + key[sum \& 3])$.
 5. end for.
-

Figure 2.2 shows the block diagram of XTEA encryption. For encryption, v_0 is applied to the left side and v_1 to the right side. The subkey generation function is shown as keygen in the block diagram. Every cycle computes new values for v_0 and v_1 . A whole cycle can be split into two half cycles. In each half cycle, a new value for v_0 and v_1 is computed. Between the first and the second half cycle, a new value for sum is computed. sum increases by a constant $Delta$, which equals to $(\sqrt{5} - 1) \times 2^{31}$. This addition can be included in the first half cycle.

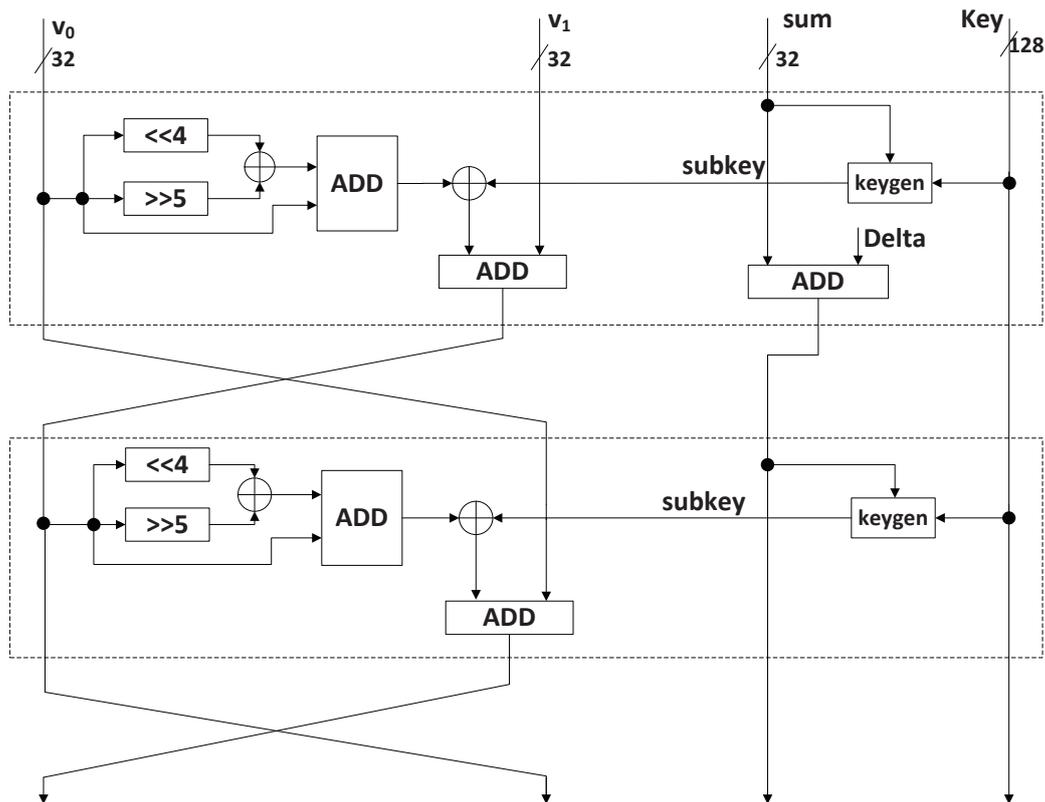


Figure 2.2: Top level block diagram of XTEA.

2.4 Proposed Approach

In this section, two different error detection approaches are proposed with the case study of XTEA. We would like to emphasize that although we use this case study, the proposed methods are applicable with slight modifications to similar lightweight block ciphers and hash functions. For the sake of brevity, only the schemes for the encryption process are presented.

We refrain presenting the double modular redundancy scheme for the sake brevity as it is straightforward and simply doubles the module and, then, compares the outputs of the two identical modules. Unless same errors occur in the same place of two modules, which is almost impossible in practice, all the errors can be detected with impractical overhead of around 100% which is not efficient.

The two error detection approaches presented in this thesis are based on signatures and RERO, whose details are presented in the followings.

