Mind the TWEAKEY Schedule: Cryptanalysis on SKINNYe-64-256

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December 4, 2022

Outline

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Background

- The TWEAKEY framework , Jean et al. [JNP14]

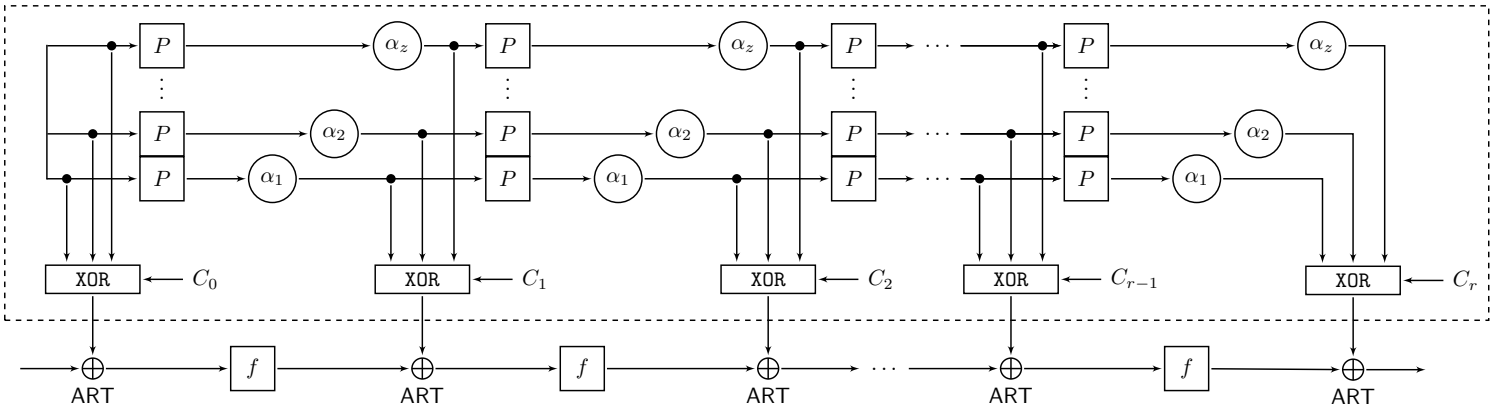
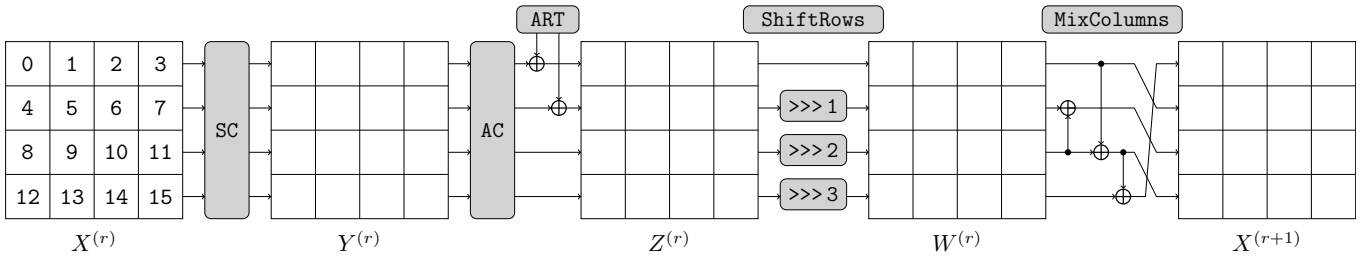


Figure: The STK construction.

SKINNY family and SKINNYe-64-256

- The SKINNY family: proposed by Beierle et al. [BJK+16]
  - SKINNY-*n*-*zn*: $n \in \{64, 128\}$, $z = 1, 2, 3$



- SKINNYe-64-256: Naito et al. [NSS20a]
  - same round function, new tweakey schedule?
  - SKINNYe-64-256 version 2 [NSS20b]

Our contribution

- Give a formal analysis of properties of the new tweakey schedule
- Cryptanalysis on SKINNYe-64-256
  - Rectangle attack in related-tweakey setting (41/44 rounds)
  - MITM attack in single-tweakey setting (37/44 rounds)
  - Impossible differential attack in related-tweakey setting
- Propose a uniformed design strategy for tweakey schedule of SKINNY-n-zn ($z \leq 14$)

