Key Guessing Strategies for Linear Key-Schedule Algorithms in Rectangle Attacks

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Outline

1. Background and Motivations
2. Key-Guessing Strategies in the Rectangle Attack
3. Automatic Model For SKINNY
4. Improved Rectangle Attacks on SKINNY
5. Conclusion and Further Disscussion

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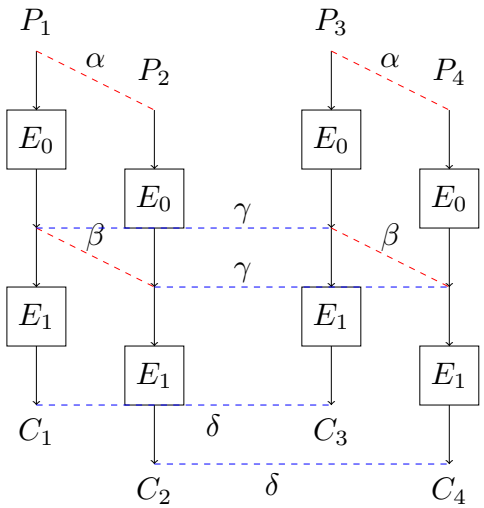
Boomerang and Retangle Attack

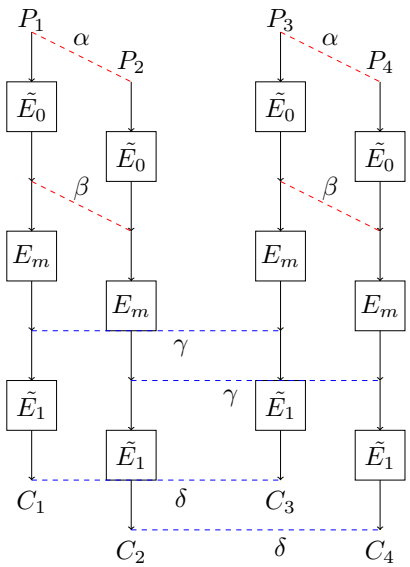
- Boomerang Attack proposed by Wagner [Wag99]
  - $E_d = \underbrace{E_1}_{\gamma \xrightarrow{q} \delta} \circ \underbrace{E_0}_{\alpha \xrightarrow{p} \beta}$
  - $Pr[E_d^{-1}(E_d(x) \oplus \delta) \oplus E_d^{-1}(E_d(x \oplus \alpha) \oplus \delta) = \alpha] = p^2 q^2$
- Adaptive chosen plaintext and ciphertext $\rightarrow$ chosen-plaintext attack:
  - amplified boomerang attack [KKS00]
  - rectangle attack [BDK01]
  - probability $2^{-n}\hat{p}^2\hat{q}^2$

$$\hat{p} = \sqrt{\sum_i Pr^2(\alpha \rightarrow \beta_i)}, \hat{q} = \sqrt{\sum_i Pr^2(\gamma_i \rightarrow \delta)}$$

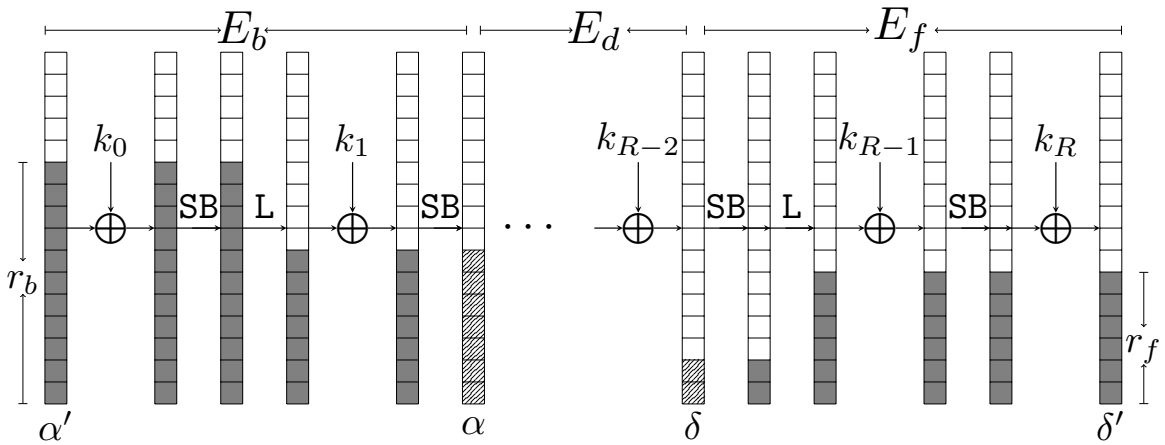


Boomerang and Retangle Attack

- Improvements based on the dependence between two differentials
  - Boomerang switch [Mur11, BK09, BDK05]
  - Sandwich attack [DKS14]
    - $E_d = \underbrace{\tilde{E}_1}_{\gamma \xrightarrow{\tilde{q}} \delta} \circ \underbrace{E_M}_{\beta \xrightarrow{t} \gamma} \circ \underbrace{\tilde{E}_0}_{\alpha \xrightarrow{\tilde{p}} \beta}$
    - probability $2^{-n}\tilde{p}^2\tilde{q}^2 t$
  - Boomerang connectivity Table [CHP+18]
  - BCT in multiple rounds [WP19, SQH19]



