

# Security Analysis of the Khudra Lightweight Cryptosystem in the Vehicular Ad-hoc Networks

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## Abstract

With the enlargement of wireless technology, vehicular ad-hoc networks (VANETs) are rising as a hopeful way to realize smart cities and address a lot of vital transportation problems such as road security, convenience, and efficiency. To achieve data confidentiality, integrity and authentication applying lightweight cryptosystems is widely recognized as a rather efficient approach for the VANETs. The Khudra cipher is such a lightweight cryptosystem with a typical Generalized Feistel Network, and supports 80-bit secret key. Up to now, little research of fault analysis has been devoted to attacking Khudra. On the basis of the single nibble-oriented fault model, we propose a differential fault analysis on Khudra. The attack can recover its 80-bit secret key by introducing only 2 faults. The results in this study will provides vital references for the security evaluations of other lightweight ciphers in the VANETs.

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**Keywords:** Vehicular Ad-hoc Networks, Khudra, Lightweight Cryptosystem, Differential Fault Analysis

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## 1. Introduction

Vehicular Ad-hoc Networks (VANETs) comprise vehicle-to-vehicle and vehicle-to-infrastructure communications based on the wireless local area network technologies, aiming to provide a wide spectrum of safety and comfort applications to drivers and passengers. It has been immensely successful and naturally attracted considerable attention from both academia and industry since its introduction [1]. However, the perfect composition of airborne computers and location devices, raises formidable research challenges. VANETs are networks with high dynamic topology and their communication is vulnerable to attacks. For instance, it is necessary to ensure that the vital information can't be interrupted by an attacker; similarly, the system should be helpful to build the drivers' responsibility; but at the same time, it should protect the privacy of the drivers and passengers as much as possible. Nodes in VANETs should be confident that each communication has been started from a trustworthy source node and messages are not varied by malicious vehicles. Although these issues seem similar to those used in traditional communication networks, there are individual characteristic for vehicular networks. The self-organized nature of the networks, the mobility of the vehicles, the relevance of their locations, and the irregular connectivity among nodes can lead to a variety of security matters [2-4]. Due to the limitations of running capabilities, power provision and memory space of devices in vehicles, classical cryptosystems cannot play direct roles in lots of security actions such as digital signature, message authentication, encryption and decryption, etc. It is very critical to realize efficient cryptosystems in VANETs, i.e., lightweight cryptosystems are mostly desired [5-16]. Thus, application of the lightweight cryptosystems can not only allow lower energy consumption for devices, but also provide more network links with devices.

As an active side channel attack technique, fault analysis can exploit easily accessible information like input-output behavior under malfunctions, magnify and estimate the leaked information by means of mathematical cryptanalysis [16-18]. In 1996, Boneh et al. proposed a fault analysis on RSA by exploiting the faulty calculations [16,17]. Later differential fault analysis (DFA) was presented to break DES and AES [18-21]. The attackers can inject faults to the running procedure of a cryptosystem by laser, electromagnetic and voltage interference in the hardware implementation, or alter the internal state of the code in the software implementation. They are often much more powerful than the classical cryptanalysis. Usually only a few faults suffice to break a cryptosystem [22-27].

## 2. Related work

The Khudra lightweight cryptosystem, proposed by Kolay et al. in 2014, has a good compact hardware implementation and maintains good software-friendly features [28]. Khudra has a 64-bit block size and supports a 80-bit secret key. It is based on a generalized type-2 Feistel Network structure with 18 rounds and the whitening layers. Since its introduction, Khudra has been the target of classical cryptanalytic efforts [28-32]. The designers of Khudra took many cryptanalytic techniques into account, such as differential cryptanalysis, linear cryptanalysis, impossible differential attack, differential-linear attack, algebraic attack, boomerang type attacks, slide key attack and related key attack, etc [28]. Then Tolba et al. made use of an offline independently distinguisher in an online phase and presented a meet-in-the-middle attack on 13 rounds and 14 rounds, respectively [29]. Later

Özen et al. improved the above 14-round meet-in-the-middle attack and reduced the memory complexity from  $2^{64.8}$  to  $2^{32.8}$ . Furthermore, they applied a guess-and-determine attack on the same 14 rounds [30]. In 2015, Ma et al. attacked 16-round Khudra without whitening key by computing the minimum number of active  $F$ -functions in differential characteristics of the related-key setting [31]. Later Yang et al. proposed a related-key impossible differential analysis to attack the full-round Khudra without whitening keys [32]. Up to now, little study has been published concerning the Khudra cryptosystem against fault analysis.

In the literature, the previous differential fault analysis targets on the last several rounds of cryptosystems [23-32]. Their basic principle is to derive the secret key by calculating the differential relationship of S-boxes resulting from a correct operation and a faulty operation. Different from the structure of other lightweight cryptosystems with Generalized Feistel Networks, every round function consists of 6-rounds S-boxes layers to provide nonlinearity. It increases the attacking difficulties in computing the input differences and output differences of S-boxes after 6-round diffusions. Furthermore, since adding protections from fault attack increasing the processing consumptions, some countermeasures are suggested to protect only the last several rounds. In the real applications of VANETs, random faults can be injected into deeper rounds of the cryptosystem. In this point, it is important to investigate the deepest rounds of Khudra with a few faults.