Outline

Tweakey schedule for SKINNYe-64-256

- 256-bit tweakey $(TK_1,\ TK_2,\ TK_3,\ TK_4)$
  - $TK^{(r)}_{m,i} \leftarrow LFSR_m(TK^{(r-1)}_{m,P[i]})$
  - $STK^{(r)}_i = TK^{(r)}_{1,i} \oplus TK^{(r)}_{2,i} \oplus TK^{(r)}_{3,i} \oplus TK^{(r)}_{4,i}$
- For a set of subtweakeys $\{STK^{(2r_1)}, STK^{(2r_2)} \cdots, STK^{(2r_t)}\}$

$$\begin{pmatrix} \boldsymbol{stk}^{(2r_1)}_{\bar{P}^{2r_1}[i]} \\ \boldsymbol{stk}^{(2r_2)}_{\bar{P}^{2r_2}[i]} \\ \vdots \\ \boldsymbol{stk}^{(2r_t)}_{\bar{P}^{2r_t}[i]} \end{pmatrix} = \begin{pmatrix} \boldsymbol{I} & \boldsymbol{L}_2^{r_1} & \boldsymbol{L}_3^{r_1} & \boldsymbol{L}_4^{r_1} \\ \boldsymbol{I} & \boldsymbol{L}_2^{r_2} & \boldsymbol{L}_3^{r_2} & \boldsymbol{L}_4^{r_2} \\ \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{I} & \boldsymbol{L}_2^{r_t} & \boldsymbol{L}_3^{r_t} & \boldsymbol{L}_4^{r_t} \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{tk}^{(0)}_{1,i} \\ \boldsymbol{tk}^{(0)}_{2,i} \\ \boldsymbol{tk}^{(0)}_{3,i} \\ \boldsymbol{tk}^{(0)}_{4,i} \end{pmatrix}$$

  - $\boldsymbol{A}_{r_j} = [\boldsymbol{I}\ \boldsymbol{L}_2^{r_j}\ \boldsymbol{L}_3^{r_j}\ \boldsymbol{L}_4^{r_j}]$, $\boldsymbol{A}_{\{r_1,r_2,\cdots,r_t\}} = [\boldsymbol{A}_{r_1}^T\ \boldsymbol{A}_{r_2}^T\ \cdots\ \boldsymbol{A}_{r_t}^T]^T$

Tweakey schedule for SKINNYe-64-256

- $rank(\boldsymbol{A}_{\{r_1,r_2,\cdots,r_t\}}) = a$
  - $|Im(\boldsymbol{A})| = 2^a$: solution space of $\{STK^{(2r_1)}_{\bar{P}^{2r_1}[i]}, STK^{(2r_2)}_{\bar{P}^{2r_2}[i]} \cdots, STK^{(2r_t)}_{\bar{P}^{2r_t}[i]}\}$
  - $|Ker(\boldsymbol{A})| = 2^{16-a}$: $Ker(\boldsymbol{A}) = \{\boldsymbol{x} \in \mathbb{F}_2^{4t} : \boldsymbol{A}\boldsymbol{x} = 0\}$
- Example: $[\boldsymbol{stk}_0^{(0)}, \boldsymbol{stk}_2^{(2)}, \boldsymbol{stk}_4^{(4)}, \boldsymbol{stk}_6^{(6)}]^T = \boldsymbol{A}_{\{0,1,2,3\}} \cdot [\boldsymbol{tk}_{1,i}^{(0)}, \boldsymbol{tk}_{2,i}^{(0)}, \boldsymbol{tk}_{3,i}^{(0)}, \boldsymbol{tk}_{4,i}^{(0)}]^T$