Generalized Key-Recovery Algorithms for Rectangle Attack



- `Attack I`: Biham-Dunkelman-Keller's Attack at EC01 [BDK01]
- `Attack II`: Biham-Dunkelman-Keller's Attack at FSE02 [BDK02]
- `Attack III`: Zhao *et al.*'s Related-Key Attack at ToSC19 and DCC20 [ZDJ19, ZDM+20]

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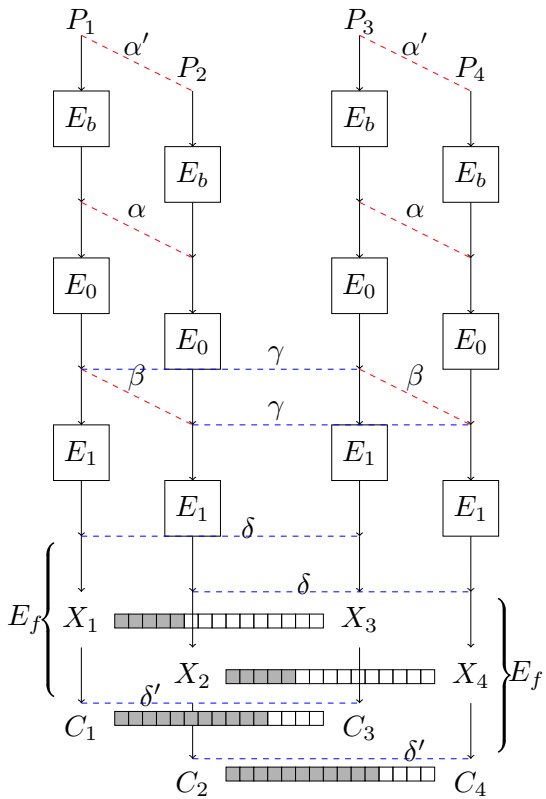
Related-key Rectangle Attack with Linear Key Schedule

- Invalid quartet: (P_1, P_2, P_3, P_4) meet (α', δ') but never suggest any key candidates. Guess k_{1b}, other k_{2b}, k_{3b}, k_{4b}, are fixed

$$\begin{cases} S(k_{1b} \oplus P_1) \oplus S(k_{2b} \oplus P_2) = \alpha, \\ S(k_{3b} \oplus P_3) \oplus S(k_{4b} \oplus P_4) = \alpha \end{cases}$$

- A tradeoff of the rectangle attack framework with linear key schedule
  - guess k_b in E_b and part of k_f in E_f
  - gain more inactive bits (or fixed differences) from the internal state

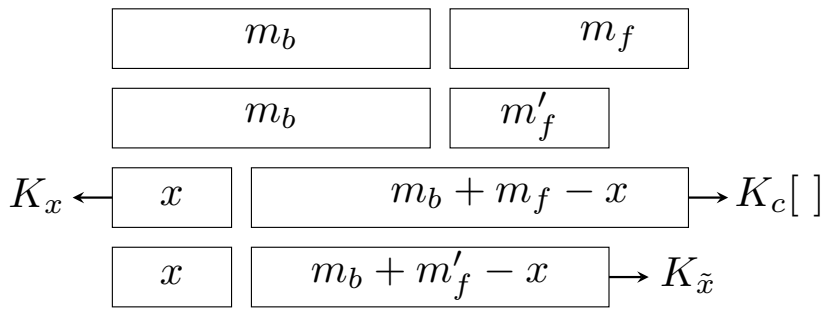


Algorithm 1 (Attack IV)

Construct y structures of 2^{rb} plaintexts each. For structure i ($1 \leq i \leq y$), query the 2^{rb} plaintexts by encryption under K_1, K_2, K_3 and K_4 and store them in $L_1[i]$, $L_2[i]$, $L_3[i]$ and $L_4[i]$
for *each of the* x*-bit key* K_x*, which is a part of* $(m_b + m'_f)$*-bit* K_1 **do**
  $K_c \leftarrow [\,]$
  for *each of* $(m_b + m'_f - x)$*-bit* $K_{\tilde{x}}$ *of* K_1 *involved in* E_b *and* E_f **do**
    for i *from* 1 *to* y **do**
      for $(P_1, C_1) \in L_1[i]$ **do**
        $P_2 = E^{-1}_{b[K_1 \oplus \Delta K]}(E_{b_{K_1}}(P_1) \oplus \alpha), S_1 \leftarrow (P_1, C_1, P_2, C_2)$
      end
      for $(P_3, C_3) \in L_3[i]$ **do**
        $P_4 = E^{-1}_{b[K_1 \oplus \Delta K \oplus \nabla K]}(E_{b[K_1 \oplus \nabla K]}(P_3) \oplus \alpha), S_2 \leftarrow (P_3, C_3, P_4, C_4)$
      end
    end
    for $(P_1, C_1, P_2, C_2) \in S_1$ **do**
      $X_1[1, \cdots, h_f] = E^{-1}_{f[K_1]}(C_1)$, $X_2[1, \cdots, h_f] = E^{-1}_{f[K_1 \oplus \Delta K]}(C_2)$
      $\tau = (X_1[1,\cdots,h_f], X_2[1,\cdots,h_f], C_1[1,\cdots,n - r_f], C_2[1,\cdots,n - r_f])$,
      $H[\tau] \leftarrow (P_1, C_1, P_2, C_2)$
    end
    for $(P_3, C_3, P_4, C_4) \in S_2$ **do**
      $X_3[1, \cdots, h_f] = E^{-1}_{f[K_1 \oplus \nabla K]}(C_3)$, $X_4[1, \cdots, h_f] = E^{-1}_{f[K_1 \oplus \Delta K \oplus \nabla K]}(C_4)$
      $\tau' = (X_3[1,\cdots,h_f], X_4[1,\cdots,h_f], C_3[1,\cdots,n - r_f], C_4[1,\cdots,n - r_f])$
      Access $H[\tau']$ to find (P_1, C_1, P_2, C_2) to generate quartet (C_1, C_2, C_3, C_4)
      for *each generated quartet* **do**
        Determine other $(m_f - m'_f)$-bit key k''_f, $K_c[K_{\tilde{x}} \| k''_f] \leftarrow K_c[K_{\tilde{x}} \| k''_f] + 1$
      end
    end
  end
  Select top $2^{m_b + m_f - x - h}$ hits in K_c. Guess remaining $k - (m_b + m_f)$-bit key to check the full key
end