This paper proposes a differential fault analysis on the full 6-round function by injecting only 2 faults into the antepenultimate round of Khudra. The attackers only inject the faults out of the  $F$ -function, and depend on the ciphertext difference to derive the accurate locations of faults. Moreover, they can take advantage of 2 faults to the most extent. Hence, it not only decreases the number of faults, but also improves the efficiency of injecting faults. To the best of our knowledge, this is the first work that a differential fault attack on Khudra has been successfully put into practice. Compared with the classical cryptanalysis, differential fault attack on Khudra has a good performance in data complexity, time complexity and memory complexity, as Table 1 shows.

**Table 1.** Cryptanalysis of Khudra

| Method                                     | Whitening layer | Rounds | Complexity  |             |             | Ref.       |
|--|-----------------|--------|-------------|-------------|-------------|------------|
|  |                 |        | Data        | Time        | Memory      |            |
| Meet-in-the-middle attack                  | Yes             | 13     | $2^{51.00}$ | $2^{66.00}$ | $2^{64.8}$  | [15]       |
|  |                 | 14     | $2^{51.00}$ | $2^{66.19}$ | $2^{32.80}$ | [16]       |
| Guess-and-determine attack                 | Yes             | 14     | $2^{1.00}$  | $2^{64.00}$ | \           | [16]       |
| Related-key rectangle attack               | No              | 16     | $2^{57.82}$ | $2^{78.68}$ | \           | [17]       |
| Related-key impossible differential attack | Yes             | 18     | $2^{63.00}$ | $2^{64.46}$ | $2^{64.00}$ | [18]       |
| Differential fault analysis                | Yes             | 18     | $2^{1.58}$  | $2^{20.17}$ | $2^{20.00}$ | This paper |

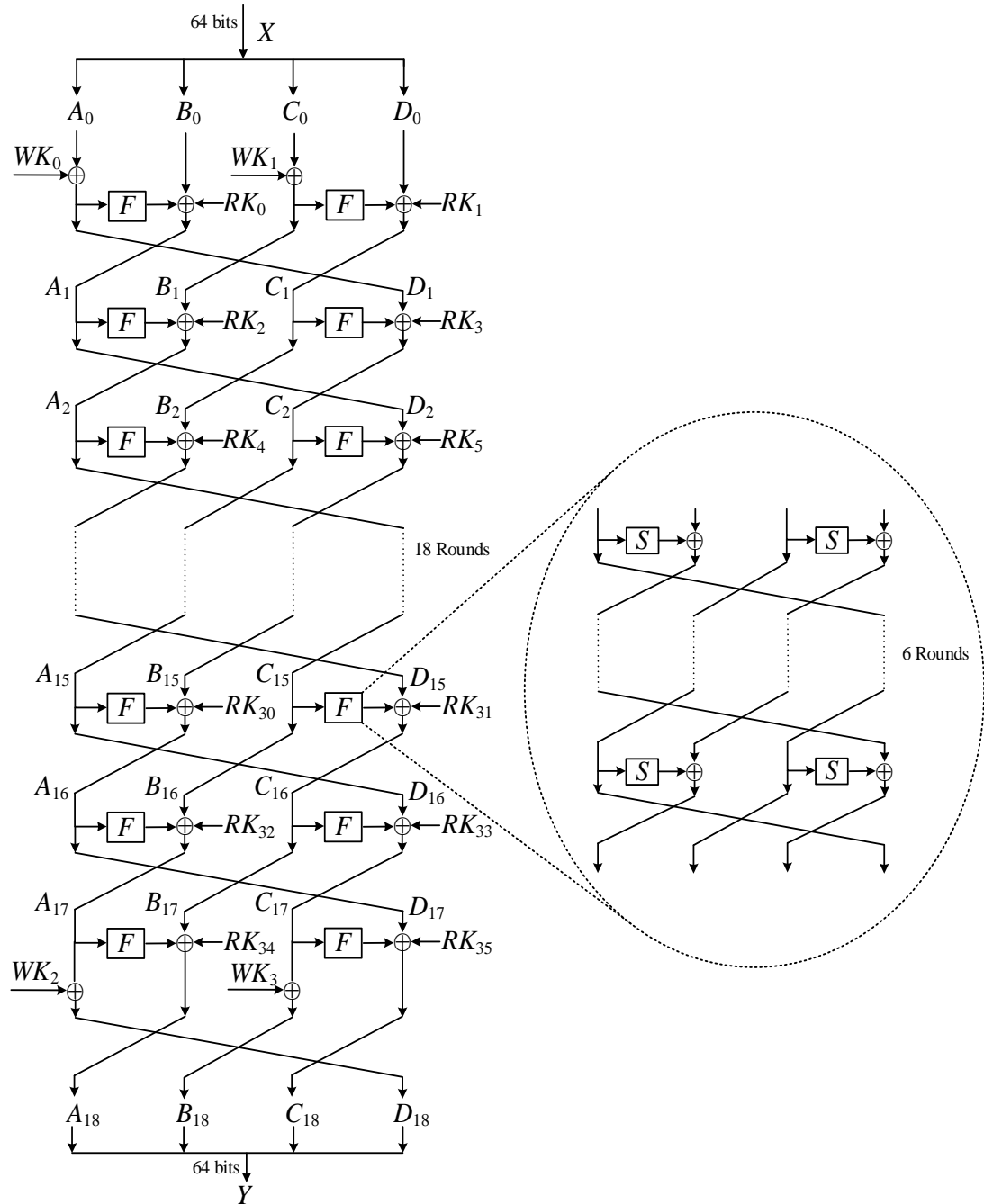
The remainder is organized as follows. Section 3 briefly describes the specification of Khudra. Section 4 proposes our differential fault analysis to break Khudra. Section 5 and 6 calculates the attacking complexity and summarizes the experimental results. The last section concludes the paper.

