



**HAL**  
open science

# A Note on Related-Tweakey Impossible Differential Attacks

Xavier Bonnetain, Virginie Lallemand

► **To cite this version:**

Xavier Bonnetain, Virginie Lallemand. A Note on Related-Tweakey Impossible Differential Attacks. IACR Communications in Cryptology, 2024, 1 (3), 10.62056/abbn-4c2h . hal-04748002

**HAL Id: hal-04748002**

**<https://hal.science/hal-04748002v1>**

Submitted on 2 Nov 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

# A Note on Related-Tweakey Impossible Differential Attacks

Xavier Bonnetain and Virginie Lallemand

Université de Lorraine, CNRS, Inria, LORIA, Nancy, France

**Abstract.** In this note we review the technique proposed at ToSC 2018 by Sadeghi *et al.* for attacks built upon several related-tweakey impossible differential trails. We show that the initial encryption queries are improper and lead the authors to miscalculate a filtering value in the key recovery phase. We identified 4 other papers (from Eurocrypt, DCC, and 2 from ToSC) that follow on the results of Sadeghi *et al.*, and in three of them the flawed technique was reused.

We thus present a careful analysis of these types of attacks and give generic complexity formulas similar to the ones proposed by Boura *et al.* at Asiacrypt 2014. We apply these to the aforementioned papers and provide patched versions of their attacks. The main consequence is an increase in the memory complexity. We show that in many cases (a notable exception being quantum impossible differentials) it is possible to recover the numeric time estimates of the flawed analysis, and in all cases we were able to build a correct attack reaching the same number of rounds.

**Keywords:** Impossible Differential Attack · Related-Tweakey · Complexity Analysis

## 1 Introduction

The impossible differential attack is a block cipher cryptanalysis technique that was independently discovered by Knudsen [Knu98] and Biham, Biryukov and Shamir [BBS99] in the late 1990s. The idea is to focus on differentials of probability zero, in opposition to differential cryptanalysis [BS91] which searches differentials of high probability. Formally, an impossible differential (or impossible differential distinguisher) is a couple of differences  $(\Delta_X, \Delta_Y)$  such that if two messages differ by  $\Delta_X$  the difference of their corresponding ciphertexts cannot be equal to  $\Delta_Y$ .

In a similar manner to what can be done for other statistical cryptanalyses, an impossible differential distinguisher can be turned into an attack by appending and/or prepending some rounds for key recovery. An attacker guesses the required key material of these rounds to check if they obtain the impossible pair of differences  $(\Delta_X, \Delta_Y)$ : if that is the case they discard the key candidate as they know it must be incorrect.

Many significant results have been obtained with this technique, among which 7-round attacks on AES-128 [ZWF07, BA08]. Quite naturally, extensions to the related-key and related-tweak scenario have also been proposed.

**Our contributions.** In this article we review the impossible differential technique proposed by Sadeghi *et al.* in [SMB18] which takes advantage of several impossible differentials requiring different tweakey differences. We show that the technique is flawed, describe how to fix the problem and provide generic formulas that estimate the time, data and memory complexity of such a process. We identified 4 papers that rely on the results

---

E-mail: [xavier.bonnetain@inria.fr](mailto:xavier.bonnetain@inria.fr) (Xavier Bonnetain), [virginie.lallemand@loria.fr](mailto:virginie.lallemand@loria.fr) (Virginie Lallemand)



of Sadeghi *et al.* and show how to fix all of the attacks presented in these. Fortunately, the patched complexities are close to the wrong ones, and the same number of rounds can be attacked.

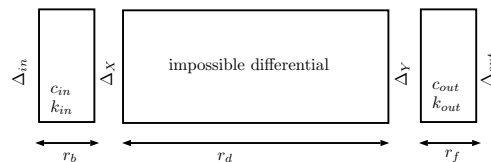
**Outline.** The following section introduces the necessary notations and recalls the working principle of an impossible differential attack, together with its generic complexity formulas expressed by Boura *et al.* in [BNS14]. As most of the studied attacks target the SKINNY block cipher or one of its variants we also briefly recall its specification. Section 3 describes the multiple-tweakey attack presented by Sadeghi *et al.* [SMB18], a brief description of the spotted issues is given right after and the corrected procedure is given in Section 5. Section 6 describes the impact of our findings on the 4 articles we identified, and provides the corrected complexities.

## 2 Preliminaries

### 2.1 Single-key Impossible Differential Attacks and their Complexity Analysis

We start by recalling the framework of single-key impossible differential attacks for block ciphers, as detailed in [BNS14]. We consider an  $n$ -bit block cipher with a  $k$ -bit master key  $K$ . The attack is built around a probability-0 differential distinguisher of  $r_d$  rounds that starts with a (set of)  $n$ -bit difference(s)  $\Delta_X$  and ends with a (set of)  $n$ -bit difference(s)  $\Delta_Y$ , as depicted in Figure 1. Then,  $r_b$  rounds are added before this differential and  $r_f$  rounds are added after. The set of possible differences at the plaintext side, denoted  $\Delta_{in}$ , is a set of differences that might lead to  $\Delta_X$  after  $r_b$  rounds. Similarly,  $\Delta_{out}$  represents the set of differences at the ciphertext side to which  $\Delta_Y$  might propagate after  $r_f$  rounds.

We let  $2^{-c_{in}}$  denote the probability that a difference in  $\Delta_{in}$  leads to a difference in  $\Delta_X$ , and  $2^{-c_{out}}$  the probability that a difference in  $\Delta_{out}$  leads to a difference in  $\Delta_Y$ . The set of key bits used to compute if a difference in  $\Delta_{in}$  leads to  $\Delta_X$  is  $k_{in}$ , while the corresponding set of key bits at the ciphertext side is  $k_{out}$ .



**Figure 1:** Setting and notation for an impossible differential attack on a block cipher.

Given a pair of messages with a plaintext difference in  $\Delta_{in}$  and a ciphertext difference in  $\Delta_{out}$ , the probability that a specific key guess leads to  $\Delta_X$  and  $\Delta_Y$  (and thus is discarded) is equal to  $2^{-c_{in}-c_{out}}$ . Not discarding a given key is thus of probability  $(1 - 2^{-c_{in}-c_{out}})$ , and not discarding a given key when considering  $N$  pairs is thus of probability  $(1 - 2^{-c_{in}-c_{out}})^N \simeq \exp(-N \times 2^{-c_{in}-c_{out}})$ .

The goal of an attacker is to reduce the set of possible keys by at least a factor of 2 in order to keep the final step (of exhaustively testing the remaining keys) of reasonable cost. We introduce the variable  $g$  to measure the number of remaining keys and denote by  $N_{min}^g$  the number of pairs satisfying  $\Delta_{in}$  and  $\Delta_{out}$  such that:

$$(1 - 2^{-c_{in}-c_{out}})^{N_{min}^g} < \frac{1}{2g}.$$

The previous approximation using the exponential function leads to:

$$N_{min}^g > g \times \ln(2) \times 2^{c_{in}+c_{out}}.$$

To build a given amount of pairs  $N$ , an attacker organizes their encryption queries into structures (either at the plaintext or at the ciphertext side). Depending on the exact number of pairs that are required, either several structures are encrypted or less than one. Combining these different scenarios, the data complexity can be approximated by:

$$D = \max\left\{\min_{\Delta \in \{\Delta_{in}, \Delta_{out}\}} \left\{\sqrt{N2^{n+1-|\Delta|}}, N2^{n+1-|\Delta_{in}|-|\Delta_{out}|}\right\}\right\}$$

where  $2^{|\Delta_{in}|}$  and  $2^{|\Delta_{out}|}$  represent the number of differences in  $\Delta_{in}$  and  $\Delta_{out}$ , respectively. This number of encryption queries must be so that  $D \leq 2^n$  (the full codebook).