Related-key Rectangle Attack with Linear Key Schedule

- The guessed keys in Algorithm 1



  - m_b-bit k_b and m_f-bit k_f in total
  - guess m_b-bit k_b and m'_f-bit k'_f before generating quartets
  - guess x-bit K_x before initializing the key counter $K_c[\ ]$

Complexity

- set $(y \cdot 2^{2r_b})^2 \cdot 2^{-2r_b} \cdot 2^{-n}\hat{p}^2\hat{q}^2 = s$, s is the expected number of right quartets
- Data complexity: $4y \cdot 2^{r_b} = \sqrt{s} \cdot 2^{n/2+2}/\hat{p}\hat{q}$
- Time complexity:
  - **Time I** : $T_1 = 2^{x+m_b+m'_f-x} \cdot y \cdot 2^{r_b} \cdot 2 = \sqrt{s} \cdot 2^{m_b+m'_f+n/2+1}/\hat{p}\hat{q}$
  - **Time II** : $T_2 = (s \cdot 2^{m_b+m'_f-n+2r_f-2h_f}/\hat{p}^2\hat{q}^2) \cdot \varepsilon$
  - **Time III** : $T_3 = 2^x \cdot 2^{m_b+m_f-x-h} \cdot 2^{k-(m_b+m_f)} = 2^{k-h}$
- Memory complexity of the key counters and data structures : $2^{m_b+m_f-x} + 4y \cdot 2^{r_b} = 2^{m_b+m_f-x} + \sqrt{s} \cdot 2^{n/2+2}/\hat{p}\hat{q}$
- Success Probability: $P_s = \Phi(\frac{\sqrt{sS_N}-\Phi^{-1}(1-2^{-h})}{\sqrt{S_N+1}})$ [Sel08]
  - $h < m_b + m_f - x$, $x \leq m_b + m'_f$

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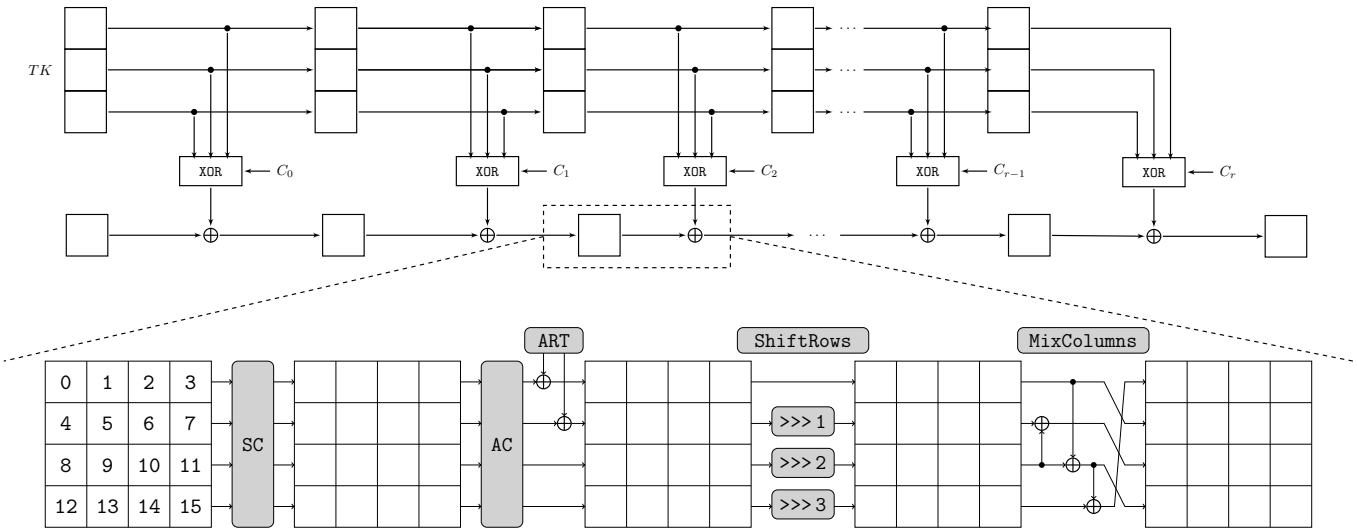
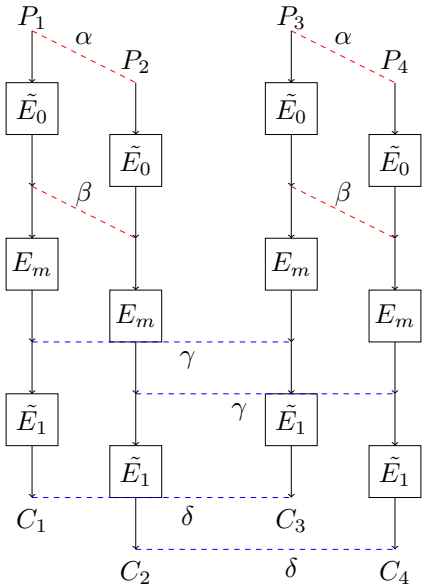
Introduction to SKINNY