### 3. Description of Khudra

#### 3.1 Structure

Khudra is an 18-round lightweight block cipher with a 64-bit plaintext size and a 80-bit key size. It employs a Generalized type-2 Feistel Structure as Fig. 1 shows. The plaintext is

divided into four 16-bit branches. To deal with these branches in every round, Khudra has two  $16 \times 16$   $F$ -functions in each round. The  $F$ -function consists of six substitution layers using two  $4 \times 4$  S-boxes in each round to provide nonlinearity. This kind of double layer structure makes Khudra more difficult to attack. The whitening keys added at last make sure that the intermediate states are inaccessible for the attackers.



**Fig. 1.** Structure of Khudra

The detailed encryption of Khudra is presented as **Table 2** shows. The decryption shares the same structure with the encryption, except for the reverse subkeys with the reverse order.

**Table 2.** Encryption of Khudra

|  |
|--|
| <b>Input:</b> $X, K$   |
| <b>Output:</b> $Y$   |
| $A_0 \parallel B_0 \parallel C_0 \parallel D_0 = X$<br>$WK_0 \parallel WK_1 \parallel WK_2 \parallel WK_3 \parallel WK_4 = K$<br>$A \parallel B \parallel C \parallel D = X$<br>$C_0 = C_0 \oplus WK_1$<br><b>for <math>i=0</math> to 17 do</b><br>$A_{i+1} = F(A_i) \oplus B_i \oplus RK_{2i}$<br>$B_{i+1} = C_i$<br>$C_{i+1} = F(C_i) \oplus D_i \oplus RK_{2i+1}$<br>$D_{i+1} = A_i$<br>$D_{18} = D_{18} \oplus WK_2$<br>$B_{18} = B_{18} \oplus WK_3$<br>$Y = A_{18} \parallel B_{18} \parallel C_{18} \parallel D_{18}$ |

As the input of a key schedule, the secret key  $K$  produces round keys for each round and whitening keys as **Table 3** shows.

**Table 3.** Key schedule of Khudra

|   |
|---|
| <b>Input:</b> $K$   |
| <b>Output:</b> $RK, WK$   |
| $WK_0 \parallel WK_1 \parallel WK_2 \parallel WK_3 \parallel WK_4 = K$<br><b>for <math>w=0</math> to 35 do</b><br>$RC_w = 0_{(1)} \parallel w_{(6)} \parallel 0_{(2)} \parallel w_{(6)} \parallel 0_{(1)}$<br>$RK_w = WK_{w \bmod 5} \oplus RC_w$ |

### 3.2 Notations

The notations of Khudra and its analysis are described as **Table 4** shows.

**Table 4.** Notations of Khudra

| Notations  | Description  |
|--|--|
| $A_i, B_{i+1}, C_i, D_{i+1}$                                     | The right inputs of the $F$ -function in round $i$ with $0 \leq i \leq 17$   |
| $\Delta A_i^*, \Delta B_{i+1}^*, \Delta C_i^*, \Delta D_{i+1}^*$ | The difference inputs of the $F$ -function in round $i$ with $0 \leq i \leq 17$ when the fault is injected in $A_{15}$ |
| $\Delta A_i', \Delta B_{i+1}', \Delta C_i', \Delta D_{i+1}'$     | The difference inputs of the $F$ -function in round $i$ with $0 \leq i \leq 17$ when the fault is injected in $C_{15}$ |
| $X = A_0 \parallel B_0 \parallel C_0 \parallel D_0$              | The plaintext  |
| $Y = A_{18} \parallel B_{18} \parallel C_{18} \parallel D_{18}$  | The right ciphertext   |
| $Y^*, Y'$  | The faulty ciphertext when the fault is injected in $A_{15}$ and $C_{15}$ , respectively                               |

|                      |  |
|----------------------|--|
| $K, WK_l, RC_w$      | The secret key, the whitening keys and the round constant, with $0 \leq l \leq 4$ and $0 \leq w \leq 35$ |
| $(m)$                | The bit number of the constant m, with $1 \leq m \leq 6$   |
| Encryption( $X, K$ ) | The encryption procedure   |

## 4. Different Fault Analysis on Khudra

### 4.1 Fault Model

The fault model is the chosen plaintext attack. Furthermore, the attackers can induce a 4-bit error to one layer. However, the location and the value of this nibble in this layer are both unknown. As for the attack, they can analyze a fault occurring near the end of the cryptosystem and assume the general random fault model where the fault modifies the processed data in a random way. Actually, the attackers can inject one-bit error. It does not influence the attacking procedure.