If we let  $C_E$  denote the cost of one encryption, the lower bound of the time complexity of the attack ( $T$ ) provided in [BNS14] is:

$$T = \left(D + \left(N + 2^{|k_{in} \cup k_{out}|} \frac{N}{2^{c_{in}+c_{out}}}\right) C'_E + 2^{k-g}\right) C_E,$$

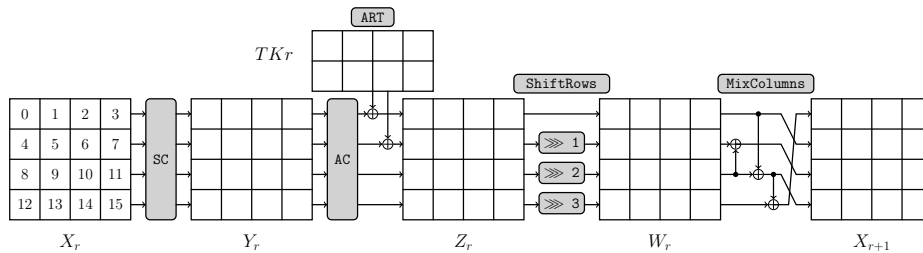
where  $C'_E$  is the ratio of the cost of partial encryption to the full encryption. This should satisfy  $T \leq 2^k C_E$ . The memory complexity corresponds to storing the  $N$  pairs.

## 2.2 The SKINNY Block Cipher

SKINNY [BJK<sup>+</sup>16] is a family of tweakable block ciphers whose variants are denoted SKINNY- $n-v$ , where  $n = 16 \times s$  is the internal state size,  $s = 4$  or  $8$  is the word size and  $v$  is the tweak size (it can be equal to  $n$ ,  $2n$  or  $3n$ ), all expressed in bits. The round function of SKINNY is recalled in Figure 2 and relies on 5 operations:

- **SubCells (SC)**: applies an  $s$ -bit Sbox to each word,
- **AddConstants (AC)**: adds a round constant to words 0, 4 and 8,
- **AddRoundTweakey (ART)**: adds the round tweakey to the first and second rows,
- **ShiftRows (SR)**: right-rotates row  $i$  by  $i$  positions,
- **MixColumns (MC)**: multiplies each column by the binary matrix

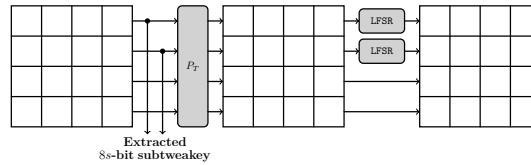
$$M = \begin{pmatrix} 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \end{pmatrix}.$$



**Figure 2:** Word numbering and round function of SKINNY (modified version of [Jea16]).

The tweak and the key are handled together with the TWEAKEY framework of Jean *et al.* [JNP14]: depending on the version of SKINNY, there are either 1, 2 or 3 master tweakey states (denoted TK1, TK2 and TK3) which are filled with the key and the tweak values. These states undergo linear operations (in the so-called tweakey schedule) to produce the round tweakeys of the  $r$  rounds of the cipher ( $TK1, TK2, \dots, TKr$ ).

The first  $8s$ -bit round tweakey is obtained by extracting the first 2 rows of each master tweakey state and xoring them together. After that and as can be seen in Figure 3, each tweakey state first sees its cells shuffled by the permutation  $P_T$ , and then the 8 cells of the first two rows are modified by a  $s$ -bit LFSR. The LFSR of the first tweakey state is the identity, and the second and third (denoted  $LFSR_2$  and  $LFSR_3$ ) are as defined below. The second round tweakey is the xor of the first two rows of each updated tweakey state, and so on.



**Figure 3:** Tweakey schedule of SKINNY (figure from [Jea16]).

$LFSR_2$  and  $LFSR_3$  are defined as follows for  $s = 4$ , where  $x_0$  is the least significant bit:

$$LFSR_2 : (x_3 || x_2 || x_1 || x_0) \rightarrow (x_2 || x_1 || x_0 || x_3 \oplus x_2)$$

$$LFSR_3 : (x_3 || x_2 || x_1 || x_0) \rightarrow (x_0 \oplus x_3 || x_3 || x_2 || x_1)$$

For  $s = 8$  we have:

$$LFSR_2 : (x_7 || x_6 || x_5 || x_4 || x_3 || x_2 || x_1 || x_0) \rightarrow (x_6 || x_5 || x_4 || x_3 || x_2 || x_1 || x_0 || x_7 \oplus x_5)$$

$$LFSR_3 : (x_7 || x_6 || x_5 || x_4 || x_3 || x_2 || x_1 || x_0) \rightarrow (x_0 \oplus x_6 || x_7 || x_6 || x_5 || x_4 || x_3 || x_2 || x_1)$$

The great performance and security of SKINNY inspired other variants, such as FORKSKINNY [ALP<sup>+</sup>19], SKINNYe-v2 [NSS20a, NSS20b] and SKINNYee [NSS22] which mainly differ on the tweakey management and reuse the same round operations.

### 3 Multiple-Tweakey Attack from ToSC 2018

This section recalls the key recovery technique used in the 23-round related-tweakey impossible differential attack on SKINNY- $n-2n$  described in [SMB18]. A 19-round attack on SKINNY- $n-n$  was also presented in [SMB18] but we do not detail it here as the technique is very similar. We propose a fix for both these attacks in Section 5.

**Description of the 23-round related-tweakey impossible differential attack on SKINNY- $n-2n$  of [SMB18].** We reuse the notations from [SMB18]. The attack is based on the 15-round related-tweakey impossible differential trail represented in Figure 4. This distinguisher is positioned between  $Y_4$  and  $X_{19}$  and a total of 23 rounds is attacked by adding 3 rounds at the top and 5 rounds at the bottom for the key-recovery phase, as detailed in Figure 5. The first round tweakey addition is moved to the end of the round (just before  $X_2$ ) by defining an equivalent tweakey for the first round as  $ETK = MC(SR(TK_1))$ . Since all the operations made before do not rely on secret values, the attacker considers

**Table 1:** The TDT from [SMB18].

TDT	$L_1$	$L_2$	$L_3$	$L_4$	$L_5$	$L_6$	$L_7$	$L_8$	$L_9$	$L_{10}$	$L_{11}$	$L_{12}$	$L_{13}$	$L_{14}$	$L_{15}$
$TK2[7]$	9	3	A	6	F	5	C	4	D	7	E	2	B	1	8
$TK4[1]$	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
$TK18[7]$	7	F	8	E	9	1	6	B	C	4	3	5	2	A	D
$TK20[1]$	D	A	7	5	8	F	2	6	B	C	1	3	E	9	4
$TK22[0]$	8	1	9	2	A	3	B	C	4	D	5	E	6	F	7

an equivalent plaintext at position  $Y_1$  (see Figure 5) that corresponds to the state before the first equivalent tweaky addition.