2.4.1 Signature-Based Diagnosis

Among signature-based approaches for fault diagnosis, parity prediction is a common method to detect errors in which a parity generator can compute the actual parity codes for outputs and if the actual parity codes are equal to the one predicted, the outputs are error free.

The block cipher XTEA only uses simple additions, XORs, and shifts functions. Thus, three different parity prediction functions are required.

For XOR function, the parity-prediction function (\hat{P} is used for predicted parities) is straightforward. Assuming two inputs are A and B (with bits a_i and b_i). The parity codes for inputs are P_A and P_B . The output is S . The predicted parity for output is \hat{P}_S .

$$P_A = \sum_{i=0}^{n-1} a_i \quad (2.1)$$

$$P_B = \sum_{i=0}^{n-1} b_i \quad (2.2)$$

$$\hat{P}_S = \sum_{i=0}^{n-1} s_i = \sum_{i=0}^{n-1} (a_i \oplus b_i) = \sum_{i=0}^{n-1} a_i \oplus \sum_{i=0}^{n-1} b_i = P_A \oplus P_B \quad (2.3)$$

For shift function, taking logical right shift of A by 5 bits as an example. In logical shift, the vacant bit-positions are filled in with zeros. Assuming $A = a_{n-1} \dots a_5 a_4 a_3 a_2 a_1 a_0$.

$$S = LRS(A) = 00000a_{n-1} \dots a_5 \quad (2.4)$$

$$\hat{P}_S = \sum_{i=5}^{n-1} a_i = \sum_{i=0}^{n-1} a_i \oplus \sum_{i=0}^4 a_i = P_A \oplus (a_4 \oplus a_3 \oplus a_2 \oplus a_1 \oplus a_0) \quad (2.5)$$

For addition function, parity-prediction function is quite complicate. Assuming two inputs are A and B . The parity codes for inputs are P_A and P_B . The output is S . The parity code for output is P_S . The output bit s_i is equal to $a_i \oplus b_i \oplus c_{i-1}$. Considering modulo2 addition, the output parity is given by the expression

$$\hat{P}_S = \sum_{i=0}^{n-1} s_i = \sum_{i=0}^{n-1} (a_i \oplus b_i \oplus c_{i-1}) = \sum_{i=0}^{n-1} a_i \oplus \sum_{i=0}^{n-1} b_i \oplus \sum_{i=0}^{n-1} c_{i-1} = P_A \oplus P_B \oplus \sum_{i=0}^{n-1} c_{i-1} \quad (2.6)$$

where c_{i-1} is the carry input of bit i .

In a system using parity encoded data, the parities P_A and P_B are already available. Thus, only $P_C = \sum_{i=0}^{n-1} c_{i-1}$ has to be computed to predict the parity code.