### 4.2 Attacking Procedure

This section proposes a novel differential fault analysis to break Khudra. [Table 5](#) shows the algorithm of our attack as follows:

**Table 5.** Differential fault analysis of Khudra

|  |
|--|
| <b>Input:</b> $X, Y, Y^*, Y'$  |
| <b>Output:</b> $K$   |
| $\Delta A'_{18} \parallel \Delta B'_{18} \parallel \Delta C'_{18} \parallel \Delta D'_{18} = Y \oplus Y^*$<br>$\Delta A'_{18} \parallel \Delta B'_{18} \parallel \Delta C'_{18} \parallel \Delta D'_{18} = Y \oplus Y'$<br><b>for</b> $t_1=0$ <b>to</b> $2^{16}-1$ <b>do</b><br><b>if</b> $F(t_1) \oplus F(t_1 \oplus \Delta D'_{18}) = \Delta A'_{18}$<br>$A_{17} = t_1$<br><b>if</b> $F(t_1) \oplus F(t_1 \oplus \Delta B'_{18}) = \Delta C'_{18}$<br>$C_{17} = t_1$<br>$WK_2 = A_{17} \oplus D_{18}$<br>$WK_3 = C_{17} \oplus B_{18}$<br><b>for</b> $t_2=0$ <b>to</b> $2^{16}-1$ <b>do</b><br><b>if</b> $F(t_2) \oplus F(t_2 \oplus \Delta B'_{18}) = F(C_{17}) \oplus F(C_{17} \oplus \Delta B'_{18}) \oplus \Delta C'_{18}$<br>$A_{15} = t_2$<br><b>if</b> $F(t_2) \oplus F(t_2 \oplus \Delta D'_{18}) = F(A_{17}) \oplus F(A_{17} \oplus \Delta D'_{18}) \oplus \Delta A'_{18}$<br>$C_{15} = t_2$<br><b>for</b> $t_3=0$ <b>to</b> $2^{16}-1$ <b>do</b><br><b>if</b> $F(t_3) \oplus F(t_3 \oplus F(C_{17}) \oplus F(C_{17} \oplus \Delta B'_{18}) \oplus \Delta C'_{18}) = \Delta D'_{18}$ <b>and</b> $F(t_3) \oplus C_{15} = RC_{32} \oplus D_{18}$<br>$A_{16} = t_3$<br><b>if</b> $F(t_3) \oplus F(t_3 \oplus F(A_{17}) \oplus F(A_{17} \oplus \Delta D'_{18}) \oplus \Delta A'_{18}) = \Delta B'_{18}$ <b>and</b> $F(t_3) \oplus A_{15} = RC_{33} \oplus B_{18}$<br>$C_{16} = t_3$<br>$WK_0 = RC_{35} \oplus A_{16} \oplus F(C_{17}) \oplus C_{18}$<br>$WK_4 = RC_{34} \oplus C_{16} \oplus F(A_{17}) \oplus A_{18}$<br><b>for</b> $t_4=0$ <b>to</b> $2^{16}-1$ <b>do</b><br>$K = WK_0 \parallel t_4 \parallel WK_2 \parallel WK_3 \parallel WK_4$ |

**if**  $Y = \text{Encryption}(X, K)$   
 $WK_1 = t_4$   
 $K = WK_0 \parallel WK_1 \parallel WK_2 \parallel WK_3 \parallel WK_4$

To recover all whitening keys, the detailed attacking steps are listed as follows:

*Step 1.* A correct ciphertext  $Y$  is derived when an arbitrary plaintext  $X$  is encrypted with a secret key  $K$ .

*Step 2.* This step aims at recovering the whitening keys  $WK_2$  and  $WK_3$ . The fault injection targets at  $A_{15}$ ,  $B_{15}$ ,  $C_{15}$ , or  $D_{15}$  in the 15<sup>th</sup> round. Any change of one nibble provokes a series of XOR-differences in the last three rounds as follows:

$$\begin{aligned} &\Delta A_{16}, \Delta D_{16}, \Delta A_{17}, \Delta C_{17}, \Delta D_{17}, \Delta A_{18}, \Delta B_{18}, \Delta C_{18}, \Delta D_{18}, \\ &\Delta A_{16}, \Delta A_{17}, \Delta D_{17}, \Delta A_{18}, \Delta B_{18}, \Delta C_{18}, \Delta D_{18}, \\ &\Delta B_{16}, \Delta C_{16}, \Delta A_{17}, \Delta B_{17}, \Delta C_{17}, \Delta A_{18}, \Delta B_{18}, \Delta C_{18}, \Delta D_{18}, \end{aligned}$$

or

$$\Delta C_{16}, \Delta B_{17}, \Delta C_{17}, \Delta A_{18}, \Delta B_{18}, \Delta C_{18}, \Delta D_{18}.$$

These alter an original ciphertext into a faulty ciphertext. **Table 6** shows the relations of the fault locations of the  $F$ -function in the 15<sup>th</sup> round and the affected  $j$ -th nonzero nibble in the ciphertext difference with  $0 \leq j \leq 15$ . Thus, the attackers can depend on the number and locations of nonzero nibbles of the ciphertext differences to derive the fault location in each register.

