Short Tweak tBC and Its Applications in Symmetric Ciphers

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Tweakable Block Cipher (TBC)

What is a TBC?

$$E : \{0,1\}^k \times \{0,1\}^n \times \{0,1\}^t \to \{0,1\}^n$$

Properties

- For any fixed key K and T, $E(K, T, \cdot) := E_K^T(\cdot)$ is a permutation over $\{0,1\}^n$
- TPRP Security: it is hard to distinguish from a random permutation

TBC Design Choice I: XE and XEX [Rogaway et al.]

XE and XEX

$$XE : E_K^{i_1,\cdots,i_t}(M) := E_K(\Delta \oplus M)$$
$$XEX : E_K^{i_1,\cdots,i_t}(M) := E_K(\Delta \oplus M) \oplus \Delta,$$

where $\Delta = \alpha_1^{i_1} \cdots \alpha_t^{i_t} \cdot L$ and $L = E_K(0)/E_K(N)$

- Examples: OCB (XEX), COLM (XE,XE)

TBC Design Chpice II: TWEAKEY Framework

TWEAKEY Framework (Jean-Nikolic-Peyrin: ASIACRYPT 2014)

- Iterated key alternating approach
- Tweak and Key processed together in the same fashion

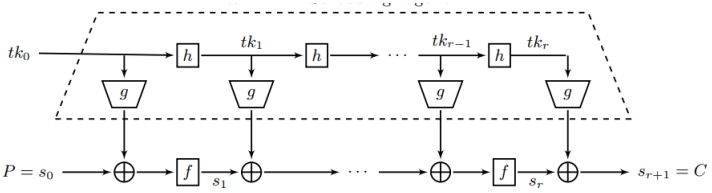

Figure: TWEAKEY Framework

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Motivation for Short Tweak TBC (tBC)

Shortcomings of XE(X) Construction

- Additional block cipher invocation
- Storage overhead
- Degradation to Birthday bound security (General Weakness)

Shortcomings of TWEAKEY (STK) Framework

- Costly tweak schedule
- Difficult to optimize for short tweaks
- Increased number of rounds affects the throughput of the cipher

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- Motivation of short-tweak Tweakable Block Ciphers
- Elastic Tweak Framework
- Instantiations
  - TweAES
  - TweGIFT
- Applications
  - Key Reduction
  - Simplicity in Design
  - Efficient Short Message Processing

Elastic Tweak Framework

Idea

- Elastic Tweak refers to elastic expansion of short tweaks
- Typically considers tweaks of size 4, 8 and 16 bits

Generic Design Framwork (BC $\rightarrow$ tBC)

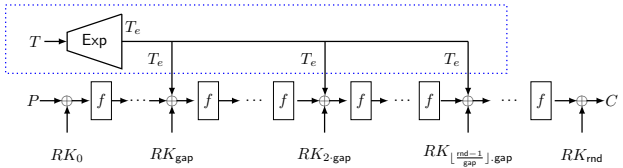
Generic framework, by which one can convert a block cipher (BC) (SPN based) to a short tweak tweakble block cipher (tBC)

Elastic Tweak Framework: Overview

BC → tBC Conversion: High-level Idea

- Expands a small tweak T (size t) to T_e (size t_e) by a linear code of high distance
- T_e is xored with the internal BC state affecting tic S-boxes
- Apply the tweak injection after a certain interval (*gap* number of rounds)
- $w := t_e/tic$ is the word size. It says how many bits of each S-box get affected

Tweak Expansion and Injection



Parameters and Recommended Instances

Parametrize tBC

- tBC is parameterized by four-tuple: (t, t_e, tic, gap), denoted by tBC$[t, t_e, tic, gap]$

Recommended Instances where BC $\in$ {AES-128, GIFT-128}

- TweAES-128 [4,8,8,2]
- TweAES-128 [8,16,8,2]
- TweAES-128 [16,32,8,2]
- TweGIFT [4,16,16,4]
- TweGIFT [4,32,32,5]
- TweGIFT [16,32,32,4]

