Attacks on the KeeLoq Block Cipher and Authentication Systems

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Suppliers

Definition

- KeeLoq was developed by Nanoteq in mid 80s
- KeeLoq is supplied by Microchip Technology Inc.
- KeeLoq is a complex automotive access control system including
  - encryption algorithm,
  - authentication protocols and
  - multiple key management schemes

Use Cases

Use Cases

- KeeLoq is used by Chrysler, Daewoo, Fiat, GM, Honda, Toyota, Volvo, VW, Jaguar for car access
- Other use cases:
  - garage door openers (HomeLink),
  - property authentication,
  - product identification, etc.

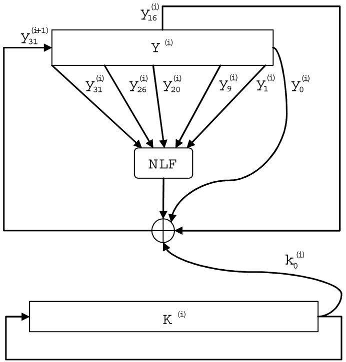
KeeLoq Block Cipher

Definition

- KeeLoq is a block cipher
- 32-bit blocks $Y = (y_{31}, y_{30}, \ldots, y_1, y_0)$
- 64-bit key $K = (k_{63}, k_{62}, \ldots, k_1, k_0)$
- NLFSR-based = extremely unbalanced Feistel network
- One encryption = 528 encryption cycles
- Hardware footprint - about 700 GE

KeeLoq Block Cipher

One encryption cycle and *NLF*



Nonlinear update function

$$NLF(x_4, x_3, x_2, x_1, x_0) = x_0 \oplus x_1 \oplus x_0x_1 \oplus x_1x_2 \oplus x_2x_3 \oplus x_0x_4 \oplus x_0x_3 \oplus x_2x_4 \oplus x_0x_1x_4 \oplus x_0x_2x_4 \oplus x_1x_3x_4 \oplus x_2x_3x_4$$

Feedback computation

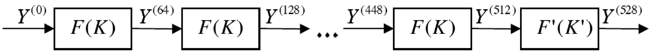
$$\varphi = NLF(y_{31}^{(i)}, y_{26}^{(i)}, y_{20}^{(i)}, y_{9}^{(i)}, y_{1}^{(i)}) \oplus y_{16}^{(i)} \oplus y_{0}^{(i)} \oplus k_{0}^{(i)}$$

Data and key update

$$\begin{aligned} Y^{(i+1)} &= (\varphi, y_{31}^{(i)}, \ldots, y_{1}^{(i)}) \\ K^{(i+1)} &= (k_{0}^{(i)}, k_{63}^{(i)}, \ldots, k_{1}^{(i)}) \end{aligned}$$

KeeLoq Block Cipher

Round Structure



Notation

$$F(K) : \mathbb{F}_2^{32} \to \mathbb{F}_2^{32} \quad = \quad \text{one round} \quad = \quad \text{64 encryption cycles}$$

$$F'(K') : \mathbb{F}_2^{32} \to \mathbb{F}_2^{32} \quad = \quad 1/4 \ \text{round} \quad = \quad \text{16 encryption cycles}$$

Basic Properties and Attack Principles

Key Schedule

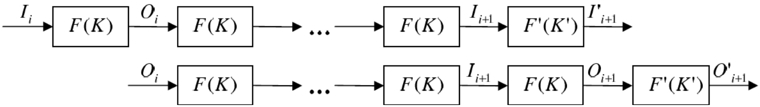
- 8 full rounds $K = (k_{63}, \ldots, k_0)$ and 1/4 round $K' = (k_{15}, \ldots, k_0)$:
  - $K, K, K, K, K, K, K, K, K'$
- The KeeLoq key schedule is very self-similar
  $\Rightarrow$ **slide attacks**

Resilience of *NLF*

NLF is 1-resilient, but not 2-resilient $\Rightarrow$ linear approximations
$\Rightarrow$ **linear analysis**

Attack Outline

Slide Attacks



Pseudo-slide group

If 16-bit subkey K' and a slide pair $(I_0, O_0), (I_1, O_1)$ are guessed, a *pseudo-slide group* can be generated if the whole code book is known:

$$\{I_i, O_i\}_{i=0}^{2^8-1},$$

where $O_i = F_K(I_i)$.