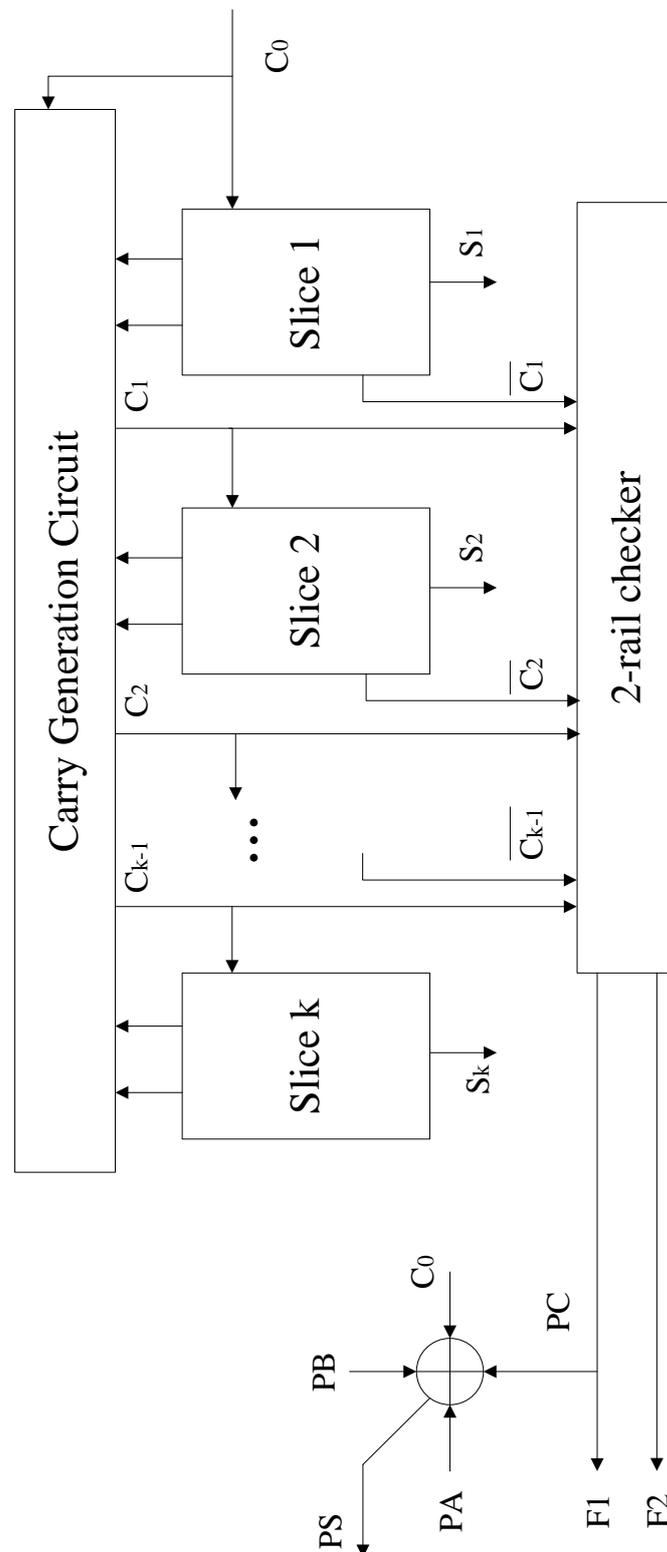


Figure 2.4: Carry checking/parity prediction adder avoiding duplication of the carry generation block.

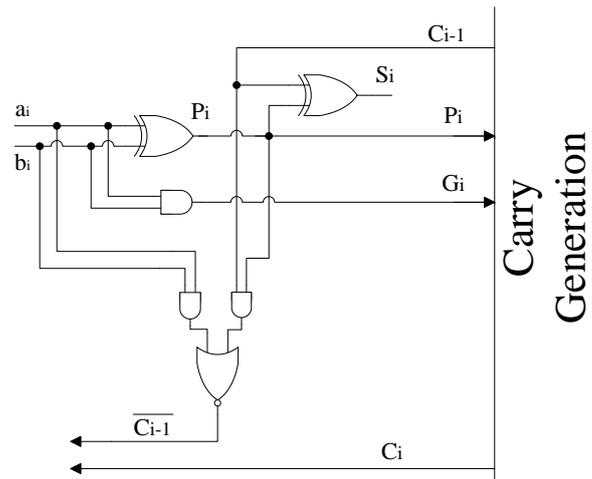


Figure 2.5: Adder bit slice using partial carry duplication.

hardware cost and using the carry inputs from the normal carry generation logic rather than the previous slice of the check carries to guarantee high speed.

The entire parity prediction schemes for XTEA can be reached by combining these three parity prediction approaches as in Figure 2.6.