Elastic Tweak Framework: Exp module

Algorithm to Expand the Tweak: Exp Module

- Define $\tau = t/w$
- Parse T as $T \leftarrow (T_1, T_2, \ldots, T_\tau)$, where $\forall i,\ T_i \in \mathbb{F}_{2^w}$
- Compute $S := T_1 \oplus \cdots \oplus T_\tau$
- Expand the Tweak: $T' := (T_1, \ldots, T_\tau, S \oplus T_1, \ldots, S \oplus T_\tau)$
- Optional Copy: $T_e := T' \| \cdots \| T'$ (Depends on the choice of the underlying BC)

Elastic Tweak Framework: Features

Features

- tBC can be applied to any SPN based block ciphers
- tBC with zero tweak turns out to be same as the underlying block cipher
- Low storage to store the tweak
- Lightweight operations to process the tweak

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TweAES-128 with 4-bit Tweaks

TweAES-128 [4,8,8,2]

- $t = 4$ bit tweak is extended to $t_e = 8$ bit tweaks
- Tweaks are affected in $tic = 8$ S-Boxes
- Tweaks are injected at the least significant bits of each of the 8 S-Boxes in the top two rows
- Tweaks are injected at the interval of $gap = 2$ rounds

Other Instances

Other instances TweAES-128 [8,16,8,2] and TweAES-128 [16,32,8,2] are defined similarly

Cryptanalysis: TweAES

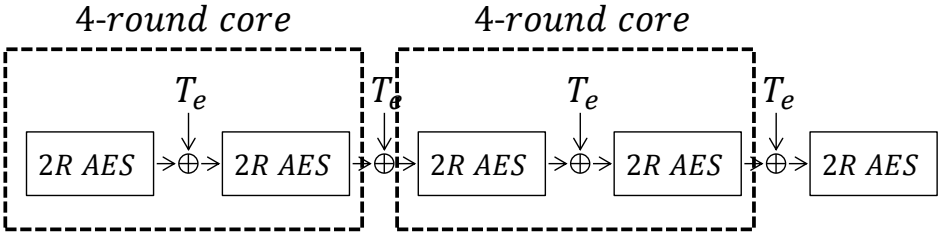

Figure: TweAES: 4-round Core

Differential Propagation through 4-round core

- 4-round core: 15 Active S-Boxes (next slide)

Cryptanalysis: TweAES

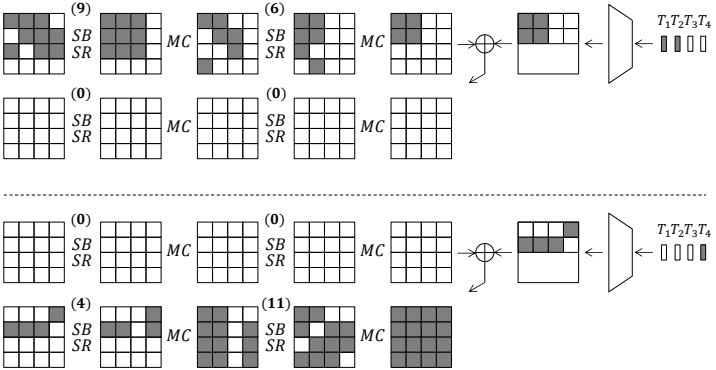

Figure: Differential Trails with 15 S-Boxes

Cryptanalysis: TweAES

Differential Propagation through 4-round core

- 4-round core: 15 Active S-Boxes
- Differential Probability: 2^{-6}
- Overall probability: 2^{-90}

- The probability of differential propagation of TweAES is bounded by 2^{-180}

TweGIFT-64 with 4-bit Tweaks

TweGIFT-64 [4,16,16,4]