Attack Outline
Linear Approximation

Lemma

For uniformly distributed $x_4, x_3, x_2 \in GF(2)$ the following holds:

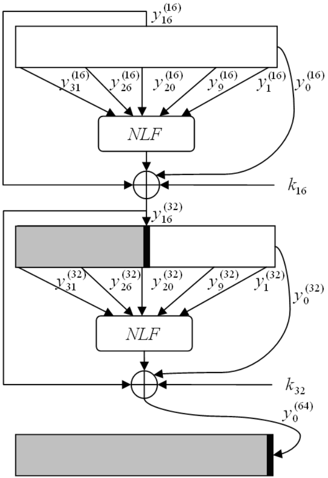
- $\Pr\{NLF(x_4, x_3, x_2, x_1, x_0) = 0 \mid x_0 \oplus x_1 = 0\} = \frac{5}{8}$,
- $\Pr\{NLF(x_4, x_3, x_2, x_1, x_0) = 1 \mid x_0 \oplus x_1 = 1\} = \frac{5}{8}$.

Corollary

NLF can be efficiently approximated by $x_0 \oplus x_1$.

Attack Outline

Correlation Step $\Rightarrow$ $k_{16} \oplus k_{32}$



Relations

$$\begin{aligned} \mathbf{y}_{\mathbf{16}}^{(\mathbf{32})} &= c_0 \oplus \mathbf{k_{16}} \\ y_0^{(64)} &= NLF(\mathbf{y}_{\mathbf{31}}^{(\mathbf{32})}, \mathbf{y}_{\mathbf{26}}^{(\mathbf{32})}, \mathbf{y}_{\mathbf{20}}^{(\mathbf{32})}, y_9^{(32)}, y_1^{(32)}) \\ &\oplus y_0^{(32)} \oplus (c_0 \oplus \mathbf{k_{16}}) \oplus \mathbf{k_{32}} \end{aligned}$$

Obtaining $k_{16} \oplus k_{32}$

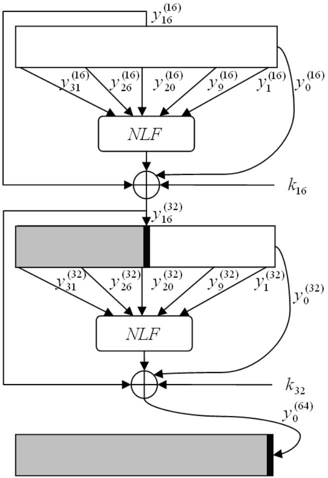
- Recover $k_{16} \oplus k_{32}$ statistically using the pseudo-slide group
- $\mathbf{k_{16}} \oplus \mathbf{k_{32}} = y_0^{64} \oplus y_0^{32} \oplus c_0 \oplus \epsilon(I_i, K')$
- $Pr\{\epsilon(I_i, K') = y_9^{(32)} \oplus y_1^{(32)}\} = 1/2 + 1/8$

Legend

= unknown
= known
= updated

Attack Outline

Correlation Step $\Rightarrow k_{16} \oplus k_{32} \Rightarrow k_{16}, k_{32}$



Obtaining k_{16} and k_{32}

- Recover $k_{16} \oplus k_{32}$ statistically using the pseudo-slide group
- Recover $k_{17} \oplus k_{33}$ and $k_{16} \oplus k_{17} \oplus k_{33}$ in a similar way using the pseudo-slide group

$$\begin{aligned} \alpha &= k_{16} \oplus k_{32} \\ \beta &= k_{17} \oplus k_{33} \\ \gamma &= k_{16} \oplus k_{17} \oplus k_{33} \end{aligned} \quad \Rightarrow \quad \begin{aligned} k_{16} &= \beta \oplus \gamma \\ k_{32} &= k_{16} \oplus \alpha \end{aligned}$$

- Recover $(k_{47}, \ldots, k_{16})$ using this technique

Legend

= unknown
= known
= updated

Attack Outline

Linear Step $\Rightarrow (k_{63}, \ldots, k_{48})$

- Now 48 key bits are known: $(k_{47}, \ldots, k_0) \Rightarrow$ compute $Y^{(48)}$
- $\mathbf{k_{48}} = y_{16}^{(64)} \oplus NLF(y_{31}^{(48)}, y_{26}^{(48)}, y_{20}^{(48)}, y_{9}^{(48)}, y_{1}^{(48)}) \oplus y_{16}^{(48)} \oplus y_{0}^{(48)}$
- Now 49 key bits are known: $(k_{48}, \ldots, k_0) \Rightarrow$ compute $Y^{(49)}$
- $\mathbf{k_{49}} = y_{17}^{(64)} \oplus NLF(y_{31}^{(49)}, y_{26}^{(49)}, y_{20}^{(49)}, y_{9}^{(49)}, y_{1}^{(49)}) \oplus y_{16}^{(49)} \oplus y_{0}^{(49)}$
- Now 50 key bits are known: $(k_{49}, \ldots, k_0) \Rightarrow$ compute $Y^{(50)}$
- $\mathbf{k_{50}} = y_{18}^{(64)} \oplus NLF(y_{31}^{(50)}, y_{26}^{(50)}, y_{20}^{(50)}, y_{9}^{(50)}, y_{1}^{(50)}) \oplus y_{16}^{(50)} \oplus y_{0}^{(50)}$
- $\ldots$