$$\begin{pmatrix} \boldsymbol{stk}_0^{(0)} \\ \boldsymbol{stk}_2^{(2)} \\ \boldsymbol{stk}_4^{(4)} \\ \boldsymbol{stk}_6^{(6)} \end{pmatrix} = \begin{pmatrix} 1&0&0&0&1&0&0&0&1&0&0&0&1&0&0&0 \\ 0&1&0&0&0&1&0&0&0&1&0&0&0&1&0&0 \\ 0&0&1&0&0&0&1&0&0&0&1&0&0&0&1&0 \\ 0&0&0&1&0&0&0&1&0&0&0&1&0&0&0&1 \\ 1&0&0&0&0&1&0&0&1&0&0&1&0&1&0&0 \\ 0&1&0&0&0&0&1&0&1&0&0&0&0&0&1&0 \\ 0&0&1&0&0&0&0&1&0&1&0&0&0&1&0&1 \\ 0&0&0&1&1&1&0&0&0&0&1&0&1&1&1&0 \\ 1&0&0&0&0&0&1&0&1&0&1&1&0&0&1&0 \\ 0&1&0&0&0&0&0&1&1&0&0&1&0&1&0&1 \\ 0&0&1&0&1&1&0&0&1&0&0&0&1&1&0&0 \\ 0&0&0&1&0&1&1&0&0&1&0&0&0&0&1&1 \\ 1&0&0&0&0&0&0&1&1&1&1&1&0&1&0&1 \\ 0&1&0&0&1&1&0&0&1&0&1&1&1&1&0&0 \\ 0&0&1&0&0&1&1&0&1&0&0&1&0&1&1&0 \\ 0&0&0&1&0&0&1&1&1&0&0&0&1&0&1&1 \end{pmatrix} \cdot \begin{pmatrix} x_{1,0} \\ x_{1,1} \\ x_{1,2} \\ x_{1,3} \\ x_{2,0} \\ x_{2,1} \\ x_{2,2} \\ x_{2,3} \\ x_{3,0} \\ x_{3,1} \\ x_{3,2} \\ x_{3,3} \\ x_{4,0} \\ x_{4,1} \\ x_{4,2} \\ x_{4,3} \end{pmatrix}$$

- $rank(\boldsymbol{A}_{\{0,1,2,3\}}) = 14 \Longrightarrow$ image space 2^{14}, kernel space 2^2

Properties of the tweakey schedule

- $\boldsymbol{A}_{\{r_1+r',r_2+r',\cdots,r_t+r'\}} = \boldsymbol{A}_{\{r_1,r_2,\cdots,r_t\}} \cdot diag(\boldsymbol{I}, \boldsymbol{L}_2^{r'}, \boldsymbol{L}_3^{r'}\ \boldsymbol{L}_4^{r'})$

$$\begin{pmatrix} \boldsymbol{I} & \boldsymbol{L}_2^{r_1+r'} & \boldsymbol{L}_3^{r_1+r'} & \boldsymbol{L}_4^{r_1+r'} \\ \boldsymbol{I} & \boldsymbol{L}_2^{r_2+r'} & \boldsymbol{L}_3^{r_2+r'} & \boldsymbol{L}_4^{r_2+r'} \\ \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{I} & \boldsymbol{L}_2^{r_t+r'} & \boldsymbol{L}_3^{r_t+r'} & \boldsymbol{L}_4^{r_t+r'} \end{pmatrix} = \begin{pmatrix} \boldsymbol{I} & \boldsymbol{L}_2^{r_1} & \boldsymbol{L}_3^{r_1} & \boldsymbol{L}_4^{r_1} \\ \boldsymbol{I} & \boldsymbol{L}_2^{r_2} & \boldsymbol{L}_3^{r_2} & \boldsymbol{L}_4^{r_2} \\ \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{I} & \boldsymbol{L}_2^{r_t} & \boldsymbol{L}_3^{r_t} & \boldsymbol{L}_4^{r_t} \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{I} & & & \\ & \boldsymbol{L}_2^{r'} & & \\ & & \boldsymbol{L}_3^{r'} & \\ & & & \boldsymbol{L}_4^{r'} \end{pmatrix}$$

  - $rank(\boldsymbol{A}_{\{r_1+r',r_2+r',\cdots,r_t+r'\}}) = rank(\boldsymbol{A}_{\{r_1,r_2,\cdots,r_t\}})$

Definition (rank-equivalent)

Given two subsets $x = \{r_1, r_2, \ldots, r_t\},\ y = \{r'_1, r'_2, \ldots, r'_t\} \subset \mathcal{K}$, we say x and y are rank-equivalent if there exits an integer r' such that

$$r_i \equiv r'_i + r' \bmod 15 \text{ for all } 1 \leq i \leq t.$$

Rank-equivalence class for SKINNYe-64-256

- Rank-equivalence class: $[x] := \{y \subset \mathcal{K} : x \text{ and } y \text{ are rank-equivalent}\}$
  - $rank(\boldsymbol{A}_x) = rank(\boldsymbol{A}_y)$
- $rank(\boldsymbol{A}_{\{r_1,r_2,\cdots,r_t\}}) = \min\{4t, 16\} \Longleftrightarrow \boldsymbol{A}_{\{r_1,r_2,\cdots,r_t\}}$ is a full rank matrix

