# On Fault Injections in Generalized Feistel Networks

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# Introduction

- Security is a key component for information technologies and communication
- Even securely designed algorithm may be vulnerable to physical attacks
- **Fault injection attacks** (FIA): disrupt and exploit the circuit behaviour
- But FIA can damage the circuit

⇒ The number of fault injections is a critical aspect of FIA

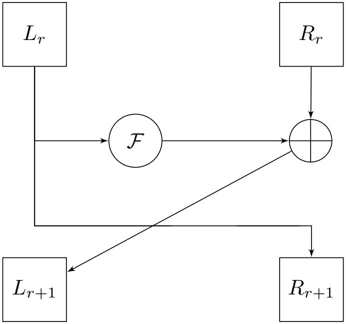
# This Paper

- FIA on **Generalized Feistel Networks**
- Single-bit fault model
- Find the most critical locations for FIA
- Assess the number of faults needed
- **Generic** Approach

# Plan

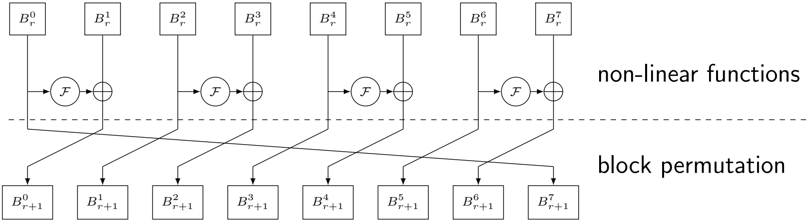
# The Original Feistel Structure

- Designed by Horst Feistel at IBM in the 1970's
- Used in DES, Camellia, MIBS, Simon,...
- Build 2*n*-bit permutation from *n*-bit to *n*-bit (Feistel) functions
- Similar encryption and decryption up to subkeys order



# Generalized Feistel Networks

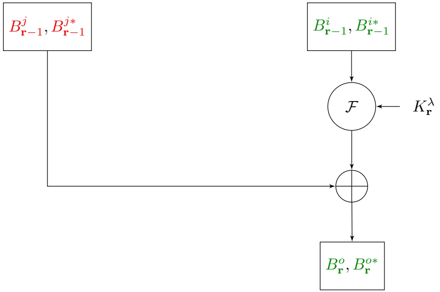
- Introduced by Zheng, Matsumoto, and Imai at CRYPTO '89
- Splits the message into **b** $\geq 2$ *n*-bit-long blocks



# Differential Fault Analysis (DFA) on GFNs

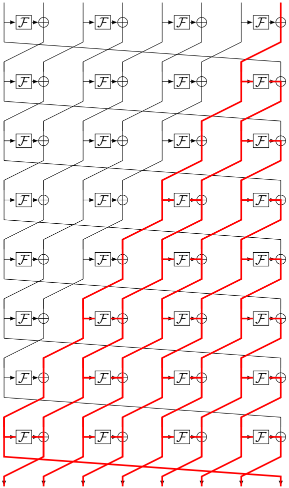
DFA is a powerful cryptanalytic technique that exploits differences between the correct ciphertext and erroneous results due to fault injections.

$$\Delta_{B_{\mathbf{r}}^{o}} = \mathcal{F}\left(B_{\mathbf{r}-1}^{i}, K_{\mathbf{r}}^{\lambda}\right) \oplus \mathcal{F}\left(B_{\mathbf{r}-1}^{i*}, K_{\mathbf{r}}^{\lambda}\right) \oplus \Delta_{B_{\mathbf{r}-1}^{j}}$$



# Diffusion

- Full Diffusion Delay: minimum number of rounds $d$ for every inputs to influence every outputs



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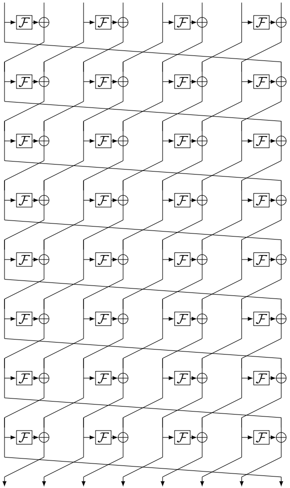
- A matrix $\mathcal{M}$ to represent the diffusion in the network:

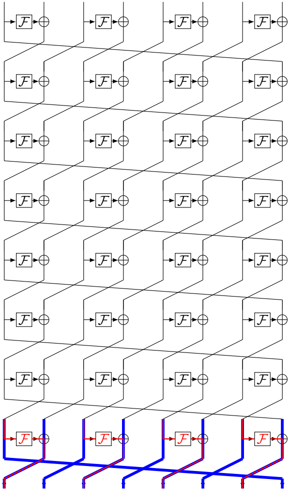


# Diffusion

- Full Diffusion Delay: minimum number of rounds $d$ for every inputs to influence every outputs

- A matrix $\mathcal{M}$ to represent the diffusion in the network:
  - 0: $B^i_{r+1}$ is influenced by $B^j_r$ directly
  - 1: $B^i_{r+1}$ is influenced by $B^j_r$ via the Feistel function $\mathcal{F}$
  - $-\infty$: not influenced (noted '.')

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



## Feistel function

- Xor with the subkey
- S-boxes: non linear
- Layers of linear functions

## Diffusion in the Feistel function

- A divide-and-conquer approach at the S-box level
- Influence of the fault on $\Delta_{B^j_{\mathbf{r}-1}}$

$$\Delta_{B^o_{\mathbf{r}}} = \mathcal{F}\left(B^i_{\mathbf{r}-1}, K^\lambda_{\mathbf{r}}\right) \oplus \mathcal{F}\left(B^{i*}_{\mathbf{r}-1}, K^\lambda_{\mathbf{r}}\right) \oplus \Delta_{B^j_{\mathbf{r}-1}}$$

- Goals:
  1. Number of pieces of subkey attacked
  2. Number of possible differences
  3. $\Rightarrow$ Number of faults required

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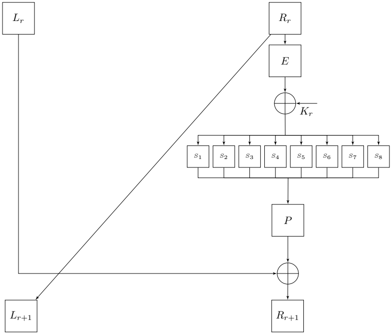
3. Use $\mathcal{F}$ to find the number of possible differential $\Delta_{B^j_{\mathbf{r}-1}}$
4. Deduce the number $n_l$ of pieces $K_r^{\lambda,l}$ attacked
5. Estimate the number $n_J$ of faults required to attack that subkey block

# Description

- NIST standard from 1977 to 2001
- A 16-round Feistel cipher
- Starts by a 64-bit permutation $IP$ and finishes by its inverse $IP^{-1}$
- Feistel function consists in 4 steps:
  - Expansion $E$ which maps 32 bits in 48 bits by duplicating half of the bits
  - Xor with the 48 bits of subkey $K_r$
  - 8 S-boxes $6 \times 4$
  - Bit permutation $P$ of 32 bits



# Results

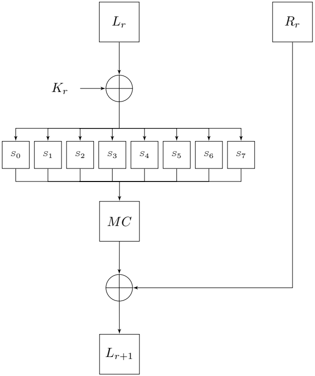
- Full diffusion delay: $d = 2$
- $\mathcal{M} = \begin{pmatrix} . & 0 \\ 0 & 1 \end{pmatrix}$
- Number of subkey blocks: $\Lambda = 1$
- Number of pieces in subkey blocks: $L = 8$
- Number of faults required to retrieve a piece of subkey: $n = 3$

Table: Results of our analysis on the DES

| Blocks $B$ | $V_{\mathcal{F}}$ | $W_{\mathcal{F}}$ | $n_l$ | $\Delta$ |
|---|---|---|---|---|
| $R_{15}$ | $(.,0)$ | $(1,0)$ | $1 \leq n_l \leq 2$ | 1 |
| $R_{14}$ | $(0,1)$ | $(2,1)$ | $2 \leq n_l \leq 8$ | 2 |
| $R_{13}$ | $(1,2)$ | $(3,2)$ | $2 \leq n_l \leq 8$ | $32 * 247$ |