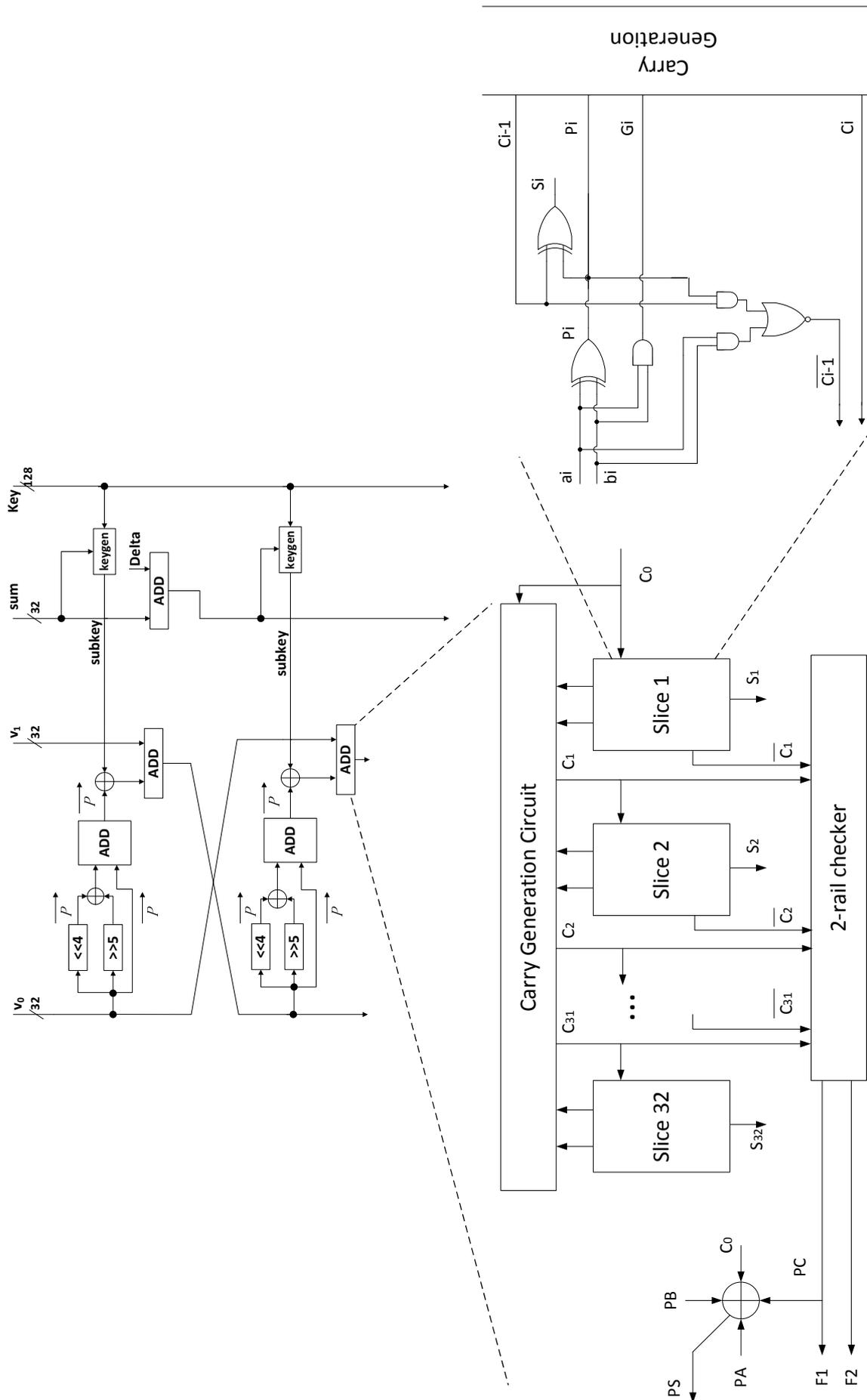


Figure 2.6: The block diagram of the signature-based scheme.

2.4.2 Recomputing with Rotated Operands (RERO)

Concurrent error detection is an appealing error detection technique because it can detect errors with performing the normal operations of the system at the same time. Redundancy is an essential part of the error detection method. Hardware redundancy and time redundancy are two general forms of redundancy.

- Hardware redundancy relies on duplication of the hardware for operations, and comparison of the results obtained by two separate hardware will allow error detection.
- Time redundancy will reduce the hardware cost at the expense of using extra time. It will redo the operation in a different way to allow errors to be detected. During the first computation step, the normal operands are applied. In the recomputation step, the operands are encoded and correct results can be generated after decoding. The mismatch of the two results indicates an error. In many applications where time is not critical, time redundancy is a good solution, because additional time is more affordable than extra hardware, and time redundancy has no impact on physical weight, size or power consumption. Therefore, time redundancy is currently received much attention.