As can be seen in Figure 4, the distinguisher starts after the `SubCells` operation and relies on a difference cancellation between the difference of the internal state and the one in the round tweaky. The difference in the master tweaky is set so that the 3 next rounds are blank rounds, and the last round of the distinguisher also relies on a cancellation between the internal state difference and the round tweaky difference.

The idea of the authors of [SMB18] is to use the set of all the possible distinguishers of this shape instead of only one. The 3 blank rounds require an inactive round tweaky in the round 3 of Figure 4, that translates into the relation

$$\Delta TK1[1] \oplus LFSR_2(\Delta TK2[1]) = 0xn \oplus LFSR_2(p) = 0.$$

There is a total of  $2^s - 1$  pairs of such (non-zero) working tweaky differences, that uniquely determine the master tweaky differences together with the internal state input and output differences of the distinguisher.

The authors of [SMB18] define the ‘‘Tweaky Differentials Table’’ (TDT) (reproduced in Table 1 for the case  $s = 4$ ) to store the  $2^s - 1$  sets of valid round tweaky differences in rounds 2, 4, 18, 20 and 22. They use  $2^s - 1$  lists ( $L_i$ ) to store the data corresponding to each distinguisher.

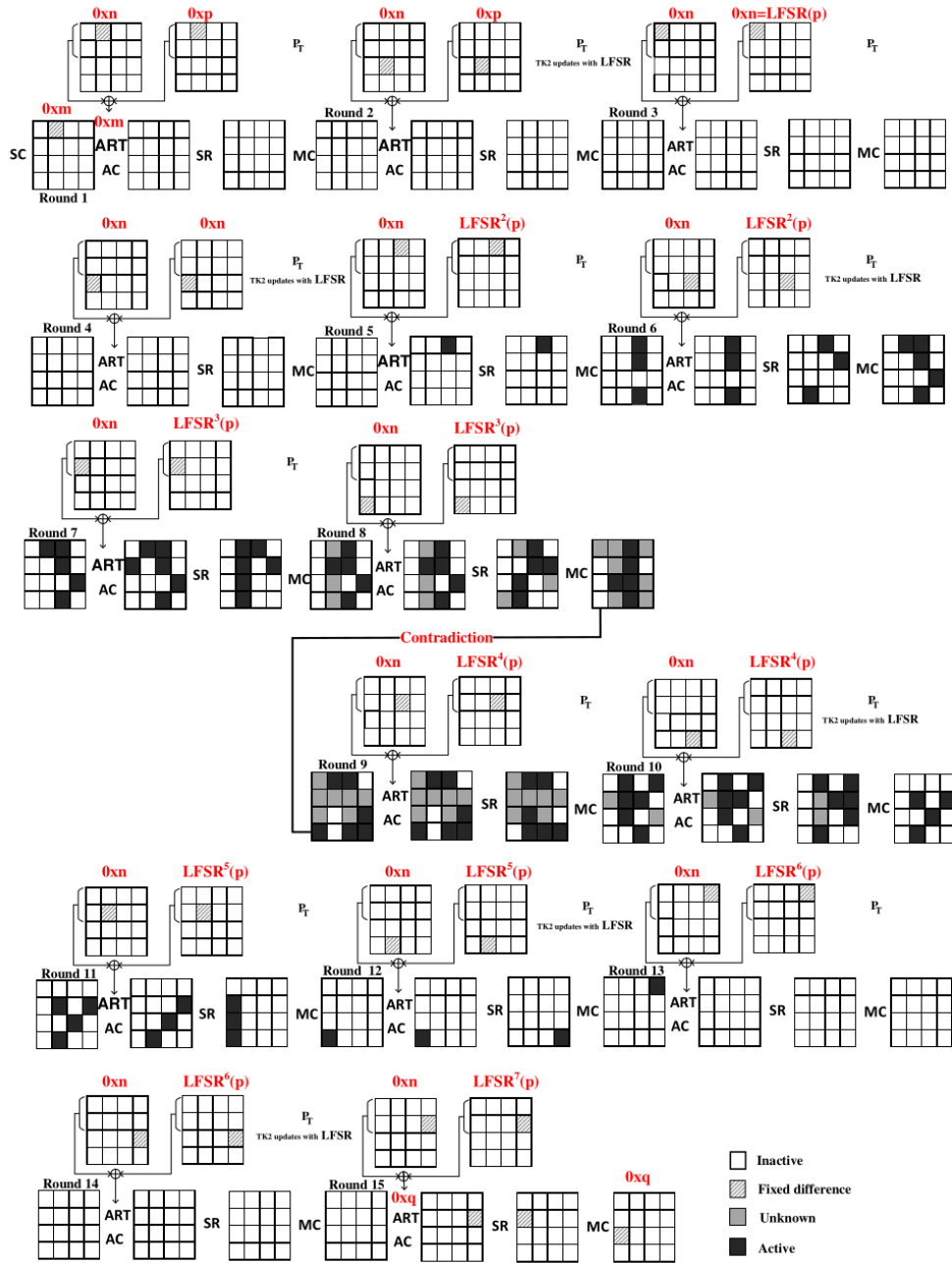
We transcribe below the beginning of the key recovery procedure proposed in [SMB18] and provide our comments in Section 4. The attack is also described in Figure 5.

The attacker queries  $2^x$  structures of  $2^{|\Delta_{in}|} = 2^{4s}$  messages with  $Y_1$  taking all the possible values in cells 5, 7, 8 and 15 and being fixed in the other positions. A total of  $2^{x+8s}$  pairs of messages  $(P, \bar{P})$  and their associated  $(C, \bar{C})$  are built from these  $2^{x+4s+1}$  initial messages ( $D = 2^{x+|\Delta_{in}|+1}$ ). As  $|\Delta_{out}| = n$ , these pairs are not further filtered on their ciphertext differences and can all be used to discard wrong key guesses.