# Description

- Presented at CANS'09
- A 32-round Feistel cipher
- Key of 64 or 80 bits
- Feistel function operates in 3 steps:
    - Xor with the subkey
    - 8 S-boxes $4 \times 4$
    - A linear mixing layer *MC* acting at nibble level



# Results

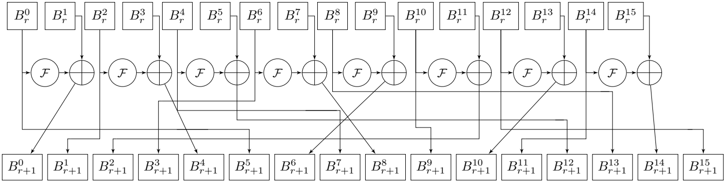
- Full diffusion delay: $d = 2$
- $\mathcal{M} = \begin{pmatrix} 1 & 0 \\ 0 & . \end{pmatrix}$
- Number of subkey blocks: $\Lambda = 1$
- Number of pieces in subkey blocks: $L = 8$
- Number of faults required to retrieve a piece of subkey: $n = 2$

Table: Results of our analysis on MIBS

| Blocks $B$ | $V_{\mathcal{F}}$ | $W_{\mathcal{F}}$ | $n_I$ | $\Delta$ |
|---|---|---|---|---|
| $L_{31}$ | $(0, .)$ | $(0, 1)$ | 1 | 1 |
| $L_{30}$ | $(1, 0)$ | $(1, 2)$ | $5 \leq n_I \leq 6$ | 4 |
| $L_{29}$ | $(2, 1)$ | $(2, 3)$ | 8 | 112 |

# Description

- 64-bit block cipher presented at SAC ’12
- GFN with 16 blocks, 4 bits each, and with 80 or 128-bit keys
- 36 rounds for both key lengths
- Feistel function used 8 times per round and consecutively made of:
  - 4-bit Xor with a subkey block
  - A single S-box $4 \times 4$



# Results

- Full diffusion delay: $d = 8$
- $$\mathcal{M} = \begin{pmatrix}
1 & 0 & . & . & . & . & . & . & . & . & . & . & . & . & . & . \\
. & . & 0 & . & . & . & . & . & . & . & . & . & . & . & . & . \\
. & . & . & . & . & . & . & . & . & . & 1 & 0 & . & . & . & . \\
. & . & . & . & . & . & 0 & . & . & . & . & . & . & . & . & . \\
. & . & 1 & 0 & . & . & . & . & . & . & . & . & . & . & . & . \\
0 & . & . & . & . & . & . & . & . & . & . & . & . & . & . & . \\
. & . & . & . & . & . & . & . & 1 & 0 & . & . & . & . & . & . \\
. & . & . & . & 0 & . & . & . & . & . & . & . & . & . & . & . \\
. & . & . & . & . & . & 1 & 0 & . & . & . & . & . & . & . & . \\
. & . & . & . & . & . & . & . & . & . & 0 & . & . & . & . & . \\
. & . & . & . & . & . & . & . & . & . & . & . & 1 & 0 & . & . \\
. & . & . & . & . & . & . & . & . & . & . & . & . & . & 0 & . \\
. & . & . & . & 1 & 0 & . & . & . & . & . & . & . & . & . & . \\
. & . & . & . & . & . & . & . & 0 & . & . & . & . & . & . & . \\
. & . & . & . & . & . & . & . & . & . & . & . & . & . & 1 & 0 \\
. & . & . & . & . & . & . & . & . & . & . & . & 0 & . & . & .
\end{pmatrix}$$
- Number of subkey blocks: $\Lambda = 8$
- Number of pieces in subkey blocks: $L = 1$
- Number of faults required to retrieve a piece of subkey: $n = 2$

# Results

- Full diffusion delay: $d = 8$
- Number of subkey blocks: $\Lambda = 8$
- Number of pieces in subkey blocks: $L = 1$
- Number of faults required to retrieve a piece of subkey: $n = 2$