- $t = 4$ bit tweak is extended to $t_e = 16$ bit tweaks
- Tweaks are affected in $tic = 16$ S-Boxes
- Tweaks are injected at bit positions $4i + 2$, for $i = 0, \ldots, 15$
- Tweaks are injected at the interval of $gap = 4$ rounds

Other Instances

Other instances TweGIFT [4,32,32,5] and TweGIFT [16,32,32,4] are defined similarly

Cryptanalysis: TweGIFT-64

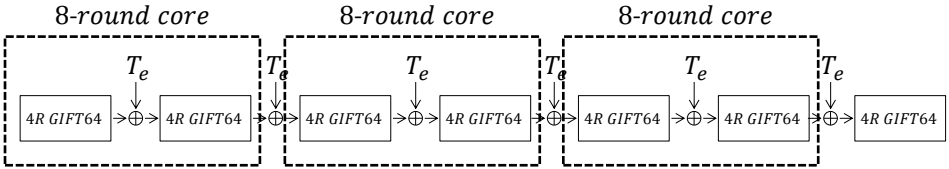

Figure: TweGIFT: 8-round Core

Differential Propagation through 8-round core

- 8-round core: 2^{-42} Differential Characteristic (next slide)

Cryptanalysis: TweGIFT-64

Table: The Best Differential Trail for 8-Round Core

Round	Differential Mask	Probability
1	0000 0000 0000 000c 0000 0000 0000 0004	2^{-2}
2	0000 0004 0000 0000 0000 0005 0000 0000	2^{-2}
3	0000 0400 0000 0100 0000 0500 0000 0500	2^{-5}
4	0000 0101 0000 0404 0000 0909 0000 0d0d	2^{-12}
tweak difference: 0808 0808 0808 0808		
5	0000 090d 0000 090d 0000 0104 0000 0104	2^{-10}
6	0000 0004 0000 0000 0000 0505 0000 0000	2^{-6}
7	0a00 0000 0000 0000 0100 0000 0000 0000	2^{-2}
8	0000 1000 0000 0000 0000 8000 0000 0000	2^{-3}

Cryptanalysis: TweGIFT-64

Differential Propagation through 8-round core

- 8-round core: 2^{-42} Differential Characteristic
- 28-round core: 2^{-126} Differential Characteristic

Differential Propagation through 10-round core

- 10-round core: $2^{-64.5}$ Differential Characteristic
- 40-round core: 2^{-258} Differential Characteristic

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Applications

Application I: Reduce the Key Size

- Reduce Key size of FCBC by replacing $(E_{K_1}, E_{K_2}, \ldots, E_{K_j})$ by $(E_K^1, E_K^2, \ldots, E_K^j)$
- State size reduction

Application II: Simplify the Design

Simplify the design of CLOC by replacing the domain separators f, g_1, g_2, h_1, h_2 (see the main paper) by varying the tweaks (4-bit tweaks are sufficient)

Reduces the complexity of the circuit (for example, by reducing Multiplexers)

Application III: Efficient Short Message Processing

- Increase the rate of LightMAC and decrease the key-size of LightMAC

Other Application: Improve SUNDAE to ESTATE

- Energy Efficiency: 1 less block cipher invocation for ESTATE
- Design Simplicity: No constant multiplication for ESTATE
- RUP Security: ESTATE is INT-RUP secure

Significance of the Result: SUNDAE vs ESTATE

- Area Efficiency:

Mode	Area (LUTs)	Throughput/Area (Mbps/LUT)
SUNDAE [GIFT]	931	0.9
ESTATE [TweGIFT]	681	1.23

- Throughput for Short Messages (16 bytes):

Mode	Throughput (Mbps)
SUNDAE [AES]	945.36
ESTATE [TweAES]	1251.1

Conclusion

Conclusion

- Short Tweak tBC Proposal
- Efficient Instance Proposal with Cryptanalysis
- Several Applications

Future Direction

- Extending the framework to ARX-based constructions
- Designing short tweak TBCs for public permutation

Thank You..!!!