Various techniques exist for using time redundancy to detect errors. The difference between them lies in the different encoding methods they apply during the recomputation step. One well-known time redundancy method is called “Recomputing with Shifted Operands by k-bit ” (RESO-k). All operations are done twice, once with the normal operands, and once with the operands shifted by k bits. This method can detect k consecutive logic errors and (k-1) arithmetic errors; however, when an n-bit operand is shifted left by k bits, its leftmost k bits move out. To preserve these bits during the recomputation step, an (n + k)-bit Arithmetic Logic Unit (ALU) and several (n + k)-bit shifters are needed. Furthermore, since the length of the ALU has increased to (n+k) bits, the recomputation takes (n+k)-bit operations rather than n-bit operations. For example, suppose the original ALU has 32 bits; if k is 16, then the new ALU should be 48

bits. As k becomes larger, a considerable increase of space and time complexity occurs. and the error probability in the ALU increases also.

Error detection schemes based on time redundancy often suffer from the inability to detect permanent faults. RERO (Recomputing with Rotated Operands) is a technique for concurrent error detection introduced for arithmetic units which is capable of detecting not only the transient faults which are common in fault attacks but also the permanent faults affecting logic gates in the cryptographic hardware and embedded systems. Suppose ψ and ψ^{-1} are n -bit rotations (or cyclic shifts) toward the least and most significant bits of a binary operand, respectively. Moreover, let π be the input to an arithmetic function g , and $g(\pi)$ be its output in such a way that $\psi^{-1}(g(\psi(\pi))) = g(\pi)$. To apply the RERO method, we need to store the result of the first computation (first run) and compare it against the result of the second computation (second run). If the results are different, it indicates an error is alerted by the error indication flag. The logic pattern before rotation is shown below:

$$n-1 \quad n-2 \quad \cdots \quad i+1 \quad i \quad \cdots \quad 2 \quad 1 \quad 0,$$

and the logic pattern after rotation is:

$$i \quad \cdots \quad 2 \quad 1 \quad 0 \quad n-1 \quad n-2 \quad \cdots \quad i+1.$$

RERO for logic gates is quite straightforward. The most involved part for RERO is the one for addition. The correctness of carry-in for logic bit $i+1$ th and carry-out from logic bit $n-1$ th should be guaranteed. As such, two measures are taken to solve the carry-in and carry-out problem for RERO; one extra bit is added as the most significant bit and the logic pattern before rotation becomes:

$$\textcircled{\text{a}} \quad n-1 \quad n-2 \quad \cdots \quad i+1 \quad i \quad \cdots \quad 2 \quad 1 \quad 0,$$

and the logic pattern after rotation becomes:

$$i \quad \cdots \quad 2 \quad 1 \quad 0 \quad @ \quad n-1 \quad n-2 \quad \cdots \quad i+1,$$

where @ is the added bit. The values of this bit are always “0”. As such, no carry-out transfers from bit @ to bit 0th. Thus, logic bit $n-1$ th is not able to affect logic bit 0th.

Moreover, one needs to link the carry-out from the most significant bit to the carry-in of bit 0th. Due to the fact that the values of the extra bit are always “0”, the carry-out from the most significant bit is “0” in the first computation and it will not affect bit 0th. During the second computation, the most significant bit contains logic bit i th. The carry-out from logic bit i th is applied to the carry-in of logic bit $i+1$ th.

2.4.2.1 Throughput and Efficiency Considerations

Time redundancy techniques suffer from degradations in performance. However, it is possible to increase the frequency of computations (and thus to increase the efficiency and throughput) through sub-pipelining. This can be performed based on the resources available and the performance boost required. Suppose one pipeline-register has been placed to sub-pipeline the structures. The location for placing the registers is chosen to break the timing path in to approximately equal halves. Let us denote the two halves of pipelined stages by Π_1 and Π_2 . The original input is first applied to the architecture in the first cycle. In the second cycle, while the second half of the circuit (Π_2) executes this first input, the rotated variant of the first input is fed to the first half of the circuit (Π_1). This trend is consecutively executed until the last rotated input is derived. We note that for detecting the errors, the outputs of the runs with the rotated-inputs are rotated back and compared against the original inputs. Therefore, any mismatch indicates an error.