rank	t	Rank-equivalence class $[\{r_1, r_2, \cdots, r_t\}]$	Num.
14	4	[{0,1,2,3}],[{0,1,2,10}],[{0,1,3,4}],[{0,1,3,7}],[{0,1,3,13}],[{0,1,4,5}], ...	28
15	4	[{0,1,2,4}],[{0,1,2,5}],[{0,1,2,6}],[{0,1,2,7}],[{0,1,2,8}],[{0,1,2,9},] ...	63
	5	[{0,1,2,3,7}],[{0,1,2,3,10}],[{0,1,2,3,11}],[{0,1,2,3,13}],[{0,1,2,4,5}], ...	77
	6	[{0,1,2,3,7,10}],[{0,1,2,3,7,11}],[{0,1,2,3,7,13}],[{0,1,2,3,10,11}], ...	35
	7	[{0,1,2,3,7,10,11}],[{0,1,2,3,7,10,13}],[{0,1,2,3,7,11,13}], ...	9
	8	[{0,1,2,3,7,10,11,13}]	1

Table: Rank-equivalence class of non-full rank coefficient matrix for SKINNYe-64-256

The subtweakey difference cancellations

- SKINNY-*n*-*zn* ($z = 2, 3$): for given active cell, $z - 1$ subtweakey difference cancellations happen in every 30 rounds
- SKINNYe-64-256: applying rank-equivalence class of non-full rank
- $\boldsymbol{A}_{[\{r_1, r_2, \cdots, r_t\}]} \cdot [\Delta \boldsymbol{tk}_{1,i}^{(0)}, \Delta \boldsymbol{tk}_{2,i}^{(0)}, \Delta \boldsymbol{tk}_{3,i}^{(0)}, \Delta \boldsymbol{tk}_{4,i}^{(0)}]^T = \boldsymbol{0}$
  - cancellations happen in $\{STK_{\bar{P}^{2r_1}[i]}^{(2r_1)} \cdots, STK_{\bar{P}^{2r_t}[i]}^{(2r_t)}\}$
  - $rank(\boldsymbol{A}_{[\{r_1, r_2, \cdots, r_t\}]}) = 16$, there has only zero solution
  - $rank(\boldsymbol{A}_{[\{r_1, r_2, \cdots, r_t\}]}) < 16$, there has non-zero solution

Difference cancellation behaviour of rank-equivalence class

- $t = 4$: $\boldsymbol{A}_{\{r_1,r_2,r_3,r_4\}}$ is non-full rank
  - for given nibble, 4 cancellations happen in arbitrary rounds
- $t \geq 5$: $rank(\boldsymbol{A}_{[\{r_1,r_2,\cdots,r_t\}]}) = 15$, $|Ker(\boldsymbol{A}_{[\{r_1,r_2,\cdots,r_t\}]})| = 2$
  - different rank-equivalence classes corresponds to same non-zero solution

$$A_{[\{0,1,2,7,10\}]} \cdot [\Delta \boldsymbol{tk}_{1,i}^{(0)}, \Delta \boldsymbol{tk}_{2,i}^{(0)}, \Delta \boldsymbol{tk}_{3,i}^{(0)}, \Delta \boldsymbol{tk}_{4,i}^{(0)}]^T = \mathbf{0}$$

$$A_{[\{0,1,3,11,13\}]} \cdot [\Delta \boldsymbol{tk}_{1,i}^{(0)}, \Delta \boldsymbol{tk}_{2,i}^{(0)}, \Delta \boldsymbol{tk}_{3,i}^{(0)}, \Delta \boldsymbol{tk}_{4,i}^{(0)}]^T = \mathbf{0}$$

$\boldsymbol{tk}_{1,i}^{(0)} = [0,0,0,1]^T$, $\boldsymbol{tk}_{2,i}^{(0)} = [0,1,1,1]^T$,
$\boldsymbol{tk}_{3,i}^{(0)} = [0,0,0,0]^T$, $\boldsymbol{tk}_{4,i}^{(0)} = [0,1,1,0]^T$