**Table 6.** The relationship between the fault locations and the affected nibbles of the ciphertext difference

| The fault location on each register | The nibble in the 15 <sup>th</sup> round | The $j$ -th nonzero nibbles of the ciphertext difference |
|-------------------------------------|--|--|
| $A_{15}$                            | 0  | 0,1,2,3,4,8,9,10,11,12,13,14,15                          |
|                                     | 1  | 0,1,2,3,5,8,9,10,11,12,13,14,15                          |
|                                     | 2  | 0,1,2,3,6,8,9,10,11,12,13,14,15                          |
|                                     | 3  | 0,1,2,3,7,8,9,10,11,12,13,14,15                          |
| $B_{15}$                            | 4  | 0,1,2,3,8,12,13,14,15                                    |
|                                     | 5  | 0,1,2,3,9,12,13,14,15                                    |
|                                     | 6  | 0,1,2,3,10,12,13,14,15                                   |
|                                     | 7  | 0,1,2,3,11,12,13,14,15                                   |
| $C_{15}$                            | 8  | 0,1,2,3,4,5,6,7,8,9,10,11,12                             |
|                                     | 9  | 0,1,2,3,4,5,6,7,8,9,10,11,13                             |
|                                     | 10                                       | 0,1,2,3,4,5,6,7,8,9,10,11,14                             |
|                                     | 11                                       | 0,1,2,3,4,5,6,7,8,9,10,11,15                             |
| $D_{15}$                            | 12                                       | 0,4,5,6,7,8,9,10,11                                      |
|                                     | 13                                       | 1,4,5,6,7,8,9,10,11                                      |
|                                     | 14                                       | 2,4,5,6,7,8,9,10,11                                      |
|                                     | 15                                       | 3,4,5,6,7,8,9,10,11                                      |

The relationship between input differences and output differences of the  $F$ -function are as follows:

$$\begin{aligned}\Delta A_{i+1} &= F(A_i) \oplus F(A_i \oplus \Delta A_i) \oplus \Delta B_i, \\ \Delta C_{i+1} &= F(C_i) \oplus F(C_i \oplus \Delta C_i) \oplus \Delta D_i,\end{aligned}$$

With the help of a pair of right and faulty ciphertexts, the relationships among these differences of the  $F$ -functions are defined in the last round. When the fault is injected in  $A_{15}$ , the attackers can deduce the value of  $A_{17}$  depending on

$$\begin{aligned}\Delta A_{18} &= F(A_{17}) \oplus F(A_{17} \oplus \Delta A_{17}) \oplus \Delta B_{17} \oplus \Delta RK_{34} \\ &= F(A_{17}) \oplus F(A_{17} \oplus \Delta D_{18}),\end{aligned}$$

where

$$\begin{aligned}\Delta A_{18} \parallel \Delta B_{18} \parallel \Delta C_{18} \parallel \Delta D_{18} &= \Delta Y, \\ \Delta A_{17} &= \Delta D_{18}, \\ \Delta C_{17} &= \Delta B_{18}, \\ \Delta B_{17} &= \Delta RK_{34} = 0.\end{aligned}$$

When the fault is injected in  $C_{15}$ , the attackers can deduce the value of  $C_{17}$  depending on

$$\begin{aligned}\Delta C_{18} &= F(C_{17}) \oplus F(C_{17} \oplus \Delta C_{17}) \oplus \Delta D_{17} \oplus \Delta RK_{35} \\ &= F(C_{17}) \oplus F(C_{17} \oplus \Delta B_{18}),\end{aligned}$$

where

$$\begin{aligned}\Delta A_{18} \parallel \Delta B_{18} \parallel \Delta C_{18} \parallel \Delta D_{18} &= \Delta Y, \\ \Delta A_{17} &= \Delta D_{18}, \\ \Delta C_{17} &= \Delta B_{18}, \\ \Delta D_{17} &= \Delta RK_{35} = 0.\end{aligned}$$

The values of  $WK_2$  or  $WK_3$  in the last round can be deduced as follows:

$$\begin{aligned}WK_2 &= A_{17} \oplus A_{18}, \\ WK_3 &= C_{17} \oplus C_{18}.\end{aligned}$$

*Step 3.* No faults are induced in this step. The attackers can depend on the faults in step 2 to get another two whitening keys. In conjunction with the ciphertext difference,  $A_{16}$  and  $C_{16}$  can be deduced. When the fault is injected in  $A_{15}$ , the following equation is helpful to deduce the value of  $A_{16}$ :

$$\begin{aligned}\Delta A_{17} &= \Delta D_{18} \\ &= F(A_{16}) \oplus F(A_{16} \oplus \Delta A_{16}) \oplus \Delta B_{16} \\ &= F(A_{16}) \oplus F(A_{16} \oplus \Delta A_{16}) \\ &= F(A_{16}) \oplus F(A_{16} \oplus \Delta D_{17}) \\ &= F(A_{16}) \oplus F(A_{16} \oplus F(C_{17}) \oplus F(C_{17} \oplus \Delta C_{17}) \oplus \Delta C_{18}) \\ &= F(A_{16}) \oplus F(A_{16} \oplus F(C_{17}) \oplus F(C_{17} \oplus \Delta B_{18}) \oplus \Delta C_{18}),\end{aligned}$$

where

$$\begin{aligned}\Delta B_{16} &= 0, \\ \Delta A_{17} &= \Delta D_{18}, \\ \Delta C_{17} &= \Delta B_{18}.\end{aligned}$$