## Summary of Results

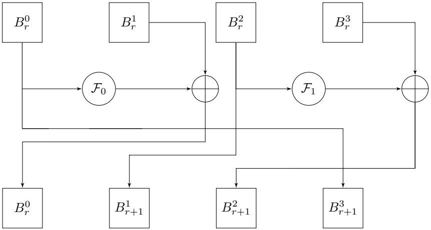
- Best case achievable: inject a fault at round 31

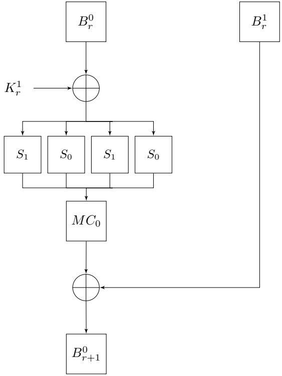
$\Rightarrow$ Attack $n_\lambda = 5$ functions (4 with non faulted $B^j_{\mathbf{r}-1}$ and one with $\#\{B^j_{\mathbf{r}-1}\} = 7$)

- If injected earlier $\Rightarrow$ at most 4 functions
- If injected after $\Rightarrow$ only up to 3 functions

# Description

- 128-bit block cipher presented at FSE '07
- Key sizes: 128, 192 or 256 bits
- Part of standard ISO/IEC 29192-2
- GFN with 4 blocks, 32 bits each
- 2 slightly different Feistel functions:
    - Xor with the subkey
    - 4 S-boxes $8 \times 8$
    - 2 linear diffusion layers, $MC_0$ and $MC_1$



# Results

- Full diffusion delay $d = 4$
- $\mathcal{M} = \begin{pmatrix} 1 & 0 & . & . \\ . & . & 0 & . \\ . & . & 1 & 0 \\ 0 & . & . & . \end{pmatrix}$
- Number of subkey blocks: $\Lambda = 2$
- Number of pieces in subkey blocks: $L = 4$
- Number of faults required to retrieve a piece of subkey: $n = 2$

# Results

- Full diffusion delay $d = 4$
- Number of subkey blocks: $\Lambda = 2$
- Number of pieces in subkey blocks: $L = 4$
- Number of faults required to retrieve a piece of subkey: $n = 2$

Table: Results of our analysis on CLEFIA

| Blocks $B$ | $V_{\mathcal{F}}$ | $W_{\mathcal{F}}$ | $n_\lambda$ | $n_l$ | $\Delta$ |
|---|---|---|---|---|---|
| $B^0_{17}$ | $(0, ., ., .)$ | $(0, 1, ., .)$ | 1 | $(1, 0)$ | $(1, -)$ |
| $B^0_{16}$ | $(1, ., ., 0)$ | $(1, 2, ., 0)$ | 1 | $(4, 0)$ | $(1, -)$ |
| $B^0_{15}$ | $(2, ., 0, 1)$ | $(2, 3, 0, 1)$ | 2 | $(4, 1)$ | $(1, \leq 127)$ |
| $B^0_{14}$ | $(3, 0, 1, 2)$ | $(3, 4, 1, 2)$ | 2 | $(4, 4)$ | $(4, \text{huge})$ |
| $B^0_{13}$ | $(4, 1, 2, 3)$ | $(4, 5, 2, 3)$ | 2 | $(4, 4)$ | $(946, \text{huge})$ |

# Conclusion

- It has been shown that some blocks are more vulnerable to DFA than others in GFNs
- A method has been proposed to identify these blocks allowing attackers to minimize single-bit fault injections
- The vulnerability evaluation is not optimal but is generic and a method to assess the vulnerabilities automatically is possible
- Further work will include multi-bit faults injection

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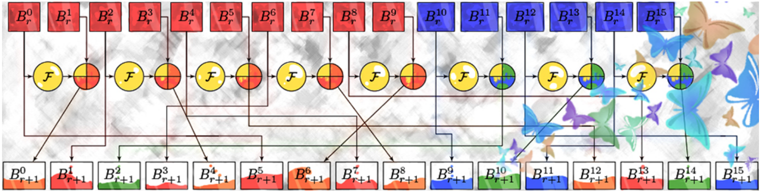
Thank you for your attention

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