  - two kinds of difference cancellation behaviours
    - $[\{0,1,2,4,5,8,10\}]$, $[\{0,1,2,3,7,10,11,13\}]$
    - 7 or 8 cancellations in fixed positions every 30 rounds

Key guessing strategy based on the relations

- similar idea of the key-bridge technique
- a set of $\{\boldsymbol{stk}^{(2r_1)}_{\bar{P}^{2r_1}[i]}, \boldsymbol{stk}^{(2r_2)}_{\bar{P}^{2r_2}[i]} \cdots, \boldsymbol{stk}^{(2r_t)}_{\bar{P}^{2r_t}[i]}, \boldsymbol{stk}^{(2r_{t+1})}_{\bar{P}^{2r_{t+1}}[i]}\}$
  - $rank(\boldsymbol{A}_{\{r_1,r_2,\cdots,r_t\}}) = a$, $rank(\boldsymbol{A}_{\{r_1,r_2,\cdots,r_t,r_{t+1}\}}) = b$
  - solution space of $\{\boldsymbol{stk}^{(2r_1)}_{\bar{P}^{2r_1}[i]}, \boldsymbol{stk}^{(2r_2)}_{\bar{P}^{2r_2}[i]} \cdots, \boldsymbol{stk}^{(2r_t)}_{\bar{P}^{2r_t}[i]}\}$: $|Im(\boldsymbol{A}_{\{r_1,r_2,\cdots,r_t\}})| = 2^a$
  - $\boldsymbol{stk}^{(2r_{t+1})}_{\bar{P}^{2r_{t+1}}[i]}$: 2^{b-a} guessing

Outline

Boomerang and Rectangle attacks

- Boomerang attack, Wagner [Wag99]
  - $E = E_f \circ \underbrace{E_1}_{\gamma \xrightarrow{q} \delta} \circ \underbrace{E_0}_{\alpha \xrightarrow{p} \beta} \circ E_b$
- Rectangle attack [BDK01]
  - several key-recovery frameworks [BDK01, BDK02, BDK06, LGS17]
  - Dong *et al.*'s related-key rectangle framework for ciphers with linear key schedule [DQSW22]