- Proposed by Beierle et al. [BJK+16]
- SKINNY-n-t: block size $n \in \{64, 128\}$, tweakey size $t = n, 2n$ or $3n$



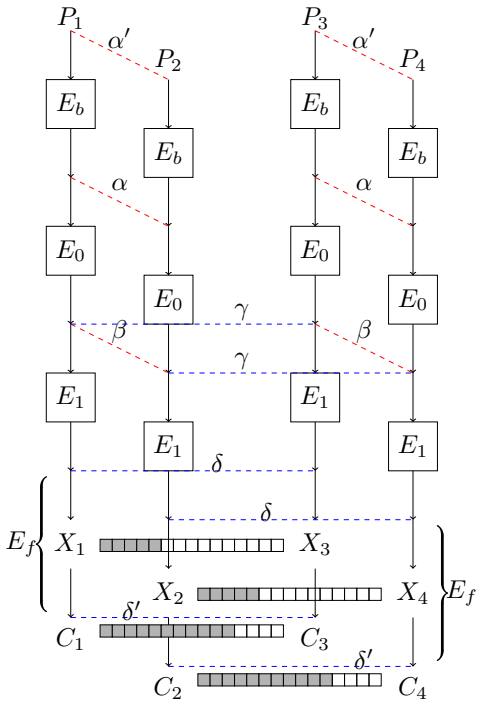
Previous Automatic Search Models for Boomerang Distinguishers on SKINNY

- MILP, Beierle et al. [BJK+16]
- MILP, Liu et al. [LGS17]
- MILP+SAT, Hadipour et al. [HBS21]
  - considering the switching effect in multiple rounds
- MILP+CP, Delaune et al. [DDV20]
  - automatically handling the middle rounds
- MILP+CP, Qin et al. [QDW+21]
  - search the entire $(N_b + N_d + N_f)$-round attack

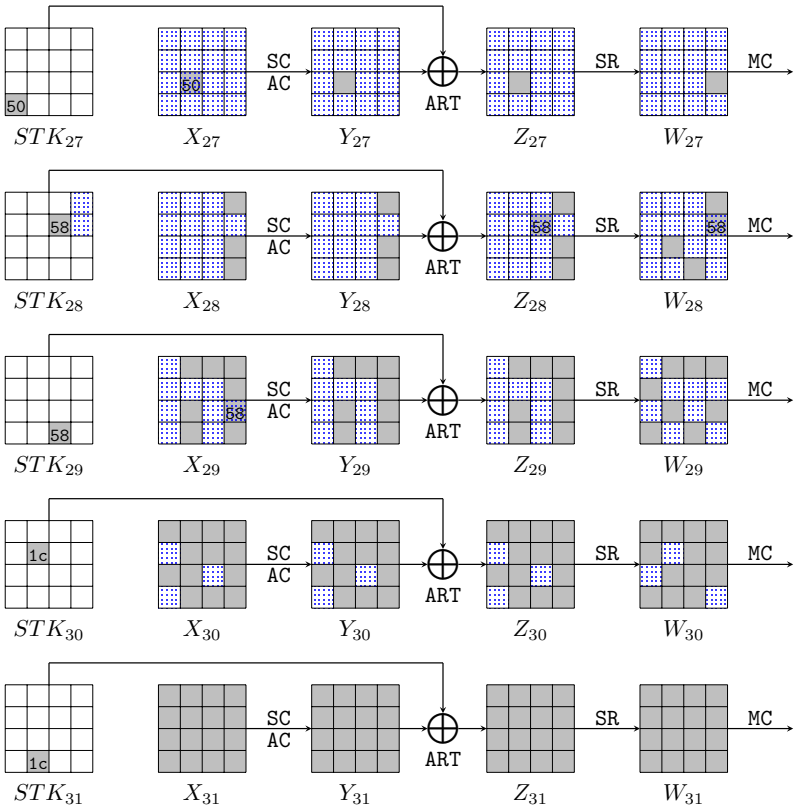


Our Model to Determine the Optimal Distinguisher

- search the entire $(N_b + N_d + N_f)$-round attack for our new rectangle framework
  - based on [HBS21, DDV20, QDW+21]
  - previous constraints: m_b, r_f, $\tilde{p}^2\tilde{q}^2 t$
  - new constraints : m_f, m'_f, h_f, h
  - objective : $\min\{T_1, T_2, T_3\}$