Similarly, when the fault is injected in  $C_{15}$ , the following equation is helpful to deduce the value of  $C_{16}$ :

$$\begin{aligned}
 \Delta C_{17} &= \Delta B_{18} \\
 &= F(C_{16}) \oplus F(C_{16} \oplus \Delta C_{16}) \oplus \Delta D_{16} \\
 &= F(C_{16}) \oplus F(C_{16} \oplus \Delta C_{16}) \\
 &= F(C_{16}) \oplus F(C_{16} \oplus \Delta B_{17}) \\
 &= F(C_{16}) \oplus F(C_{16} \oplus F(A_{17}) \oplus F(A_{17} \oplus \Delta A_{17}) \oplus \Delta A_{18}) \\
 &= F(C_{16}) \oplus F(C_{16} \oplus F(A_{17}) \oplus F(A_{17} \oplus \Delta D_{18}) \oplus \Delta A_{18}),
 \end{aligned}$$

where

$$\begin{aligned}
 \Delta D_{16} &= 0, \\
 \Delta A_{17} &= \Delta D_{18}, \\
 \Delta C_{17} &= \Delta B_{18}.
 \end{aligned}$$

The attackers can make advantage of the previous faults to deduce  $A_{15}$  and  $C_{15}$ , respectively. It is helpful to reduce the number of subkey candidates and improve the attacking efficiency. The previous fault injected in  $A_{15}$  can deduce the value of  $A_{15}$ :

$$F(A_{15}) \oplus F(A_{15} \oplus \Delta A_{15}) \oplus \Delta B_{15} = \Delta A_{16},$$

where

$$\begin{aligned}
 \Delta A_{15} &= \Delta B_{18}, \\
 \Delta B_{15} &= 0, \\
 \Delta A_{16} &= F(C_{17}) \oplus F(C_{17} \oplus \Delta B_{18}) \oplus \Delta C_{18}.
 \end{aligned}$$

Similarly, the previous fault injected in  $C_{15}$  can deduce the value of  $C_{15}$ :

$$F(C_{15}) \oplus F(C_{15} \oplus \Delta C_{15}) \oplus \Delta D_{15} = \Delta C_{16},$$

where

$$\begin{aligned}
 \Delta C_{15} &= \Delta D_{18}, \\
 \Delta D_{15} &= 0, \\
 \Delta C_{16} &= F(A_{17}) \oplus F(A_{17} \oplus \Delta D_{18}) \oplus \Delta A_{18}.
 \end{aligned}$$

Thus the attackers can derive the correct  $A_{16}$  and  $C_{16}$  directly by checking whether the following equations are right or not.

$$\begin{aligned}
 F(A_{16}) &= RK_{32} \oplus A_{17} \oplus B_{16} \\
 &= RC_{32} \oplus WK_2 \oplus WK_2 \oplus D_{18} \oplus C_{15} \\
 &= RC_{32} \oplus D_{18}, \\
 F(C_{16}) &= RK_{33} \oplus C_{17} \oplus D_{16} \\
 &= RC_{33} \oplus WK_3 \oplus WK_3 \oplus B_{18} \oplus A_{15} \\
 &= RC_{33} \oplus B_{18}.
 \end{aligned}$$

Hence,

$$\begin{aligned}
 RK_{34} &= F(A_{17}) \oplus B_{17} \oplus A_{18} \\
 &= F(D_{18} \oplus WK_2) \oplus C_{16} \oplus A_{18}, \\
 RK_{35} &= F(C_{17}) \oplus D_{17} \oplus C_{18} \\
 &= F(B_{18} \oplus WK_3) \oplus A_{16} \oplus C_{18},
 \end{aligned}$$

and two whitening keys can be recovered on the basis of the key schedule:

$$WK_0 = RK_{35} \oplus RC_{35},$$

$$WK_4 = RK_{34} \oplus RC_{34}.$$

*Step 4.* The attackers can do brute-force search for the value of the remaining 16-bit whitening key  $WK_1$ . The 80-bit secret key can be recovered as follows:

$$K = WK_0 \parallel WK_1 \parallel WK_2 \parallel WK_3 \parallel WK_4.$$

## 5. Attacking Complexity

The attacking procedure is summarized to select whitening key candidates for a secret key. The time complexity of brute-force search for one fault injection is

$$\mu = 2^\sigma,$$

where  $\sigma$  denotes the size of the  $F$ -function layer. Furthermore, the calculation of the number of faults is important. In the above attacking steps, both the fault location and the fault model decide the number of faulty ciphertexts to break a whitening key.