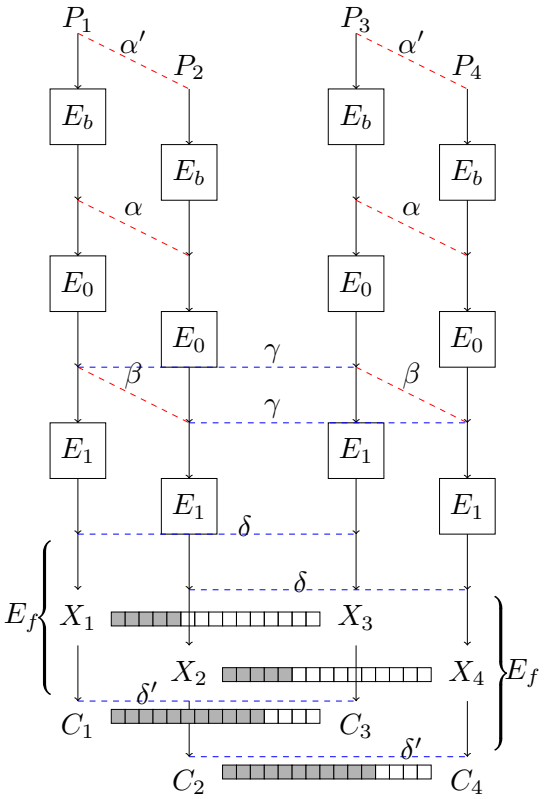
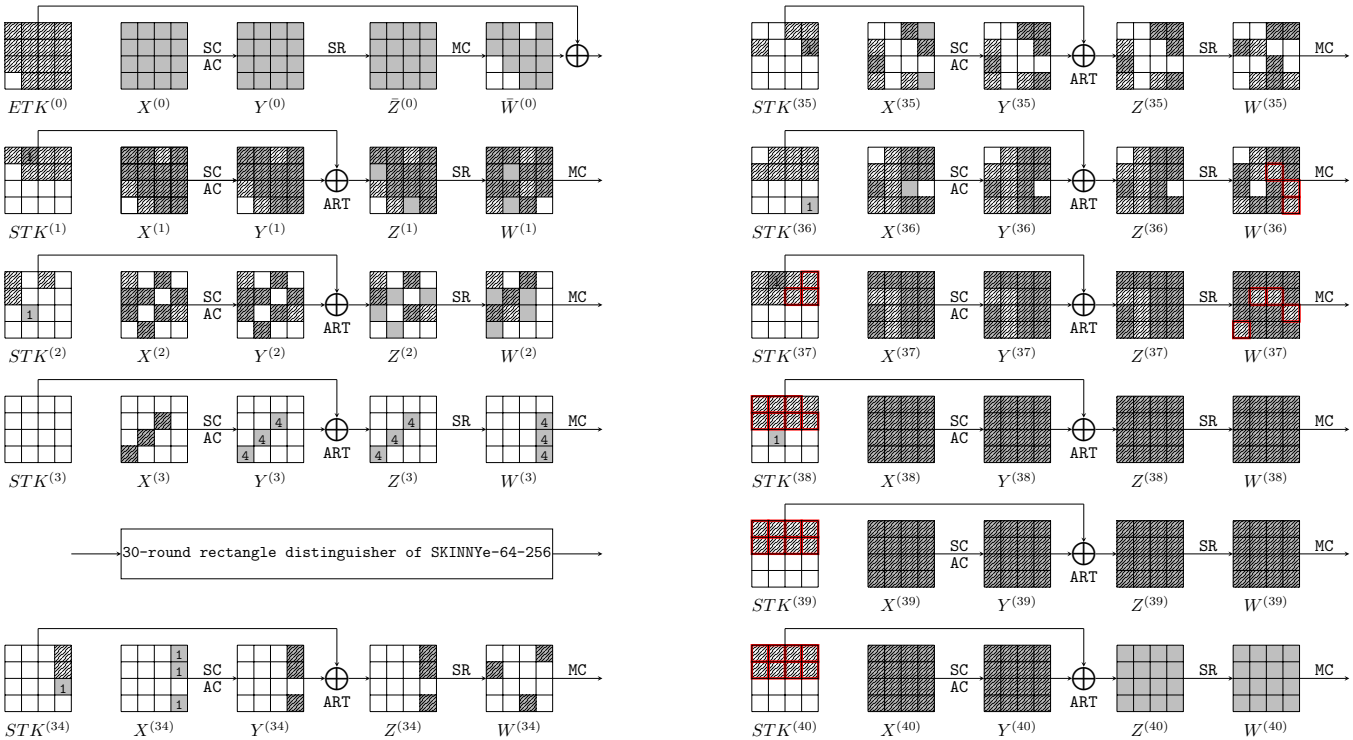


Figure: [DQSW22]

Rectangle attacks on SKINNYe-64-256

- Dong *et al.*'s rectangle attack framework: search the entire $(N_b + N_d + N_f)$-round attack [DQSW22]
- Constraints of different subtweakey difference cancellations:
  - $t \leq 4$: $stk_0^{(0)} + stk_{P^2[0]}^{(2)} + \cdots + stk_{P^{28}[0]}^{(28)} - 15 \cdot \mathrm{LANE}_0 \geq -4$
  - $t > 4$: fixed the positions of difference cancellation with rank-equivalence class $[\{0, 1, 2, 4, 5, 8, 10\}]$ and $[\{0, 1, 2, 3, 7, 10, 11, 13\}]$
- 30-round distinguisher following $[\{0, 1, 2, 3, 7, 10, 11, 13\}]$

Related-key rectangle attack on 41-round SKINNYe-64-256



- 41-round attack: 4-round E_b + 30-round E_d + 7-round E_f
  - key relations in the key-recovery phase

MITM and impossible differential attacks on SKINNYe-64-256

- Meet-in-the-Middle attack [BR10, Iso11]
  - MILP model for MITM key-recovery attack on SKINNY [DHS+21]
  - MITM key-recovery attacks on 31-round SKINNYe-64-256 in single-tweakey setting
- Impossible differential attack [BBS99, Knu98]
  - 21-round impossible differential on SKINNYe-64-256 in related-tweakey setting