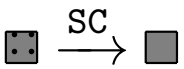


Modelling Propagation of Cells with Known Differences in E_f



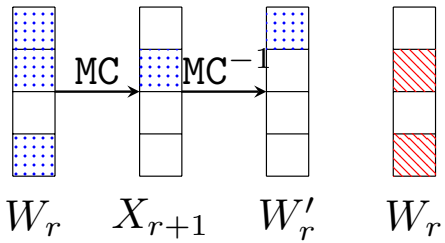
- `DXFixed(DWFixed)`: cells with known differences in $X_r(W_r)$, marked by ⚀ and ⚅
- the impact of `SC` and `SR` : $\texttt{DWFixed}[r][i] = \neg\texttt{DXL}[r_m + r_1 + r][P_{\texttt{SR}}[i]]$
- the impact of `MC` : $\texttt{DXFixed}[r+1][i] = \texttt{DWFixed}[r][i] \wedge \texttt{DWFixed}[r][i+8] \wedge \texttt{DWFixed}[r][i+12]$

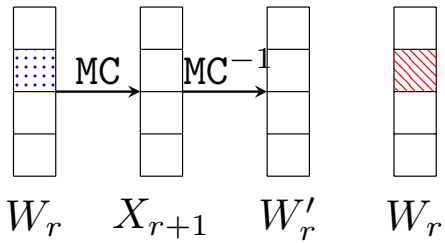
Modeling Cells that could be Used to Filter Quartets in E_f

- `DXFilter`: cells can be used as filters in X_r
  - cells with nonzero fixed difference: 

$\texttt{DXFixed}[r][i]$	$\texttt{DXL}[r_m + r_1 + r][i]$	$\texttt{DXFilter}[r][i]$
0	1	0
1	0	0
1	1	1

- `DWFilter`: cells can be used as filters in W_r
  - $r = N_f - 1$, $\texttt{DWFilter}[N_f - 1][i] = \texttt{DWFixed}[N_f - 1][i]$
  - $0 \leq r \leq N_f - 2$, extra cells with fixed differences in W_r than W'_r (deduced from X_{r+1}) can act as filters





Modeling m'_f-bit Subtweakeys in E_f for Generating Quartets

- $\texttt{DXGuess(DWGuess)}$: cells need to know in $X_r(W_r)$ in decryption from ciphertexts to the filters
- $0 \leq r \leq N_f - 1$, the cells in W_r need to know involve two types
  - cells to be known from X_r over the $\texttt{SR}$ operation
  - cells used as filters in W_r

$$\texttt{DWGuess}[r][i] = \texttt{DWisFilter}[r][i] \vee \texttt{DXGuess}[r][P_{\texttt{SR}}[i]]$$

- $0 \leq r \leq N_f - 2$, the cells in X_{r+1} need to know involve two types:
  - cells need to known from W_r over the $\texttt{MC}$ operation
  - cells used as filters in X_{r+1}

Modeling the Advantage h in the Key-recovery Attack

- $\texttt{Adv}$: the advantage h determines the exhaustive search time T_3
- $\texttt{KnownDec}$: the cells in Y_r need to know in the decryption from ciphertext to δ
- $h \leq m_b + m_f - x$ and $x \leq m_b + m'_f$:

$$\begin{cases} \texttt{x} \leq \sum\limits_{0 \leq r \leq N_b - 2,\ 0 \leq i \leq 7} \texttt{KnownEnc}[r][i] + \sum\limits_{0 \leq r \leq N_f - 1,\ 0 \leq i \leq 7} \texttt{DXGuess}[r][i] \\ \texttt{Adv} + \texttt{x} \leq \sum\limits_{0 \leq r \leq N_b - 2,\ 0 \leq i \leq 7} \texttt{KnownEnc}[r][i] + \sum\limits_{0 \leq r \leq N_f - 1,\ 0 \leq i \leq 7} \texttt{KnownDec}[r][i] \end{cases}$$

The Objective Function

- Time complexities: **Time I (T_1)**, **Time II (T_2)** and **Time III (T_3)**
  - $\texttt{DXU} \xrightarrow[w_0]{\text{upper differential}} \tilde{p}$, $\texttt{DXL} \xrightarrow[w_1]{\text{lower differential}} \tilde{q}$, $\texttt{DXU}\wedge\texttt{DXL} \xrightarrow[w_m]{\text{middle part}} t$
  - $\texttt{KnownEnc} \xrightarrow[w_{m_b}]{} m_b$, $\texttt{DXGuess} \xrightarrow[w_{m_f}]{} m_f'$
  - $\texttt{DXisFilter+DWisFilter} \xrightarrow[w_{h_f}]{} h_f$
  - $\texttt{Adv} \rightarrow h$
- The uniformed objective:

$$\text{Minimize } obj,\ obj \geq T_1,\ obj \geq T_2,\ obj \geq T_2.$$

New Distinguishers of SKINNY

- MILP+CP model (based on [DDV20, HBS21, QDW+21])

Version	N_d	Probability $\tilde{p}^2\tilde{q}^2t$	$N_b + N_d + N_f$	Ref.
64-128	17	$2^{-29.78}$	-	[SQH19]
	17	$2^{-48.72}$	21	[LGS17]
	19	$2^{-51.08}$	23	[HBS21]
	19	$2^{-54.36}$	-	[DDV20]
	18	$2^{-55.34}$	24	[QDW+21]
	18	$2^{-55.34}$	25	Ours
64-192	22	$2^{-42.98}$	-	[SQH19]
	22	$2^{-54.94}$	26	[LGS17]
	23	$2^{-55.85}$	29	[HBS21]
	23	$2^{-57.93}$	-	[DDV20]
	22	$2^{-57.73}$	30	[QDW+21]
	22	$2^{-57.56}$	31	Ours
128-256	18	$2^{-77.83}$	-	[SQH19]
	18	$2^{-103.84}$	22	[LGS17]
	20	$2^{-85.77}$	-	[DDV20]
	21	$2^{-116.43}$	24	[HBS21]
	19	$2^{-116.97}$	25	[QDW+21]
	18	$2^{-108.51}$	25	Ours
	19	$2^{-121.07}$	26	Ours
128-384	22	$2^{-48.30}$	-	[SQH19]
	23	2^{-112}	27	[LGS17]
	23	2^{-112}	28	[ZDM+20]
	24	$2^{-86.09}$	-	[DDV20]
	25	$2^{-116.59}$	30	[HBS21]
	22	$2^{-101.49}$	30	[QDW+21]
	23	$2^{-115.09}$	32	Ours