The attackers can inject a random fault at any round of the lightweight cryptosystem. If the fault is injected in the last round, only one single nibble in the input of the SubBytes layer will be modified. It can recover no more than one nibble of the last two whitening keys by the analysis. To recover the last two whitening keys, it is essential to inject more faults into other nibbles. If the fault is induced before the last round, there is only one modified nibble in the input difference and output difference of the  $F$ -function in this round. However, on the diffusion of linear transformation, there are multinibbles in the output difference of the MixRows layer. Hence, there are multinibbles in the input difference of the SubBytes layer of the last round.

We take the derivation of  $WK_2$  as an example. On the differential relationship of  $F$ -function, if  $A_{17}$  is a candidate,  $A_{17} \oplus \Delta A_{17}$  may be another whitening key candidate. In other words, when the input candidates set of  $F$ -functions is not null, the input  $A_{17}$  may have several candidates. It indicates that  $WK_2$  may have some possible elements. Usually, more than two faults can have an intersection of  $WK_2$ . The attackers continue deriving intersection of whitening key candidates sets until the intersection has only one element. Thus, over two faults are required to derive multinibbles of a whitening key. In the proposed method, when the faults are injected  $A_{15}$  and  $C_{15}$ , any whitening key can be deduced by only one fault. The theoretical minimum number of faults to recover one whitening key is defined as

$$v = \begin{cases} 0 & \text{if } q = 0 \\ \left\lceil \frac{\theta \cdot \sigma}{q} \right\rceil & \text{if } 1 \leq q \leq 16 \end{cases},$$

where

$$\theta = \begin{cases} 1 & \text{if a fault is injected in } A_{15} \text{ or } C_{15} \\ 2 & \text{if a fault is injected in } B_{15} \text{ or } D_{15} \end{cases},$$

$\sigma$  represents the size of the  $F$ -function, and  $q$  denotes the maximum number of bits in the  $F$ -function derived by two faults. To calculate the whitening key, the value of  $q$  is the same as the number of bits in the nonzero output difference of the nonlinear transformation in this round. When  $q=0$ , there is no bits of a whitening key derived and thus  $v=0$ .

The overall time complexity to recover a secret key is

$$\mu \cdot v \cdot g + 2^{r-\eta} = \begin{cases} 2^{r-\eta} & \text{if } q = 0 \\ 2^\sigma \cdot \left\lceil \frac{\theta \cdot \sigma \cdot g}{q} \right\rceil + 2^{r-\eta} & \text{if } 1 \leq q \leq 16 \end{cases},$$

the data complexity is

$$v \cdot g + 1 = \begin{cases} 1 & \text{if } q = 0 \\ \left\lceil \frac{\theta \cdot \sigma \cdot g}{q} \right\rceil + 1 & \text{if } 1 \leq q \leq 16 \end{cases},$$

and the memory complexity is

$$64 \cdot 2 + \eta + 2^{r-\eta},$$

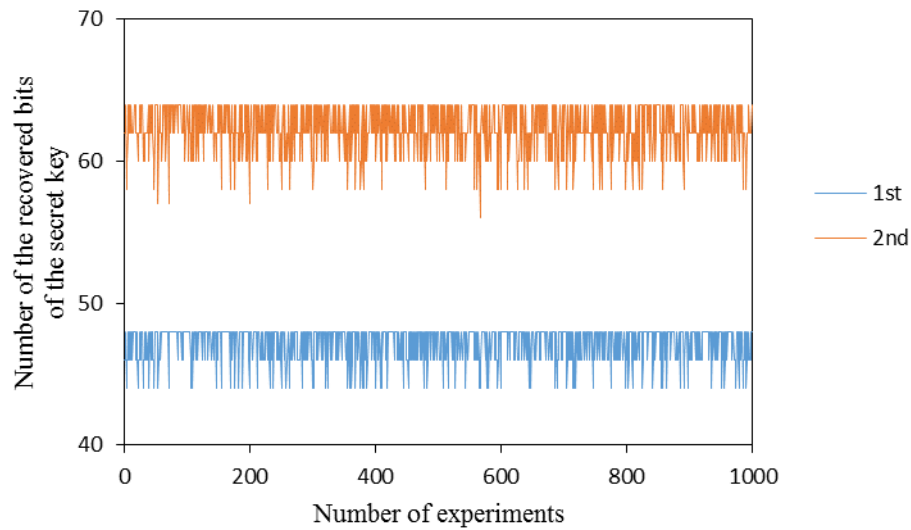
where  $\theta$  is the coefficient of fault injection,  $g$  represents the number of whitening keys to break the secret key,  $\sigma$  denotes the size of the  $F$ -function,  $q$  is the maximum number of bits in the  $F$ -function derived by DFA,  $r$  represents the size of the secret key, and  $\eta$  denotes the minimal number of bits in the secret key derived by the differential fault analysis. When  $q = 0$ , then there is no bits of a whitening key derived and thus  $\eta = 0$ .

In general, when the faults are injected in  $A_{15}$  or  $C_{15}$ , the time complexity to recover the 80-bit keys of Khudra is  $2^{20.17}$ , the data complexity is  $2^{1.58}$  and the memory complexity is  $2^{20.00}$ , where  $\theta=1, \sigma=16, q=16, g=2, r=80$ , and  $\eta=60$ . When the faults are injected in  $B_{15}$  or  $D_{15}$ , the time complexity is  $2^{18.32}$ , the data complexity is  $2^{2.32}$  and the memory complexity is  $2^{16.01}$ , where  $\theta=2, \sigma=16, q=16, g=2, r=80$ , and  $\eta=64$ .