Attacks on SKINNY-64 and SKINNYe-64-256 and its version 2

Version	Rounds	Data	Time	Memory	Approach	Setting	Ref.
SKINNY-64-128	23/36	$2^{60.54}$	$2^{120.7}$	$2^{60.9}$	Rectangle	RK	[HBS21]
	24/36	$2^{61.67}$	$2^{96.83}$	2^{84}	Rectangle	RK	[QDW+21]
	25/36	$2^{61.67}$	$2^{118.43}$	$2^{64.26}$	Rectangle	RK	[DQSW22]
SKINNY-64-192	29/40	$2^{62.92}$	$2^{181.7}$	2^{80}	Rectangle	RK	[HBS21]
	30/40	$2^{62.87}$	$2^{163.11}$	$2^{68.05}$	Rectangle	RK	[QDW+21]
	31/40	$2^{62.78}$	$2^{182.07}$	$2^{62.79}$	Rectangle	RK	[DQSW22]
SKINNYe-64-256	41/44	$2^{62.24}$	$2^{237.06}$	$2^{62.26}$	Rectangle	RK	Ours
SKINNYe-64-256 v2	37/44	$2^{62.8}$	$2^{240.03}$	$2^{62.8}$	Rectangle	RK	Ours
SKINNY-64-128	18/36	2^{16}	2^{124}	2^{4}	MITM	SK	[HLC+22]
SKINNY-64-192	23/40	2^{52}	2^{188}	2^{4}	MITM	SK	[DHS+21]
SKINNYe-64-256	31/44	2^{52}	2^{254}	2^{52}	MITM	SK	Ours
SKINNYe-64-256 v2	27/44	2^{52}	2^{252}	2^{52}	MITM	SK	Ours

Outline

A proposal for tweakey schedule of SKINNY family

- SKINNY-n-zn $(1 \leq z \leq 14)$
  - *Subtweakey difference cancellation property* (similar to STK)
  - for a given cell, $z-1$ cancellations in every 15 rounds for TK-z

$$\begin{pmatrix} \boldsymbol{stk}^{(2\times 0)}_{\bar{P}^{2\times 0}[i]} \\ \boldsymbol{stk}^{(2\times 1)}_{\bar{P}^{2\times 1}[i]} \\ \vdots \\ \boldsymbol{stk}^{(2\times 14)}_{\bar{P}^{2\times 14}[i]} \end{pmatrix} = \begin{pmatrix} \boldsymbol{I} & \boldsymbol{L}_2^0 & \cdots & \boldsymbol{L}_z^0 \\ \boldsymbol{I} & \boldsymbol{L}_2^1 & \cdots & \boldsymbol{L}_z^1 \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{I} & \boldsymbol{L}_2^{14} & \cdots & \boldsymbol{L}_z^{14} \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{tk}^{(0)}_{1,i} \\ \boldsymbol{tk}^{(0)}_{2,i} \\ \vdots \\ \boldsymbol{tk}^{(0)}_{z,i} \end{pmatrix}$$

$$\Longrightarrow \det \begin{pmatrix} \boldsymbol{I} & \boldsymbol{L}_2^{r_1} & \cdots & \boldsymbol{L}_z^{r_1} \\ \boldsymbol{I} & \boldsymbol{L}_2^{r_2} & \cdots & \boldsymbol{L}_z^{r_2} \\ \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{I} & \boldsymbol{L}_2^{r_z} & \cdots & \boldsymbol{L}_z^{r_z} \end{pmatrix} \neq 0$$

The choice of L_i

- $\boldsymbol{L}_1 = \boldsymbol{I}$,$\{\boldsymbol{L}_i\}_{1\le i\le z} = \{\boldsymbol{L}^{\alpha+1}, \cdots, \boldsymbol{L}^{\alpha+z}\}$ $(\alpha \in [-z, -1])$

Proposition

Suppose $\boldsymbol{L}$ *is a* 4×4 *matrix over* $GF(2)$ *such that the characteristic polynomial* $p_{\boldsymbol{L}}(\lambda)$ *is a primitive polynomial of degree* 4 *over* $GF(2)$*. Then* $\boldsymbol{L}$ *has cycle* 15*, and for any integer* α*,*

$$\det\begin{pmatrix} (\boldsymbol{L}^{\alpha+1})^{r_1} & (\boldsymbol{L}^{\alpha+2})^{r_1} & \cdots & (\boldsymbol{L}^{\alpha+z})^{r_1} \\ (\boldsymbol{L}^{\alpha+1})^{r_2} & (\boldsymbol{L}^{\alpha+2})^{r_2} & \cdots & (\boldsymbol{L}^{\alpha+z})^{r_2} \\ \vdots & \vdots & \ddots & \vdots \\ (\boldsymbol{L}^{\alpha+1})^{r_z} & (\boldsymbol{L}^{\alpha+2})^{r_z} & \cdots & (\boldsymbol{L}^{\alpha+z})^{r_z} \end{pmatrix} \neq 0$$

for all $0 \le r_1 < r_2 < \cdots < r_z \le 14$*.*

Construction of L

- L: the companion matrix of a primitive polynomial
  - Example: primitive polynomial $\lambda^4 + \lambda + 1$