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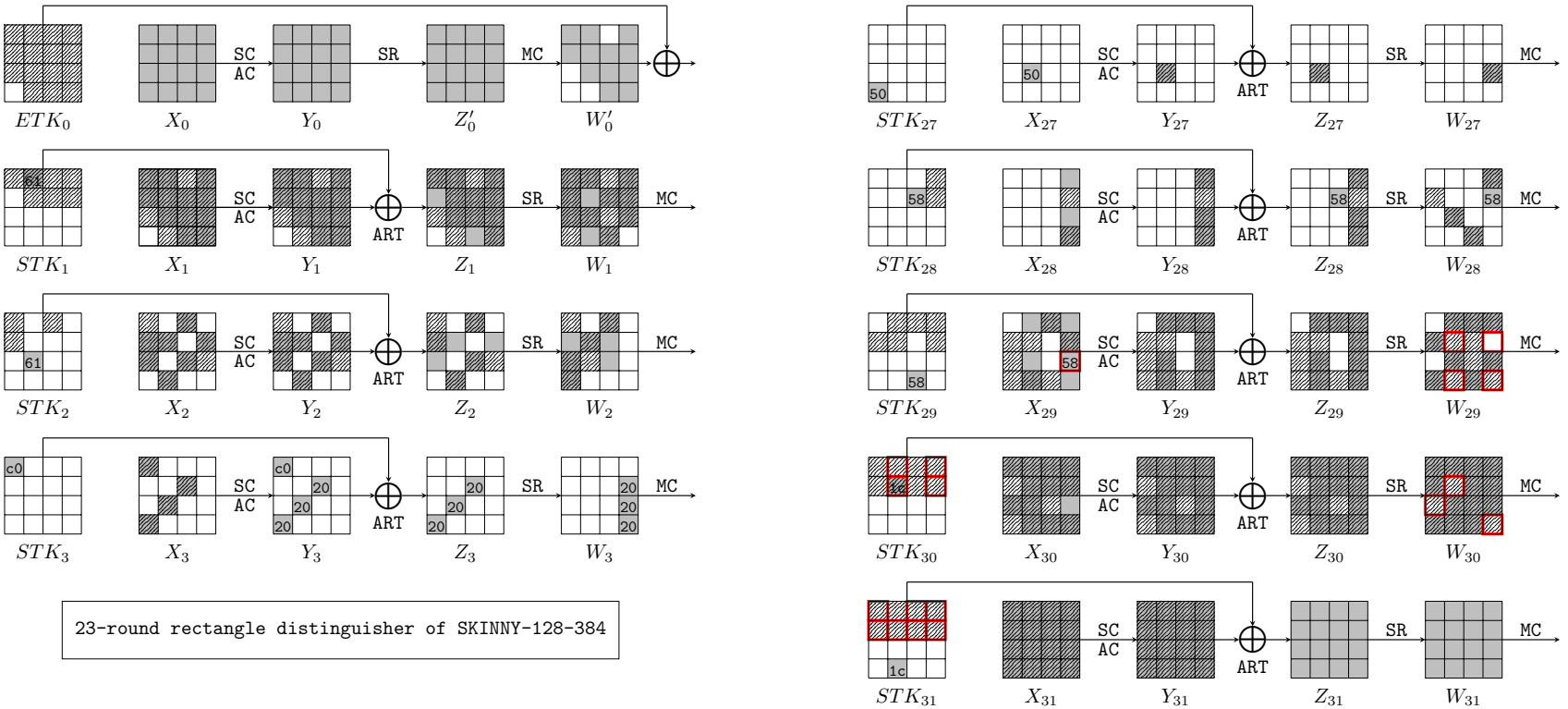
Improved Attack on 32-round SKINNY-128-384



- 4-round E_b+ 23-round distinguisher+5-round E_f
  - W'_0 →plaintext, Z_{31} →ciphertext
  - $r_b = 12c$, $m_b = 18c$, $r_f = 16c$, $m_f = 24c$