## 6. Experimental Results

The attack is implemented in a personal computer with 32GB memory. The fault injections are simulated by the Java program. The attack algorithm runs with 1000 process units. The parameters of accuracy, reliability and latency are applied to estimate the experimental results.

There are 5 groups in average divided in the experiments. They are denoted as  $G_1, G_2, G_3, G_4$  and  $G_5$ . Fig. 2 shows the number of bits recovered in the 80-bit secret key. The x-axis denotes the number of experiments, and the y-axis represents the recovered bits number of the secret key. The colored lines denote the number of the recovered bits of the secret key by injecting faults into  $A_{15}$  or  $C_{15}$ . We use accuracy, reliability and latency for evaluating the experimental results in detail.



**Fig. 2.** Number of bits recovered in Khudra

Accuracy defines how close the number of the secret key is to the true number of whitening key candidates. The closer the experimental number of the secret key candidates is to the true number, the more accurate the experiment is. Thus, the Root Mean-Square Error (RMSE) is to measure the accuracy by

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (h_0 - h_i)^2},$$

where  $N$  is the number of experiments in a set,  $i$  represents the index of the experiment,  $h_0$  denotes the number of bits in the secret key, and  $h_i$  represents the number of bits recovered in the secret key candidates. The closer the RMSE value is to 0, the more accurate the experiments are. The RMSE values for every fault injections of whitening key candidates are shown in **Table 7**, where  $N=200$ ,  $i \in \{1, \dots, 1000\}$  and  $h_0 = 64$ . Eventually, the values of RMSE by two fault injections is nearly zero, so we can derive at least 60 and at most 64 bits of the secret key in the

**Table 7.** Accuracy measured by RMSE for Khudra

| Fault | $G_1$ | $G_2$ | $G_3$ | $G_4$ | $G_5$ |
|-------|-------|-------|-------|-------|-------|
| 1st   | 4.09  | 4.12  | 4.12  | 4.10  | 4.11  |
| 2nd   | 1.24  | 1.31  | 1.32  | 1.34  | 1.33  |

corresponding injections. That is, 2 faulty ciphertexts are required to recover secret key. Furthermore, the accuracy in each group for the target interaction is very similar.

Reliability is the ratio of successful experiments out of all experiments made. When only one secret key is derived, the experiment is successful. **Table 8** shows the ratios of successful experiments in each fault injection. The experimental results show that two faults are enough to recover the secret key. That is, the reliability is nearly 100% if the attackers induce only 2 random faults to break a secret key. The reliability in each group for the target interaction is very close.

**Table 8.** Reliability for Khudra

| Fault | $G_1$  | $G_2$  | $G_3$  | $G_4$  | $G_5$  |
|-------|--------|--------|--------|--------|--------|
| 1st   | 73.88% | 73.45% | 73.53% | 73.70% | 73.64% |
| 2nd   | 97.60% | 97.31% | 97.30% | 97.20% | 97.23% |

Latency is the time consumption to the recovery of the whitening key by fault injections. It is measured in seconds. Fig. 3 shows that the latency of 1000 experiments. The attacking procedure requires 30.88s on average for one experiment.

The attackers only require 2 faults to recover the 80-bit key of Khudra. The overall time complexity is

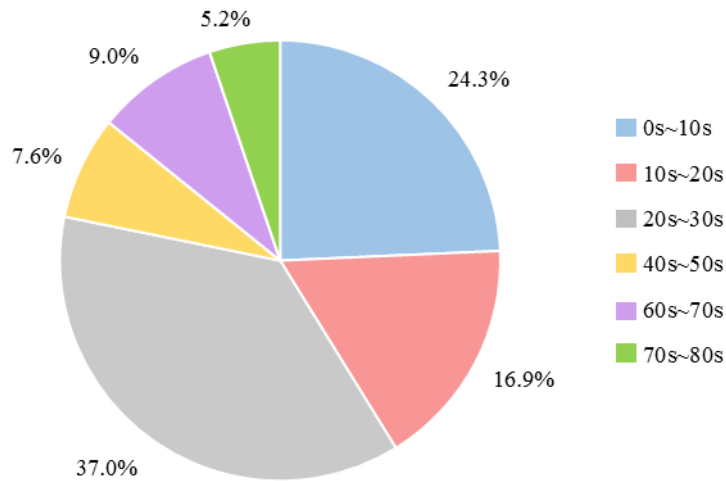
$$2^{16} \cdot 2 + 2^{20} \approx 2^{20.17},$$

the data complexity is

$$2 + 1 = 3,$$

and the memory complexity is

$$2 \cdot 2^6 + 60 + 2^{20} \approx 2^{20.00}.$$

**Fig. 3.** Latency in DFA attacking

## 7. Conclusion

This paper presents a differential fault analysis on Khudra in a single nibble-oriented fault model. The analysis can break Khudra by only 2 faults. It shows that Khudra is vulnerable to the differential fault analysis. Hence, more software and hardware protection of the last several rounds should be strengthened in the VANETs.

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