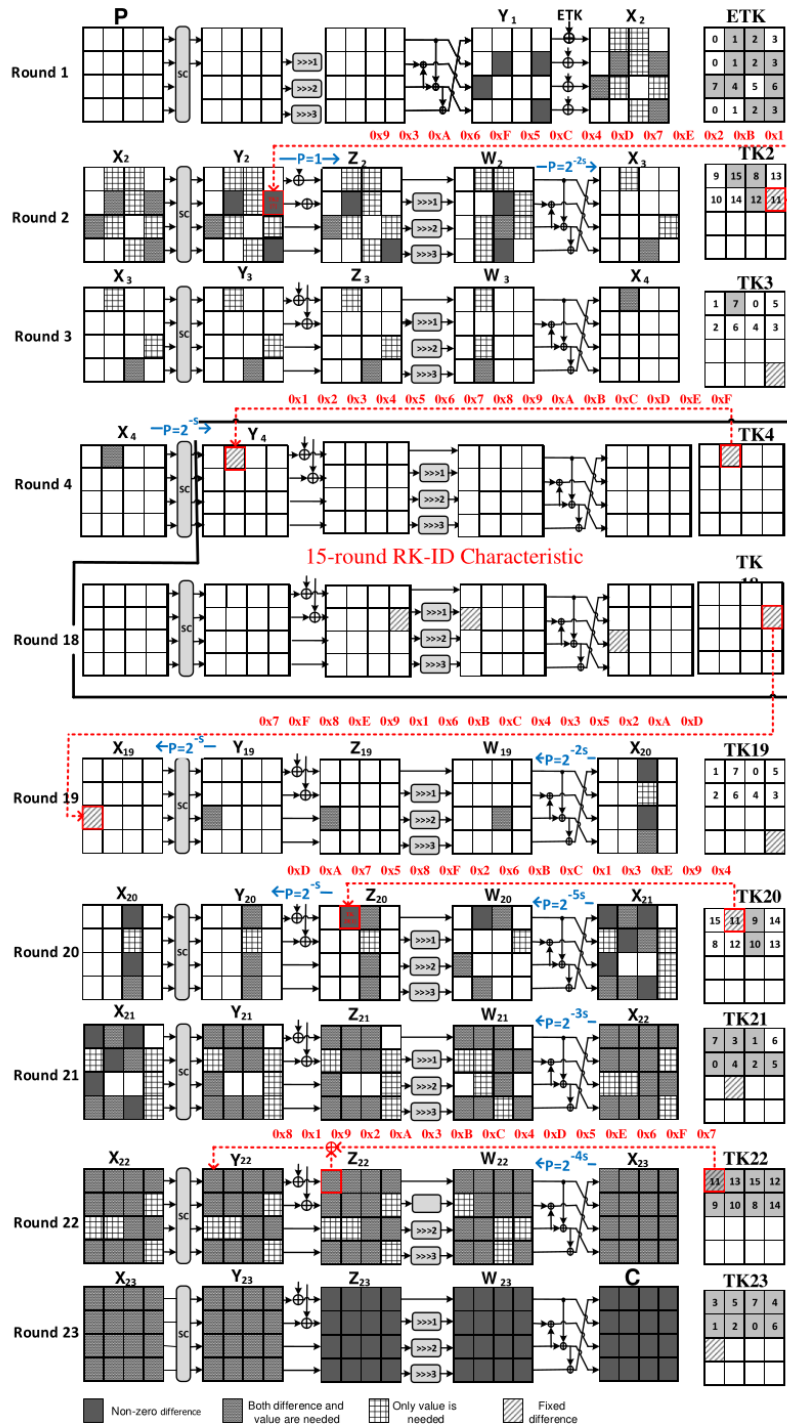
Once these pairs have been generated, the attacker guesses the value of  $ETK[7]$  to compute the difference in the cell  $Y_2[7]$  of each pair of plaintexts. By looking for the index  $i$  such that  $\Delta Y_2[7] = TDT[1][i]$  in the TDT, the attacker deduces in which list  $L_i$  to store the pair. This identifies which of the  $2^s - 1$  impossible trails is considered for this key guess.

The TDT is also used in round 4, where the attacker needs to check if the correct difference happens at the start of the distinguisher. Namely, it corresponds to checking that  $\Delta Y_4[1] = TDT[2][i]$  (and if not, to discard the pair) as this is the required condition to have a cancellation.

We do not transcribe here the remainder of the key recovery as it is standard and not relevant to our discussion. The claimed complexities of the 23-round attacks are of  $D = 2^{62.47}$  chosen plaintexts for SKINNY-64-128, and  $D = 2^{124.41}$  for SKINNY-128-256. The time complexities (expressed in number of encryptions) are respectively of  $T = 2^{124.21}$  and  $T = 2^{243.61}$ .



**Figure 4:** Screenshot of the 15-round related-tweakey impossible distinguisher for SKINNY- $n-2n$  from [SMB18].



**Figure 5:** Screenshot of the 23-round related-tweakey impossible attack for SKINNY- $n-2n$  from [SMB18].



## 4 Analysis of the Key-Recovery in [SMB18]

There are a few interlinked issues in the previous process.

**Data generation.** First, the authors mention a total of  $2^{x+|\Delta_{in}|+1}$  encryption queries corresponding to  $2^x$  structures of  $2^{|\Delta_{in}|}$  messages that can form a total of  $2^{x+2|\Delta_{in}|}$  pairs. This presupposes that each plaintext is encrypted twice, under two different tweaks.

**TDT.** The TDT misses that the set of relevant tweakkey differences is actually a vector space (if we add the 0 difference) and not an arbitrary set of values. Such vector space stems from the linearity of the tweakkey schedule and of the condition it needs to fulfill. It implies that the queries of the plaintexts under several tweaks can be done efficiently, as will be detailed next section.

**On the “choice” of  $i$ .** Following the first key guess (of *ETK*[7]), the attacker computes  $\Delta Y_2[7]$  for each pair of plaintexts  $(P, \bar{P})$  and deduces from it the impossible differential trail that is used for this pair by selecting  $i$  and putting the pair in the corresponding list  $L_i$ , where  $i$  is such that  $\Delta Y_2[7] = TDT[1][i]$ . This means the tweakkey difference depends on the value of *ETK*[7], and cannot be predicted beforehand. Thus, the approach breaks if each plaintext is encrypted under only 2 tweakkeys.

**Filtering factor at round 2.** In the initial attack, the first cancellation between  $\Delta Y_2[7]$  and  $\Delta TK2[7]$  happens with probability 1 as  $\Delta TK2[7]$  is chosen with  $i$ . We showed in the previous point that  $i$  cannot be chosen and that  $\Delta TK2[7]$  is fixed with the pair, so actually checking this cancellation creates a filter of  $2^{-s}$  of the pairs.

Following these observations we detail a corrected algorithm in the next section and reassess the attacks of [SMB18] together with the attacks proposed in 4 papers that are based on it ([HSE23, HGSE23, BDL20, DNS24]).

## 5 Detailed Description of the Patched Key-Recovery

In this section we describe a technique to organize an attack taking advantage of a valid set of impossible differential trails based on several tweakkey differences. We start by discussing how to modify the 23-round attack of [SMB18] and next provide generic complexity formulas.

### 5.1 Principle

The encryption queries must allow to take advantage of the set of  $2^s - 1$  impossible differential distinguishers. As both the tweakkey schedule and the condition to obtain the 3 blank rounds are linear, the set of relevant tweakkey differences is actually a vector space. The attacker can thus exploit this mathematical pattern by querying structures of plaintexts under a set of tweakkey values that take all possible values on an affine coset of the space of tweakkey differences. Similar to the original attack presented in [SMB18], the considered plaintext values are organized in one structure where all the possible values for the 4 active cells of  $Y_1$  are spanned while the other cells are fixed to a given value. What is different is that these  $2^{4s}$  messages are each encrypted under a set of  $2^s$  tweakkeys.

By pairing any two different messages encrypted under any two different master tweakkeys within a structure, an attacker obtains a valid message difference and a valid tweakkey difference. A total of approximately  $2^{4s+s} \times 2^{4s+s} \times 2^{-1} \approx 2^{10s-1}$  such (unordered) pairs are obtained from  $2^{4s+s}$  initial encryption queries. This is thus repeated  $2^x$  times to get enough pairs for the attack.