Internal State Used for Filtering and Involved Subtweakeys

	Round	Filter	Involved subtweakeys
1	30	$\boldsymbol{\Delta W_{30}[5] = 0}$	$STK_{31}[5]$
2		$\boldsymbol{\Delta W_{30}[8] = 0}$	$STK_{31}[4]$
3		$\boldsymbol{\Delta W_{30}[15] = 0}$	$STK_{31}[3]$
4	29	$\boldsymbol{\Delta W_{29}[5] = 0}$	$STK_{30}[5]$, $STK_{31}[0,6,7]$
5		$\boldsymbol{\Delta W_{29}[7] = 0}$	$STK_{30}[7]$, $STK_{31}[2,4,5]$
6		$\Delta W_{29}[10] = 0$	$STK_{30}[6]$, $STK_{31}[1,7]$
7		$\boldsymbol{\Delta W_{29}[13] = 0}$	$STK_{30}[1]$, $STK_{31}[0,5]$
8		$\boldsymbol{\Delta W_{29}[15] = 0}$	$STK_{30}[3]$, $STK_{31}[2,7]$
9		$\boldsymbol{\Delta X_{29}[11]} = 0\text{x}58$	$STK_{30}[5]$, $STK_{31}[0,6]$
10	28	$\Delta W_{28}[5] = 0$	$STK_{29}[5]$, $STK_{30}[0,6,7]$, $STK_{31}[1,2,3,4,7]$
11		$\Delta W_{28}[11] = 0$	$STK_{29}[7]$, $STK_{30}[2,4]$, $STK_{31}[1,3,5,6]$
12		$\Delta W_{28}[13] = 0$	$STK_{29}[1]$, $STK_{30}[0,5]$, $STK_{31}[3,4,6]$
13		$\Delta W_{28}[15] = 0$	$STK_{29}[3]$, $STK_{30}[2,7]$, $STK_{31}[1,4,6]$
14	27	$\Delta W_{27}[7] = 0$	$STK_{28}[7]$, $STK_{29}[2,4,5]$, $STK_{30}[0,1,3,5,6]$, $STK_{31}[0,1,2,3,4,5,6,7]$
15		$\Delta W_{27}[15] = 0$	$STK_{28}[3]$, $STK_{29}[2,7]$, $STK_{30}[1,4,6]$, $STK_{31}[0,3,5,6,7]$
16		$\Delta X_{27}[9] = 0\text{x}50$	$STK_{28}[7]$,$STK_{29}[2,4]$, $STK_{30}[1,3,5,6]$, $STK_{31}[0,1,2,5,6,7]$

- $k'_f = \{STK_{30}[1,3,5,7], STK_{31}[0,2,3,4,5,6,7]\}$ $(m'_f = 11c)$
- $h_f = \{X_{29}[11], W_{29}[5,7,13,15], W_{30}[5,8,15]\}$ $(h_f = 8c)$

Tweakey Recovery for 32-round SKINNY-128-384

Step	Internal state	Involved subtweakeys
A	$Z_{30}[6]$	$STK_{31}[7]$
	$Z_{30}[14]$	$STK_{31}[1]$
B	$Z_{29}[1]$	$STK_{30}[5]$, $STK_{31}[6]$
	$Z_{29}[9]$	$STK_{30}[7]$, $STK_{31}[2,4]$
	$Z_{29}[13]$	$STK_{30}[0]$, $STK_{31}[3,4]$
C	$Z_{29}[3]$	$STK_{30}[7]$, $STK_{31}[4]$
	$Z_{29}[7]$	$STK_{30}[4]$, $STK_{31}[3,5,6]$
	$Z_{29}[15]$	$STK_{30}[2]$, $STK_{31}[1,6]$
D	$Z_{28}[3]$	$STK_{29}[7]$, $STK_{30}[4]$, $STK_{31}[3,5,6]$
	$Z_{28}[11]$	$STK_{29}[5]$, $STK_{30}[0,6]$, $STK_{31}[1,3,4,7]$
	$Z_{28}[15]$	$STK_{29}[2]$, $STK_{30}[1,6]$, $STK_{31}[0,5,7]$
E	$X_{27}[9]$	$STK_{28}[7]$,$STK_{29}[2,4]$, $STK_{30}[1,3,5,6]$, $STK_{31}[0,1,2,5,6,7]$

- set $s = 1$, $h = 40$, $x = 208$
- Time complexity: $2^{354.99}$
  - $T_1 = \sqrt{s} \cdot 2^{m_b+m'_f+n/2+1} / \sqrt{\tilde{p}^2 t \tilde{q}^2} = 2^{354.54}$
  - $T_3 = s \cdot 2^{m_b+m'_f-2h_f-n+2r_f} / (\tilde{p}^2 t \tilde{q}^2) \cdot \varepsilon = 2^{353.1}$
  - $T_3 = 2^{k-h} = 2^{344}$
- Success probability [Sel08]: $P_s = \Phi(\frac{\sqrt{sS_N} - \Phi^{-1}(1-2^{-h})}{\sqrt{S_N+1}}) = 82.1\%$