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

- Example $z = 4$: $\{L^{-1}, L^0, L^1, L^2\}$, $L_2 = L^1$, $L_3 = L^{-1}$, $L_4 = L^2$

$$L_2 = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 \end{pmatrix}, L_3 = \begin{pmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}, L_4 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

Efficiency considerations

- Implementation optimization of minimizing the total number of XORs required by the LFSRs

z	$\boldsymbol{L}$	$\{\boldsymbol{L}_i\}_{2\leq i\leq z}$	Number of XORs	Total XORs
4	$\begin{pmatrix}0&1&0&0\\0&0&1&0\\0&0&0&1\\1&1&0&0\end{pmatrix}$	$\{\boldsymbol{L}, \boldsymbol{L}^{-1}, \boldsymbol{L}^2\}$	$\{1, 1, 2\}$	4
5	$\begin{pmatrix}0&1&0&0\\0&0&1&0\\0&0&0&1\\1&1&0&0\end{pmatrix}$	$\{\boldsymbol{L}, \boldsymbol{L}^{-1}, \boldsymbol{L}^2, \boldsymbol{L}^{-2}\}$	$\{1, 1, 2, 3\}$	7
6	$\begin{pmatrix}0&1&0&0\\0&0&1&0\\0&0&0&1\\1&1&0&0\end{pmatrix}$	$\{\boldsymbol{L}, \boldsymbol{L}^{-1}, \boldsymbol{L}^2, \boldsymbol{L}^{-2}, \boldsymbol{L}^3\}$	$\{1, 1, 2, 3, 3\}$	10
7	$\begin{pmatrix}0&1&0&0\\0&0&1&0\\0&0&0&1\\1&1&0&0\end{pmatrix}$	$\{\boldsymbol{L}, \boldsymbol{L}^{-1}, \boldsymbol{L}^2, \boldsymbol{L}^{-2}, \boldsymbol{L}^3, \boldsymbol{L}^4\}$	$\{1, 1, 2, 3, 3, 5\}$	15

Table: Optimal number of XORs required in our construction

Efficiency considerations

- Optimization of minimizing the circuit area of the LFSRs

z	$\{L_i\}_{2\leq i\leq z}$	Instantiated circuit	Area	Latency
4	$\{L, L^2, L^3\}$	$\{L\}$	1	6
	$\{L, L^2, L^3\}$	$\{L, L^2\}$	2	2
5	$\{L, L^2, L^3, L^4\}$	$\{L\}$	1	10
	$\{L, L^{-1}, L^2, L^{-2}\}$	$\{L, L^{-1}\}$	2	3
	$\{L, L^2, L^3, L^4\}$	$\{L, L^2, L^3\}$	3	2
6	$\{L, L^2, L^3, L^4, L^5\}$	$\{L\}$	1	15
	$\{L, L^2, L^3, L^4, L^5\}$	$\{L, L^2\}$	2	4
	$\{L, L^2, L^3, L^4, L^5\}$	$\{L, L^2, L^4\}$	3	3
	$\{L, L^2, L^3, L^4, L^5\}$	$\{L, L^2, L^3, L^4\}$	4	2
7	$\{L, L^2, L^3, L^4, L^5, L^6\}$	$\{L\}$	1	21
	$\{L, L^{-1}, L^2, L^{-2}, L^3, L^{-3}\}$	$\{L, L^{-1}\}$	2	6
	$\{L, L^2, L^3, L^4, L^5, L^6\}$	$\{L, L^2, L^4\}$	3	3
	$\{L, L^{-1}, L^2, L^{-2}, L^3, L^{-3}\}$	$\{L, L^{-1}, L^2, L^{-2}\}$	4	2

Table: The area-latency trade-off for our construction.

Thanks for Your Attention!

Reference I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In *EUROCRYPT '99, Proceeding*, volume 1592 of *LNCS*, pages 12–23, 1999.


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