Note that this change can be seen as increasing the size of the structure by using the additional degree of freedom on the tweakey.

In summary, the first point of Section 4 is fixed with this new data generation, the second point (TDT use) is replaced by the subspace of tweakkeys, which also fixes the value of the previous “ $i$ ” of point 3. The filtering factor (point 4) must be taken into account in the complexity.

## 5.2 Generic Formulas

We consider the same notation as previously and in particular denote by  $|\Delta_{in}|$  the number of active bits at the plaintext side, by  $|\Delta_{out}|$  the number of active bits at the ciphertext side and by  $n$  the block size. We introduce  $|\Delta_t|$  to denote the number of active tweakey bits. We assume here for simplicity that all the  $2^{|\Delta_t|}$  tweakey differences correspond to a valid impossible differential trail, but the formulas can easily be adapted to cover more complex cases.

The probability to keep a key is, as in Section 2.1,

$$(1 - 2^{-c_{in}-c_{out}})^N \simeq \exp(-N \times 2^{-c_{in}-c_{out}}),$$

where  $N$  is the number of pairs with an input difference in  $\Delta_{in}$ , an output difference in  $\Delta_{out}$  and a tweakey difference in  $\Delta_t$ . Again we can choose the number of pairs  $N_{min}^g$  such that  $N_{min}^g > g \times \ln(2) \times 2^{c_{in}+c_{out}}$  to get  $(1 - 2^{-c_{in}-c_{out}})^{N_{min}^g} < \frac{1}{2^g}$ .

To build these pairs, the attacker organizes the (plaintext or ciphertext) queries in  $2^x$  structures of  $2^{|\Delta_{in}|+|\Delta_t|}$  (resp.  $2^{|\Delta_{out}|+|\Delta_t|}$ ) encryption queries each, corresponding to the encryption of all the possible plaintexts (resp. ciphertexts) with varying values on the active positions (and a fixed value on the other cells) under all the  $2^{|\Delta_t|}$  master tweakey differences of the linear subspace.

If more than one full structure is necessary ( $2^x \geq 1$ ), with  $2^{x+|\Delta_{in}|+|\Delta_t|}$  encryptions, the attacker can approximately build  $2^x \times \binom{2^{|\Delta_{in}|+|\Delta_t|}}{2} \approx 2^{x+2|\Delta_{in}|+2|\Delta_t|-1}$  pairs with the correct  $\Delta_{in}$  and  $\Delta_t$ . Otherwise, if only a portion of  $2^x < 1$  of a structure is required, with  $2^{x+|\Delta_{in}|+|\Delta_t|}$  encryptions the attacker can build around  $\binom{2^{x+|\Delta_{in}|+|\Delta_t|}}{2} \approx 2^{2(x+|\Delta_{in}|+|\Delta_t|)-1}$  pairs with the correct<sup>1</sup>  $\Delta_{in}$  and  $\Delta_t$ .

Only the pairs with a ciphertext difference lying in  $\Delta_{out}$  are of interest, so we have:

$$N = \begin{cases} 2^{x+2|\Delta_{in}|+2|\Delta_t|-1-(n-|\Delta_{out}|)} & \text{if } 2^x \geq 1 \\ 2^{2x+2|\Delta_{in}|+2|\Delta_t|-1-(n-|\Delta_{out}|)} & \text{if } 2^x \leq 1. \end{cases}$$

Consequently,  $2^x$  and thus the data complexity  $D$  should be chosen so that:

$$D = \begin{cases} 2^{x+|\Delta_{in}|+|\Delta_t|} \approx g \ln(2) 2^{c_{in}+c_{out}-|\Delta_{in}|-|\Delta_t|+1+n-|\Delta_{out}|} & \text{if } 2^x \geq 1 \\ 2^{x+|\Delta_{in}|+|\Delta_t|} \approx \min_{\Delta \in \{\Delta_{in}, \Delta_{out}\}} \left\{ \sqrt{g \ln(2) 2^{c_{in}+c_{out}+1+n-|\Delta|}} \right\} & \text{if } 2^x \leq 1. \end{cases}$$

There is finally the cost of guessing and filtering the pairs. This approach is identical to the single-tweak(ey) case. Using early-abort and the heuristic from [BNS14], we can estimate it to cost

$$N 2^{|k_{in} \cup k_{out}| - c_{in} - c_{out}}.$$

The exhaustive search of the remaining key bits requires  $2^{k-g}$  encryptions so in the end the total time complexity is (where  $C_E$  and  $C'_E$  are as defined in Section 2.1):

$$T = \left( D + \left( N + 2^{|k_{in} \cup k_{out}|} \frac{N}{2^{c_{in}+c_{out}}} \right) C'_E + 2^{k-g} \right) C_E.$$

<sup>1</sup>Note that a refinement of these approximations can be obtained to take into account the fact that the tweakey has to be active, by multiplying the previous formula by  $\frac{2^{|\Delta_t|-1}}{2^{|\Delta_t|}}$ . In particular we will use this in the case  $|\Delta_t| = 1$ , as it corresponds to a factor  $\frac{1}{2}$ .

While the formula is the same as for the single key case in Section 2.1, the values of  $N$  and  $D$  depend on the value of  $|\Delta_t|$ .

### 5.3 Differences with [SMB18]

If there are  $2^{|\Delta_t|}$  possible tweakey differences, assuming the initial attack uses at least  $2^{|\Delta_t|}$  structures, the correction is:

- Instead of encrypting each plaintext under two different tweaks, it is encrypted under  $2^{|\Delta_t|}$  tweaks.
- The tweakey constraint is no longer free in our model, and divides the number of pairs by  $2^{|\Delta_t|}$  (that is, in general formulas, we need to add  $|\Delta_t|$  to  $c_{in}$  or  $c_{out}$ ).

Overall, the main change is the number of pairs, which is significantly increased. Every other parameters, including the data complexity, can be reused as-is. Interestingly, the parts of the key recovery after checking the tweakey constraints are identical. Thus, in some regimes, the estimated time cost is not changed, and the only difference is the larger memory footprint, as pairs need to be stored in memory for filtering.

## 6 Impact on Concrete Key-Recoveries

Including the original [SMB18], we identified 5 articles [SMB18, BDL20, DNS24, HSE23, HGSE23] that build upon this technique. Among them, 3 explicitly reuse the key-recovery technique, while 2 apply the original SKINNY related-tweakey distinguisher in different contexts. All these attacks are against variants of SKINNY. For clarity, we express the attack parameters in function of  $s$ .

### 6.1 Revisiting the Original Article [SMB18]

In addition to the 23-round attack that we detailed in Section 3, Sadeghi *et al.* proposed a 19-round related tweakey impossible differential attack on SKINNY-n-n (see [SMB18, Appendix A]) that uses the same technique. By applying the formulas from Section 5.2 to both these attacks (aiming for the same success probability as in [SMB18]), we obtain the patched parameters and complexities as presented in Table 2.