Summary of Attacks on Skinny in Related-tweakey Setting

Version	Rounds	Data	Time	Memory	Approach	Setting	Ref.
64-128	22	$2^{63.5}$	$2^{110.9}$	$2^{63.5}$	Rectangle	RK	[LGS17]
	23	$2^{62.47}$	$2^{125.91}$	2^{124}	ID	RK	[LGS17]
	23	$2^{62.47}$	2^{124}	$2^{77.47}$	ID	RK	[SMB18]
	23	$2^{71.4}$	2^{79}	$2^{64.0}$	ID	RK	[ABC$^+$]
	23	$2^{60.54}$	$2^{120.7}$	$2^{60.9}$	Rectangle	RK	[HBS21]
	24	$2^{61.67}$	$2^{96.83}$	2^{84}	Rectangle	RK	[QDW$^+$21]
	25	$2^{61.67}$	$2^{118.43}$	$2^{64.26}$	Rectangle	RK	Ours
64-192	27	$2^{63.5}$	$2^{165.5}$	2^{80}	Rectangle	RK	[LGS17]
	29	$2^{62.92}$	$2^{181.7}$	2^{80}	Rectangle	RK	[HBS21]
	30	$2^{62.87}$	$2^{163.11}$	$2^{68.05}$	Rectangle	RK	[QDW$^+$21]
	31	$2^{62.78}$	$2^{182.07}$	$2^{62.79}$	Rectangle	RK	Ours
128-256	22	2^{127}	$2^{235.6}$	2^{127}	Rectangle	RK	[LGS17]
	23	$2^{124.47}$	$2^{251.47}$	2^{248}	ID	RK	[LGS17]
	23	$2^{124.41}$	$2^{243.41}$	$2^{155.41}$	ID	RK	[SMB18]
	24	$2^{125.21}$	$2^{209.85}$	$2^{125.54}$	Rectangle	RK	[HBS21]
	25	$2^{124.48}$	$2^{226.38}$	2^{168}	Rectangle	RK	[QDW$^+$21]
	25	$2^{120.25}$	$2^{193.91}$	2^{136}	Rectangle	RK	Ours
	26	$2^{126.53}$	$2^{254.4}$	$2^{128.44}$	Rectangle	RK	Ours
128-384	27	2^{123}	2^{331}	2^{155}	Rectangle	RK	[LGS17]
	28	2^{122}	$2^{315.25}$	$2^{122.32}$	Rectangle	RK	[ZDM$^+$20]
	30	$2^{125.29}$	$2^{361.68}$	$2^{125.8}$	Rectangle	RK	[HBS21]
	30	2^{122}	$2^{341.11}$	$2^{128.02}$	Rectangle	RK	[QDW$^+$21]
	32	$2^{123.54}$	$2^{354.99}$	$2^{123.54}$	Rectangle	RK	Ours

Outline

1 Background and Motivations

2 Key-Guessing Strategies in the Rectangle Attack

3 Automatic Model For SKINNY

4 Improved Rectangle Attacks on SKINNY

5 Conclusion and Further Disscussion

Application to ForkSkinny, Deoxys-BC and GIFT

Version	Rounds	Data	Time	Memory	Approach	Setting	Ref.
ForkSkinny							
128-256 (256-bit key)	26	2^{125}	$2^{254.6}$	2^{160}	ID	RK	[BDL20]
	26	2^{127}	$2^{250.3}$	2^{160}	ID	RK	[BDL20]
	28	$2^{118.88}$	$2^{246.98}$	2^{136}	Rectangle	RK	[QDW+21]
	28	$2^{118.88}$	$2^{224.76}$	$2^{118.88}$	Rectangle	RK	Ours
Deoxys-BC							
128-384	13	2^{127}	2^{270}	2^{144}	Rectangle	RK	[CHP+17]
	14	2^{127}	$2^{286.2}$	2^{136}	Rectangle	RK	[ZDJ19]
	14	$2^{125.2}$	$2^{282.7}$	2^{136}	Rectangle	RK	[ZDJM19]
	14	$2^{125.2}$	2^{260}	2^{140}	Rectangle	RK	Ours
GIFT							
64-128	25	$2^{63.78}$	$2^{120.92}$	$2^{64.1}$	Rectangle	RK	[JZZD20]
	26	$2^{60.96}$	$2^{123.23}$	$2^{102.86}$	Differential	RK	[SWW21]
	26	$2^{63.78}$	$2^{122.78}$	$2^{63.78}$	Rectangle	RK	Ours

Application in Single-key Setting

- Rectangle attack in single-key model: set differences of keys to 0
  - set $y = \sqrt{s} \cdot 2^{n/2-r_b+1.5}/\hat{p}\hat{q}$, data complexity $y \cdot 2^{r_b}$
  - $T_1 = 2^{m_b+m_f'} \cdot y \cdot 2^{r_b} = \sqrt{s} \cdot 2^{m_b+m_f'+\frac{n}{2}+1.5}/\hat{p}\hat{q}$
  - $T_2 = (s \cdot 2^{m_b+m_f'-n+2r_f-2h_f}/\hat{p}^2\hat{q}^2) \cdot \varepsilon$
- Application to Serpent:
  - reuse the rectangle distinguisher by Biham, Dunkelman and Keller [BDK01]

Key size	Time	Data	Memory	Approach	Ref.
256	$2^{173.8}$	$2^{126.3}$	$2^{126.3}$	rectangle	[BDK02]
256	2^{164}	$2^{126.3}$	$2^{126.3}$	rectangle	ours

Overall Analysis of the Four Attack Models

- For generating quartets:
  - `Attack I`: guesses all the $(m_b + m_f)$-bit key at once
  - `Attack II`: does not guess the key involved in E_b and E_f
  - `Attack III`: guesses m_b-bit key in E_b
  - Our new attack: guesses m_b-bit key in E_b and m'_f-bit key in E_f
- Time complexities:
  - `Attack I`: $T_{\mathtt{I}} = 2^{m_b+m_f+n/2+t+2}$
  - `Attack II`: $T_{\mathtt{II}} = 2^{m_b+r_b+2r_f-n+2t} + 2^{m_f+2r_b+r_f-n+2t}$
  - `Attack III`: $T_{\mathtt{III}} = 2^{m_b+2r_f-n+2t} \cdot \varepsilon$
  - `Attack IV`: $T_{\mathtt{IV}} = 2^{m_b+2r_f-n+m'_f-2h_f+2t} \cdot \varepsilon$

Thanks for Your Attention!

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