Attack Outline

Attack Complexity

- Guess 16 key bits: $K' = (k_{15}, \ldots, k_0)$
- Guess the output O_0 of the first round for some input I_0:

$$O_0 = F(I_0)$$

- For each guess:
  - Generate a pseudo-slide group of size 2^8
  - Determine $(k_{47}, \ldots, k_{16})$ statistically (correlation step)
  - Compute $(k_{63}, \ldots, k_{48})$ deterministically (linear step)
- **Overall complexity: $2^{50.6}$ encryptions and 2^{32} PTs**

Permutation Structure Analysis [CB07]

- For a random n-bit permutation: In 2^n cycles
- About 22 cycles and about 11 even cycles for F_K
- Permutation $F_K^8(\cdot)$ has about $22/2^{\log 8} \approx 2.75$ even cycles
- To determine K':
  - Guess K'
  - Count the number of even cycles for $F_K^8(\cdot)$
  - If > 6 even cycles $\Rightarrow$ incorrect hypothesis (random)
  - If ≤ 6 even cycles $\Rightarrow$ correct (8 iterations)
- **Complexity (K$'$): 2^{37} encryptions and 2^{32} PTs**

Combined Attack

Linear Sliding Attack + Permutation Structure Analysis

- Recover $K' = (k_{15}, \ldots, k_0)$ using permutation structure analysis $\Rightarrow$ 2^{37}
- Guess (I_0, O_0)
- For each guess perform the linear sliding attack (correlation and linear steps) $\Rightarrow$ 2^{33}
- **Overall complexity: 2^{37} encryptions and 2^{32} PTs**

Rolling Codes

$$T \rightarrow V: \quad \textsc{KeeLoq}(C_{15,0}|D_{11,0}|F), N_{27,0}|F|A$$

KeeLoq-encrypted			Plaintext		
$C_{15,0}$	$D_{11,0}$	F	$N_{27,0}$	F	A

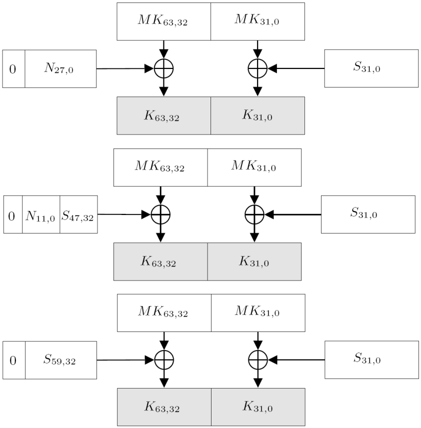
- $C_{15,0}$ = synchronized counter
- $D_{11,0}$ = discrimination value
- $F = F_{3,0}$ = functional bits
- $N_{27,0}$ = transponder's identifier
- A = several auxiliary bits

Identify Friend or Foe (IFF)

$$\begin{array}{llll} V \to T: & R & & (32) \\ T \to V: & \textsc{KeeLoq}(R) & & (32) \end{array}$$

- R = 32-bit random challenge
- Simple challenge-response protocol

XOR-Based Secure Key Generation



Notation

S	=	seed (32, 48 or 60 bit)
MK	=	64-bit **global** manufacturer key
K	=	64-bit individual key

Attacks on Key Generation

Scenario 1: Seed unknown

- K known and 32-bit seed $\Rightarrow$ 32 bits of MK known $\Rightarrow 2^{32}$
- K known and 48-bit seed $\Rightarrow$ 16 bits of MK known $\Rightarrow 2^{48}$
- K known and 60-bit seed $\Rightarrow$ 4 bits of MK known $\Rightarrow 2^{60}$

Scenario 2: Seed known

- K completely defines MK
- Obtaining MK instantly from K

Conclusion

- KeeLoq block cipher cryptanalyzed:
  - Basic Attack: $2^{50.6}$ KeeLoq encryptions and 2^{32} PTs
  - Enhanced Attack: 2^{37} KeeLoq encryptions and 2^{32} PTs $\Rightarrow$ best known attack working for the whole key space
- KeeLoq key management analyzed:
  - 3 vulnerable key generation schemes found
  - Breaking one key leads to the recovery of master key bits