**Table 2:** Claimed and patched parameters and costs for the attacks of [SMB18] against SKINNY.

Attack	Version	rounds	$ \Delta_{in} $	$c_{in}$	$ \Delta_{out} $	$c_{out}$	$ \Delta_t $	$x$	$D$	$N$	$T$
[SMB18]	64-64	19	4s	4s	9s	8s	1	44.3	$2^{61.3}$	$2^{48.3}$	$2^{62.83}$
	128-128							89.47	$2^{122.47}$	$2^{97.47}$	$2^{124.43}$
	64-128	23	4s	3s	16s	16s	1	45.47	$2^{62.47}$	$2^{77.47}$	$2^{124.21}$
	128-256							91.40	$2^{124.41}$	$2^{155.41}$	$2^{243.61}$
patch	64-64	19	4s	4s	9s	9s	s	41.3	$2^{61.3}$	$2^{52.3}$	$2^{62.83}$
	128-128							82.47	$2^{122.47}$	$2^{105.47}$	$2^{124.43}$
	64-128	23	4s	4s	16s	16s	s	42.47	$2^{62.47}$	$2^{81.47}$	$2^{124.21}$
	128-256							84.40	$2^{124.40}$	$2^{163.40}$	$2^{243.61}$

Note that it's the error in the  $c_{in}/c_{out}$  value that creates the error in  $N$ .

## 6.2 Attacks Presented at Eurocrypt 2023 [HSE23]

The article [HSE23] presents a new CP-based method to search for impossible-differential, integral and zero-correlation attacks. Among the impossible differential attacks that are presented, only two attacks are related-tweakey attacks that use the framework from [SMB18]. The two are almost-identical, with distinct targets: SKINNY-64-192 and SKINNY-128-384. They are both detailed in the full version of the article [HSE22, Appendix F.4].

As with the previous application, we need to consider  $|\Delta_t| = s$  and an increased  $c_{in}$ . The changes in the attack parameters are detailed in Table 3. While the increase of  $c_{in}$  and thus of  $N$  impacts the key-recovery detailed in [HSE23], its first step is to tackle the tweakey difference. This first filtering step has a negligible cost compared with later steps and hence, the overall cost of the pair filtering is the same. In the end, the time and data complexities of our patched version match the ones obtained with the flawed technique.

**Table 3:** Claimed and patched parameters and costs for the 27-round attacks against SKINNY from [HSE23, Table 1]. † The caption of [HSE22, Fig. 10] claims  $c_{in} = 4s$ . This is however inconsistent with the computations on the previous page and likely a typo.

Attack	Version	$ \Delta_{in} $	$c_{in}$	$ \Delta_{out} $	$c_{out}$	$ \Delta_t $	$x$	$D$	$N$	$T$
[HSE23]	64-192	4s	3s†	16s	16s	1	46.64	$2^{63.64}$	$2^{78.64}$	$2^{183.26}$
	128-384						91.99	$2^{124.99}$	$2^{155.99}$	$2^{362.61}$
patch	64-192	4s	4s	16s	16s	s	43.64	$2^{63.64}$	$2^{82.64}$	$2^{183.26}$
	128-384						84.99	$2^{124.99}$	$2^{163.99}$	$2^{362.61}$

## 6.3 Follow-up of the Eurocrypt Article [HGSE23]

A follow-up of the previous article was posted on ePrint [HGSE23] in November 2023. Among other things, it proposes an extension of the previous CP model that covers bit-oriented ciphers and that does not require the attacker to set the contradiction point of the impossible differential distinguisher.

The authors applied this improved model to various variants of SKINNY (SKINNY, FORKSKINNY and SKINNYe-v2) and proposed 15 impossible differential attacks. As with the previous article, the key-recovery technique of [SMB18] is explicitly used. For most of the attacks the time cost is unaffected. Still, for 2 of them the updated costs are slightly above what was initially claimed. Our results are summarized in Table 4.

We communicated our observations to the authors of the preprint who confirmed our findings and added a discussion in the published version of their article (see Appendix A of [HGSE24]).

## 6.4 Cryptanalysis of ForkSKINNY [BDL20]

In [BDL20], Bariant *et al.* proposed two attacks on FORKSKINNY-128-256. The first one, which attacks the 128-bit key version, reuses the attack against 19-rounds SKINNY-128-128 from [SMB18] to attack 24-round FORKSKINNY. As the conversion is essentially independent on the details of the attack, the flawed key-recovery is only implicitly used. Moreover, the correction is roughly the same as the one in Section 6.1.

The second attack, which targets the 256-bit key version, relies on an extension of the distinguisher described in [SMB18] on SKINNY-128-256. By taking advantage of

**Table 4:** Claimed and updated parameters and costs for the attacks from [HGSE23]. Patched variants keep the same data complexity, reoptimized variants change it to minimize the time.

Cipher	rounds	Version	$ \Delta_{in} $	$c_{in}$	$ \Delta_{out} $	$c_{out}$	$ \Delta_t $	$x$	$D$	$N$	$T$
ForkSKINNY 64-192	28	[HGSE23, G.1]	13s	11s	14s	14s	1	8	$2^{60}$	$2^{104}$	$2^{169.6}$
		patch	13s	13s	14s	14s	2s	1.2	$2^{61.2}$	$2^{112}$	$2^{169.6}$
	28	[HGSE23, G.2]	6s	5s	16s	16s	1	38	$2^{62}$	$2^{86}$	$2^{123.73}$
		patch	6s	6s	16s	16s	s	35	$2^{63}$	$2^{90}$	$2^{123.73}$
	30	[HGSE23, G.4]	6s	5s	16s	16s	1	38	$2^{62}$	$2^{86}$	$2^{123.73}$
		patch	6s	6s	16s	16s	s	35	$2^{63}$	$2^{90}$	$2^{123.73}$
32	[HGSE23, G.3]	13s	12s	16s	16s	1	10	$2^{62}$	$2^{114}$	$2^{186.27}$	
	patch	13s	13s	16s	16s	s	7	$2^{63}$	$2^{118}$	$2^{186.27}$	
ForkSKINNY 128-256	20	[HGSE23, G.8]	5s	4s	10s	7s	1	61	$2^{101}$	$2^{93}$	$2^{102.2}$
		patch	5s	5s	10s	7s	s	54	$2^{102}$	$2^{101}$	$2^{107.26}$
		reoptimized	5s	5s	10s	7s	s	53.2	$2^{101.2}$	$2^{100.2}$	$2^{106.5}$
	24	[HGSE23, G.6]	8s	6s	8s	8s	1	54.4	$2^{118.4}$	$2^{118.4}$	$2^{123.17}$
		patch	8s	7s	8s	8s	s/2	51.4	$2^{119.4}$	$2^{122.4}$	$2^{126.83}$
		reoptimized	8s	7s	8s	8s	s/2	50	$2^{118}$	$2^{121}$	$2^{126.27}$
26	[HGSE23, G.7]	8s	7s	12s	12s	1	62.7	$2^{126.7}$	$2^{158.7}$	$2^{246.62}$	
	patch	8s	8s	12s	12s	s/2	59.7	$2^{127.7}$	$2^{162.7}$	$2^{246.62}$	
	[HGSE23, G.5]	13s	12s	9s	9s	1	23.6	$2^{127.6}$	$2^{175.6}$	$2^{238.5}$	
patch	13s	13s	9s	9s	s/2	20.6	$2^{128.6}$	$2^{179.6}$	$2^{238.5}$		
ForkSKINNY 128-288	26	[HGSE23, G.12]	s	0	8s	8s	1	116.6	$2^{124.5}$	$2^{68.6}$	$2^{126.74}$
		patch	s	s	8s	8s	s/2	113.6	$2^{125.6}$	$2^{72.6}$	$2^{126.74}$
	28	[HGSE23, G.10]	8s	7s	5s	5s	1	60.8	$2^{124.8}$	$2^{100.8}$	$2^{126.68}$
		patch	8s	8s	5s	5s	s/2	57.8	$2^{125.8}$	$2^{104.8}$	$2^{126.67}$
		[HGSE23, G.11]	7s	6s	13s	13s	1	70.9	$2^{126.9}$	$2^{158.9}$	$2^{277.23}$
	patch	7s	7s	13s	13s	s/2	67.9	$2^{127.9}$	$2^{162.9}$	$2^{277.23}$	
31	[HGSE23, G.9]	8s	7s	16s	16s	1	62.5	$2^{126.5}$	$2^{190.5}$	$2^{280.5}$	
	patch	8s	8s	16s	16s	s/2	59.5	$2^{127.5}$	$2^{194.5}$	$2^{280.5}$	
SKINNY 128-288	23	[HGSE23, H.2]	7s	6s	5s	5s	1	64.8	$2^{120.8}$	$2^{88.8}$	$2^{126.73}$
		patch	7s	7s	5s	5s	s	57.8	$2^{121.8}$	$2^{96.8}$	$2^{126.73}$
	26	[HGSE23, H.1]	9s	8s	16s	16s	1	50	$2^{122}$	$2^{194}$	$2^{286.38}$
patch	9s	9s	16s	16s	s	43	$2^{123}$	$2^{202}$	$2^{286.38}$		
SKINNYe-v2	31	[HGSE23, H.3]	12s	11s	16s	16s	1	14	$2^{62}$	$2^{110}$	$2^{251.14}$
		patch	12s	12s	16s	16s	s	11	$2^{63}$	$2^{114}$	$2^{251.14}$