We can take advantage of multi-level sub-pipelining to reduce the throughput degradation of the proposed scheme. In this regard, the order of applying the inputs is managed so that we take advantage of concurrent executions. Although the added sub-pipelining registers slightly increase the induced hardware overhead, it is more preferable to use the

time-redundancy schemes which introduce much more overall design overhead. Time-redundancy techniques inherently tend to increase the number of cycles needed for computations. This reduces the throughput of the hardware implementations accordingly. Therefore, in our proposed approach, by introducing sub-pipelining, we increase the frequency of the clock to make sure the design throughput is acceptable compared to the original architecture.

2.5 False-Alarm Explorations

We would like to emphasize that the false-alarm immunity of such crypto-systems also determines the immunity against the attacks intending to induce distrust to users. Such malicious intents might try to divert the fault diagnosis stream so that without having errors at the output of the crypto-architectures used in smart infrastructures, alarms get falsely initiated which would eventually cause abandoning the entire system. For instance, in an implantable medical device, one could receive such false-alarms, warning the existence of a defect or attack in the embedded hardware systems within the device. This false-alarm can cause much discomfort and a potential replacement of the medical device which could be either impossible or vitally dangerous. In short, protecting against such cases would result in reliable and false-alarm immune smart infrastructures that are trustworthy and can be used safely for different usage models.

Error detection schemes result in approaches to reach their respective error indication flags. The merit of these flags is that they alarm the user of the infrastructures-to-become-secure in case of any faults detected. However, one needs to observe that in addition to these true alarms, we might get false-alarms in case the faults occurred or injected in the inner architectures are masked and not get translated into errors at the output. The percentage of such alarms are very low that we could safely denote the proposed structures false-alarm free and, thus, resistant against falsely-alarmed flags due to the faults that are not propagated to the output.

Chapter 3

Error Simulations

To evaluate the error detection capability of the proposed structures, fault-injection simulations have been performed. The fault model used is elaborated in the following.

3.1 Fault Model

Throughout this thesis, both single and multiple stuck-at faults have been considered (note that these could be transient or permanent). These two models cover both malicious fault attacks and natural faults. Indeed, single stuck-at faults model the natural failures (such as single event upsets) and are the ideal cases for the attackers. However, due to technological constraints, single stuck-at fault injections become more difficult for an attacker to gain information (it is still a possibility due to larger components such as bus-lines). Thus, multiple bits will actually be flipped, and, thus, multiple stuck-at faults are also considered in this thesis.

3.2 Simulation Results

If exactly only one bit error appears, the coverage is 100%, thus, no simulation is needed. Most internal faults can be modeled by transient random faults. These could be localized faults with 50% detection rate if they affect just one parity unit or very high if randomly-distributed faults occur. We note that each parity cannot detect with more than 50% rate

but the combination of parity bits if the fault model is multiple, randomly-distributed faults (permanent or transient) can detect with higher rate. One side-note is that through testing, permanent faults can be detected as well but transient faults (in case they are randomly-distributed) can be detected with high ratio using the proposed methods. We note that, however, even a half-round has a number of parities so theoretically, the detection rate is much higher even for half-round localized faults affecting the blocks covered by the respective parities. 10,000 faults are injected using eight different test cases and validated for error coverage and assessed through a linear-feedback shift register (LFSR)-based simulation environment. It is noted that we use Fibonacci implementation LFSRs with the required output taps for injecting random multiple errors, where the numbers, locations, and types of the errors are randomly chosen.

For each injection, error indication flags are monitored, and the detected errors are counted. The results of the performed simulations show very high error coverage (all the cases have at least 9,996 faults detected out of 10,000 samples, i.e., 99.96% detection rate for this case). For the signature-based scheme, multiple parities for multiple detection points are used to achieve such high coverage as single parities are ineffective even for single errors. It is noted that the implemented architecture utilizes the RERO method for one computation of a round to have a practical scheme.

If an attacker is capable of injecting faults in the parity circuitry, the following cases can happen: (a). the injected single or multiple stuck-at faults (if not masked) in only the parity prediction circuitry are detected, (b). for multiple stuck-at faults, in both the original and prediction circuits (which are not ideal cases for attacks), such dual injections can make the respective parity prediction blocks ineffective (if not masked). However, it is emphasized that multiple stuck-at faults are not preferable and even if they occur, it will make just the respective parity blocks ineffective and might not have large effects on final error coverage. Nevertheless, the presented RERO scheme is not vulnerable to such injections and its comparison unit is assumed to be fault tolerant.

Chapter 4

FPGA Implementations

In this chapter, we present the results of the overhead assessments using the FPGA hardware platforms. The analysis has been performed for the original and the error detection structures of the encryption process of the XTEA. Vivado version 2013.2 and Kintex FPGA device xc7k70tlfbg676-2L have been utilized for the FPGA implementations. VHDL has been used as the design entry for the original and the error detection structures.

To benchmark the performance of the proposed schemes, we have done implementations for the original and fault diagnosis schemes as seen in Table 4.1. Moreover, based on the sub-pipelining approach presented in this thesis, one can alleviate the inherent performance degradations of the RERO method. Specifically, with the expense of adding registers for deep sub-pipelining (for instance, one stage sub-pipelining in Table 4.1), higher frequencies are achieved for the RERO scheme which make the degradations in throughput less intense.

The results of the FPGA architectures are shown in Table 4.2 for the area and power consumptions. In order to have complete benchmarks for the entire error detection architectures, every component in the presented structures is synthesized and implemented. All the syntheses and implementations are performed using the same settings, tools, and FPGA devices. These results are for benchmarking purposes and the original architectures could be optimized. However, this does not change the performance of the proposed

Table 4.1: Performance degradations of the proposed schemes.

Structure	Delay (ns)	Overhead	Throu. (Mbps)	Deg.
Original	3.833	-	39.57	-
Parity Prediction	4.913	28.2%	28.69	27.5%
RERO ¹	2.891	-	26.42	33.2%

1. One stage sub-pipelined architecture.

Table 4.2: Area and power consumption overheads of the proposed schemes.

Structure	Area (#slices)	Overhead	Power (<i>mW</i>)	Overhead
Original	177	-	87	-
Parity-based	203	14.7%	92	5.7%
RERO	228	28.8%	91	4.6%

architectures.

In Table 4.2, the area and power consumptions for the original and the error detection structures of the XTEA are presented. The area of the FPGA implementations are presented in terms of the number of occupied slices and the total power consumptions (working frequency of 100MHz) are derived using Vivado version 2013.2 and Kintex FPGA device xc7k70tlfbg676-2L.

We have performed implementations for the hardware redundancy scheme and with 333 slices used (area overhead of 88.1%), this scheme is not preferable for low-complexity architectures. As seen in Table II, the area overheads of the parity-based and RERO structures are 14.7% and 28.8%, respectively. Moreover, we get around 5% increase in power consumptions for these two architectures. Based on the simulation results, these overheads are added for the error coverage of very close to 100%. The proposed fault diagnosis approaches provide high error coverage at the expense of the acceptable overheads on the FPGA hardware platforms, making the hardware architectures of the XTEA more reliable.

Chapter 5

Insights and Discussions

Smart infrastructures such as implantable and wearable medical devices need to transfer data securely as the information transferred is often sensitive and private. The fact that these structures often perform sensitive and in some cases life-saving tasks makes it extremely attractive for the malicious attackers to attack to gain information. In this regard, security mechanisms (such as lightweight block ciphers providing confidentiality to the sensitive data) are crucial.

The proposed approaches in this thesis are much suitable to provide fault immunity and reliability to smart infrastructures (these not only include natural faults but also malicious faults aiming at compromising the entire system). Through the proposed architectures, such cases are detected and, consequently, warn the users of security systems so that later precautions are provided. We have proposed a framework which can be tailored based on the objectives in terms of reliability and fault immunity and can be used to detect various faults with different fault models provided.