FORKSKINNY’s structure, the authors add 3 blank rounds to the distinguisher and are able to attack 26 rounds of FORKSKINNY with  $r_i = 7$ ,  $r_0 = 27$  and  $r_1 = 19$  rounds.

Given that their distinguisher has a distinct input difference, the authors made their own key recovery. The proposed data generation step begins with the encryption of each structure under several keys, as in the correction we propose.

Their distinguisher requires an initial tweak difference that makes the round tweakeys  $TK_6$  and  $TK_9$  inactive which corresponds to selecting  $\delta \in \mathbb{F}_2^s$  so that  $\delta \oplus LFSR_2^{15}(\delta) = 0$ . For both  $s = 4$  and  $s = 8$  there are 15 such solutions  $\delta$  (and hence there are 15 related-key impossible differential trails for 18 rounds), and as the condition is linear the solutions form a linear subspace.

We agree with the parameters and with the complexity analysis made by the authors.

## 6.5 Quantum Impossible Differential Attacks [DNS24]

The article [DNS24] proposes a framework for quantum impossible attacks, and gives as an application a quantum attack heavily inspired by [SMB18], but with 2 less rounds in the output. Unfortunately, they reuse as-is the parameters for the input, that is, there is no tweak variation and a cancellation is free. While the authors use these flawed parameters to estimate the number of pairs, they also describe a detailed key-recovery, which is correct (and in particular is inconsistent with the claimed value for  $c_{in}$ ). The authors also seek enough filtering to directly obtain the correct  $k_{in} \cup k_{out}$  subkey.

As quantum computing is not the focus of this paper, we refer to [DNS24] for details and formulas. In particular, the quantum framework can be used with our key recovery, it only amounts in changing some parameters in their formulas.

We can patch the attack by adding  $|\Delta_t| = s$  to the initial  $|\Delta_{in}|$  (each plaintext is encrypted with all tweaks) and  $c_{in}$ . We can then reuse their formulas to obtain an updated quantum cost. This cost corresponds to what the authors would have obtained had they used correct parameters.

**Optimization.** We also propose an improved variant, that contains the following changes:

- The rejection probability of a key is estimated more precisely, using the natural logarithm,
- As the first filtering step in their key recovery does not depend on any key guess, it is moved to the pair generation part.

Our results are summarized in Table 5.

**Table 5:** Parameters and costs for the attacks against 21-round SKINNY-128-256.  $s = 8$  bits. Note that the “no QRAM” attack requires classical pair generation in  $2^{128}$  classical time and queries. † Using the formulas from [DNS24] we obtain  $2^{114.46}$ . The  $2^{117.46}$  is likely a typo.

Attack	$ \Delta_{in}  +  \Delta_t $	$c_{in}$	$ \Delta_{out} $ and $c_{out}$	$N$	Pair generation cost (with QRAM)	Pair filtering cost	
						With QRAM	no QRAM
Original	$4s$	$3s$	$9s$	$2^{103.17}$	$2^{119.17}$	$2^{104.32}$	$2^{117.46} \dagger$
Direct patch	$5s$	$4s$	$9s$	$2^{111.17}$	$2^{121.84}$	$2^{112.32}$	$2^{122.70}$
Optimized	$5s$	$4s$	$8s$	$2^{102.64}$	$2^{118.64}$	$2^{103.79}$	$2^{114.15}$

## 7 Conclusion

In this paper, we analysed the technique proposed at ToSC 2018 by Sadeghi et al. and we highlighted an inaccuracy that was propagated to multiple follow-up works over a span of 6 years. We showed that the technique misestimated the data generation and in particular does not encrypt the plaintexts under the full set of relevant tweaks as it is required. A second (related) problem comes from a condition that was considered to be passed for free.

We showed how to fix these problems and proposed generic formulas that we used to reevaluate 5 papers using this technique. By taking advantage of tweakey structures we obtained corrected attacks covering the same number of rounds and with complexities that are close to the wrong ones. Shortly after noticing the problem, we shared an early version of this note with the authors of the 5 papers, who agreed with our findings. Moreover, the authors of [HGSE23] provided a short discussion of the impact of our fix on their automated tool in the final version of their article, published at ToSC 2024 issue 1 (see [HGSE24, Appendix A]).

On a more general note, our work can be seen as a reminder to be cautious when relying on previously published techniques and to carefully analyze existing methods before reusing them.

## Acknowledgments

The authors would like to thank the authors of [SMB18, HSE23, HGSE23, BDL20] and [DNS24] for their valuable feedback.

This work has been partially supported by the French Agence Nationale de la Recherche through the OREO project under Contract ANR-22-CE39-0015, and through the France 2030 program under grant agreement No. ANR-22-PECY-0010 CRYPTANALYSE.

## References

- [ALP<sup>+</sup>19] Elena Andreeva, Virginie Lallemand, Antoon Purnal, Reza Reyhanitabar, Arnab Roy, and Damian Vizár. Forkcipher: A new primitive for authenticated encryption of very short messages. In Steven D. Galbraith and Shihō Moriai, editors, *Advances in Cryptology – ASIACRYPT 2019, Part II*, volume 11922 of *Lecture Notes in Computer Science*, pages 153–182. Springer, Heidelberg, December 2019. doi:10.1007/978-3-030-34621-8\_6.
- [BA08] Behnam Bahrak and Mohammad Reza Aref. Impossible differential attack on seven-round AES-128. *IET Inf. Secur.*, 2(2):28–32, 2008. URL: <https://doi.org/10.1049/iet-ifs:20070078>, doi:10.1049/IET-IFS:20070078.
- [BBS99] Eli Biham, Alex Biryukov, and Adi Shamir. Cryptanalysis of Skipjack reduced to 31 rounds using impossible differentials. In Jacques Stern, editor, *Advances in Cryptology – EUROCRYPT’99*, volume 1592 of *Lecture Notes in Computer Science*, pages 12–23. Springer, Heidelberg, May 1999. doi:10.1007/3-540-48910-X\_2.
- [BDL20] Augustin Bariant, Nicolas David, and Gaëtan Leurent. Cryptanalysis of forkciphers. *IACR Transactions on Symmetric Cryptology*, 2020(1):233–265, 2020. doi:10.13154/tosc.v2020.i1.233-265.
- [BJK<sup>+</sup>16] Christof Beierle, Jérémy Jean, Stefan Kölbl, Gregor Leander, Amir Moradi, Thomas Peyrin, Yu Sasaki, Pascal Sasdrich, and Siang Meng Sim. The SKINNY family of block ciphers and its low-latency variant MANTIS. In Matthew



- Robshaw and Jonathan Katz, editors, *Advances in Cryptology – CRYPTO 2016, Part II*, volume 9815 of *Lecture Notes in Computer Science*, pages 123–153. Springer, Heidelberg, August 2016. doi:10.1007/978-3-662-53008-5\_5.
- [BNS14] Christina Boura, María Naya-Plasencia, and Valentin Suder. Scrutinizing and improving impossible differential attacks: Applications to CLEFIA, Camellia, LBlock and Simon. In Palash Sarkar and Tetsu Iwata, editors, *Advances in Cryptology – ASIACRYPT 2014, Part I*, volume 8873 of *Lecture Notes in Computer Science*, pages 179–199. Springer, Heidelberg, December 2014. doi:10.1007/978-3-662-45611-8\_10.
- [BS91] Eli Biham and Adi Shamir. Differential cryptanalysis of DES-like cryptosystems. In Alfred J. Menezes and Scott A. Vanstone, editors, *Advances in Cryptology – CRYPTO’90*, volume 537 of *Lecture Notes in Computer Science*, pages 2–21. Springer, Heidelberg, August 1991. doi:10.1007/3-540-38424-3\_1.
- [DNS24] Nicolas David, María Naya-Plasencia, and André Schrottenloher. Quantum impossible differential attacks: applications to AES and SKINNY. *Designs, Codes and Cryptography*, 92(3):723–751, 2024. doi:10.1007/s10623-023-01280-y.
- [HGSE23] Hosein Hadipour, Simon Gerhalter, Sadegh Sadeghi, and Maria Eichlseder. Improved search for integral, impossible-differential and zero-correlation attacks: Application to ascon, forkskinny, skinny, mantis, PRESENT and qarmav2. Cryptology ePrint Archive, Report 2023/1701, version 20231123:125414, 2023. <https://eprint.iacr.org/archive/2023/1701/20231123:125414>.
- [HGSE24] Hosein Hadipour, Simon Gerhalter, Sadegh Sadeghi, and Maria Eichlseder. Improved search for integral, impossible differential and zero-correlation attacks application to Ascon, ForkSKINNY, SKINNY, MANTIS, PRESENT and QARMAv2. *IACR Transactions on Symmetric Cryptology*, 2024(1):234–325, 2024. doi:10.46586/tosc.v2024.i1.234-325.
- [HSE22] Hosein Hadipour, Sadegh Sadeghi, and Maria Eichlseder. Finding the impossible: Automated search for full impossible differential, zero-correlation, and integral attacks. Cryptology ePrint Archive, Report 2022/1147, 2022. <https://eprint.iacr.org/2022/1147>.
- [HSE23] Hosein Hadipour, Sadegh Sadeghi, and Maria Eichlseder. Finding the impossible: Automated search for full impossible-differential, zero-correlation, and integral attacks. In Carmit Hazay and Martijn Stam, editors, *Advances in Cryptology – EUROCRYPT 2023, Part IV*, volume 14007 of *Lecture Notes in Computer Science*, pages 128–157. Springer, Heidelberg, April 2023. doi:10.1007/978-3-031-30634-1\_5.
- [Jea16] Jérémy Jean. TikZ for Cryptographers. <https://www.iacr.org/authors/tikz/>, 2016.
- [JNP14] Jérémy Jean, Ivica Nikolic, and Thomas Peyrin. Tweaks and keys for block ciphers: The TWEAKEY framework. In Palash Sarkar and Tetsu Iwata, editors, *Advances in Cryptology – ASIACRYPT 2014, Part II*, volume 8874 of *Lecture Notes in Computer Science*, pages 274–288. Springer, Heidelberg, December 2014. doi:10.1007/978-3-662-45608-8\_15.
- [Knu98] Lars Knudsen. Deal-a 128-bit block cipher. *complexity*, 258(2):216, 1998.



- [NSS20a] Yusuke Naito, Yu Sasaki, and Takeshi Sugawara. Lightweight authenticated encryption mode suitable for threshold implementation. In Anne Canteaut and Yuval Ishai, editors, *Advances in Cryptology – EUROCRYPT 2020, Part II*, volume 12106 of *Lecture Notes in Computer Science*, pages 705–735. Springer, Heidelberg, May 2020. doi:10.1007/978-3-030-45724-2\_24.
- [NSS20b] Yusuke Naito, Yu Sasaki, and Takeshi Sugawara. Lightweight authenticated encryption mode suitable for threshold implementation. Cryptology ePrint Archive, Report 2020/542, 2020. <https://eprint.iacr.org/2020/542>.
- [NSS22] Yusuke Naito, Yu Sasaki, and Takeshi Sugawara. Secret can be public: Low-memory AEAD mode for high-order masking. In Yevgeniy Dodis and Thomas Shrimpton, editors, *Advances in Cryptology – CRYPTO 2022, Part III*, volume 13509 of *Lecture Notes in Computer Science*, pages 315–345. Springer, Heidelberg, August 2022. doi:10.1007/978-3-031-15982-4\_11.
- [SMB18] Sadegh Sadeghi, Tahereh Mohammadi, and Nasour Bagheri. Cryptanalysis of reduced round SKINNY block cipher. *IACR Transactions on Symmetric Cryptology*, 2018(3):124–162, 2018. doi:10.13154/tosc.v2018.i3.124-162.
- [ZWF07] Wentao Zhang, Wenling Wu, and Dengguo Feng. New results on impossible differential cryptanalysis of reduced AES. In Kil-Hyun Nam and Gwangsoo Rhee, editors, *ICISC 07: 10th International Conference on Information Security and Cryptology*, volume 4817 of *Lecture Notes in Computer Science*, pages 239–250. Springer, Heidelberg, November 2007. doi:10.1007/978-3-540-76788-6\_19.