To conclude this chapter, we would like to also emphasize that the false-alarm immunity of such crypto-systems also determines the immunity against the attacks intending to induce distrust to users. For instance, in an implantable medical device, one could receive such false-alarms, warning the existence of a defect or attack in the embedded hardware systems within the device. In short, protecting against such cases would result in reliable and false-alarm immune smart infrastructures that are trustworthy.

Chapter 6

Conclusions

In this thesis, two fault diagnosis approaches for the lightweight block cipher XTEA have been proposed. These include parity-based structure and RERO structure. The results of the simulations show very high error coverage (very close to 100%) for the presented error detection structures for the injected stuck-at faults. Moreover, the FPGA implementation analysis results show acceptable overheads for the XTEA when the presented schemes are utilized. The proposed designs are also extendable to other lightweight block ciphers with similar operations. The proposed schemes can be used to protect the extremely-sensitive and resource-constrained applications.

Appendix A

XTEA Algorithm in Verilog

```
module xtea(clock, reset, mode, data_in1, data_in2, key_in,
           data_out1, data_out2, all_done);

Parameter s0 = 8'd0, s1 = 8'd1, s2 = 8'd2, s3 = 8'd3, s4 = 8'd4,
           s5 = 8'd5, s6 = 8'd6, s7 = 8'd7, s8 = 8'd8, s9 = 8'd9, s10 =
           8'd10, s11 = 8'd11, s12 = 8'd12, s13 = 8'd13, s14 = 8'd14,
           s15 = 8'd15, s16 = 8'd16, s17 = 8'd17;

input clock, reset, mode;
input [31:0] data_in1, data_in2;
input [127:0] key_in;
output [31:0] data_out1, data_out2;
output all_done;

wire clock, reset;
wire [31:0] data_in1, data_in2;
wire [127:0] key_in;
reg all_done, while_flag, modereg;
reg [1:0] selectslice;
```

```
reg [7:0] state;
reg [7:0] x;
reg [31:0] data_out1, data_out2, sum, workunit1, workunit2, delta
;

always @(posedge clock or posedge reset)
begin
    if (reset)
        //reset state
        state = s0;
    else begin
        case (state)
            s0: state = s1;
            s1: state = s2;
            s2: state = s3;
            s3: state = while_flag ? s4 : s14;
            s4: state = modereg ? s10 : s5;
            s5: state = s6;
            s6: state = s7;
            s7: state = s8;
            s8: state = s9;
            s9: state = s2;
            s10: state = s11;
            s11: state = s12;
            s12: state = s13;
            s13: state = s14;
            s14: state = s2;
            s15: state = s16;
            s16: state = s17;
```

```
        s17: state = s17;
        default: state = 4'bxxxx;
    endcase
end
end

end

always @(posedge clock or posedge reset)
begin
    if (reset) begin
        //reset all our outputs and registers
        data_out1 = 32'h00000000;
        data_out2 = 32'h00000000;
        x = 8'b00000000;
        sum = 32'h00000000;
        while_flag = 1'b0;
        workunit1 = 32'h00000000;
        workunit2 = 32'h00000000;
        selectslice = 1'b0;
        all_done = 1'b0;
        delta = 32'h00000000;
        modereg = 1'b0;
    end
    else begin
        case (state)
            s1: begin
                //store input values to registers in
                case they're not stable
                workunit1 = data_in1;
                workunit2 = data_in2;
```

```
        delta = 32'h9E3779B9;
sum = 32'hc6ef3720;
modereg = mode;
end
s2: if (x < 8'd32) while_flag = 1'b1;
    else while_flag = 1'b0;
s3: begin
    //This null state was necessary to
        fix a timing issue.
    //s2 sets while_flag and previously
        the control path read it in the
        same state
    //(but in the next clock cycle),
        however the reg wasn't set when
        we tried to
    //read it, so this state was
        inserted to add a delay. This was
        when running @25MHz.
    //FIXME: there's got to be a better
        solution to this...
end
s4: begin
    //This state does nothing in the
        data path; it's used for an if
        statement in the
    //control path.
end
/* States 5-9 used for decipher
operations */
```


end

endmodule

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