KATAN & KTANTAN — A Family of Small and Efficient Hardware-Oriented Block Ciphers

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Outline

Why the AES is not Suitable for Low-end Devices

- The AES was selected at the end of a very long development effort.
- It is deemed as the block cipher to answer all symmetric keys needs in the 21st century.

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Is it?

- AES can be efficient in hardware, but the smallest implementation is 3.1 Kgates.
- AES may not be suitable in constrained environments due to other considerations.
- Cache-timing attacks may render AES unsuitable to some software environments.

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- Block ciphers
  - HIGHT, mCrypton, DESL, DES, PRESENT.
  - Can we do better?

Design Goals

- Secure block cipher
  - Differential/Linear cryptanalysis — very large safety margins.
  - Related-Key/Slide attacks — foil using no constants.
  - Related-Key differentials — do not exist.
- Efficient block cipher
  - Small foot-print
  - Low power consumption
  - Reasonable performance (+ possible speed-ups)

Really Low-end Devices

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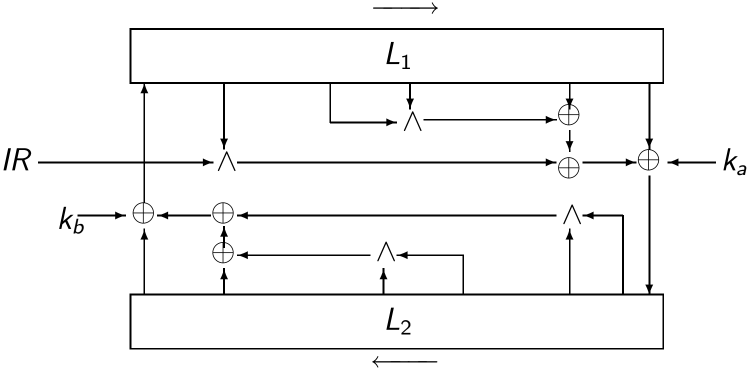
- Some low-end devices have one key throughout their life cycle.
- Why to waste good gates on their key-agility features?
- Some low-end devices are going to encrypt very little data throughout their life cycles.
- Why to waste good gates on their ability to encrypt more messages than that?

The Basic Building Blocks

- Bivium (Trivium with two registers) in a block cipher mode.
- LFSR counts rounds (rather than a counter).
- Two round functions (the one to use is controlled by a bit of the LFSR).

The Basic Building Blocks — Bivium



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- When counting the number of rounds, you can use a counter.
- n-bit counter $\Rightarrow$ $n-1$-long carry chain.
- n-bit LFSR — a bit of control logic.
- Checking end conditions: overflow in counter (carry chain longer) or special internal state (LFSR/counter).

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- *IR* is a bit which defines which of the two round functions to use.
- It toggles between two functions.
- Prevents any slide attacks, and increases diffusion.
- Uses the MSB of from the LFSR to pick the function (another advantage of an LFSR over counter).

The KATAN Block Ciphers

- KATAN has 3 flavors: KATAN-32, KATAN-48, KATAN-64.
- Block size: 32/48/64 bits.
- Key size: 80 bits.
- Share the same key schedule algorithm, and the only difference in the encryption — tap positions.
- Share same number of rounds — 254 (LFSR of 8 positions).

The KATAN Block Ciphers — Key Schedule

- Key is loaded into an 80-bit LFSR.
- Each round, the LFSR is clocked twice, and two bits are selected k_a and k_b.
- (Polynomial: $x^{80} + x^{61} + x^{50} + x^{13} + 1$).

The KATAN Block Ciphers — Tap Positions

Cipher	$\lvert L_1 \rvert$	x_1	x_2	x_3	x_4	x_5
KATAN32	13	12	7	8	5	3
KATAN48	19	18	12	15	7	6
KATAN64	25	24	15	20	11	9

Cipher	y_1	y_2	y_3	y_4	y_5	y_6
KATAN32	18	7	12	10	8	3
KATAN48	28	19	21	13	15	6
KATAN64	38	25	33	21	14	9

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- KATAN48 is clocked twice in each round (k_a and k_b are the same for both invocations).
- KATAN64 is clocked three times in each round (k_a and k_b are the same for the three invocations).

The KTANTAN Block Ciphers

- KTANTAN has 3 flavors: KTANTAN-32, KTANTAN-48, KTANTAN-64.
- Block size: 32/48/64 bits.
- Key size: 80 bits.
- KATAN-n and KTANTAN-n are the same up to key schedule.
- In KTANTAN, the key is burnt into the device and cannot be changed.

The KTANTAN Block Ciphers — Burnt Key?!?

- Many devices are deployed in such a manner that the key is initialized once and never changed.
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- Many devices are deployed in such a manner that the key is initialized once and never changed.
- Maintaining key agility is not important.
- And it saves about 80 bits of memory + 4 XOR gates for the feed back.
- For such devices, we allow the key to be burnt once, and the key schedule algorithm is composed of picking the next bit.

The KTANTAN Block Ciphers — Key Schedule

- Main problem — related-key and slide attacks.
- Solution A — two round functions, prevents slide attacks.
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- Main problem — related-key and slide attacks.
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- Solution B — divide the key into 5 words of 16 bits, pick bits in a nonlinear manner.
- Specifically, let $K = w_4||w_3||w_2||w_1||w_0$, $T = T_7 \ldots T_0$ be the round-counter LFSR, set:

$$a_i = MUX16to1(w_i, T_7T_6T_5T_4)$$

$$k_a = \overline{T_3} \cdot \overline{T_2} \cdot (a_0) \oplus (T_3 \vee T_2) \cdot MUX4to1(a_4a_3a_2a_1, T_1T_0),$$

$$k_b = \overline{T_3} \cdot T_2 \cdot (a_4) \oplus (T_3 \vee \overline{T_2}) \cdot MUX4to1(a_3a_2a_1a_0, \overline{T_1T_0})$$

Performance Analysis — A Story of a Memory Bit

- A standard D flip-flop uses 8 NAND gates.
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- Not so good idea, especially as the internal state of low-end devices takes most of the area! We use a scan flip-flop (6.25 GE/bit).

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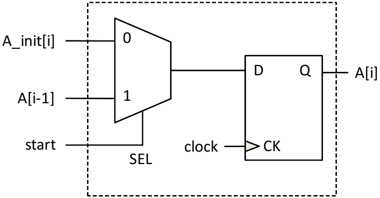

7.25 ~ 13.75 GE

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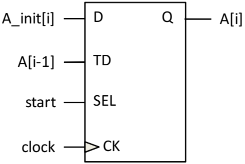

6.25 ~ 11.75 GE

Implementation Results

- We used *fsc0l_d_sc_tc* $0.13\mu m$ family standard cell library tailored for UMC's $0.13\mu m$ Low Leakage process.
- Aimed for lowest possible foot print (but also explored more throughput in exchange for more hardware).

Performance Analysis — Implementation Results (cont.)

Cipher	Block	Key	Area	GE/bit	Throughput	Logic
AES-128	128	128	3100	5.8	0.08	0.13 μm
DES	64	56	2309†	12.19	44.4	0.18 μm
DESL	64	56	1848†	12.19	44.4	0.18 μm
PRESENT-80	64	80	1570	6	200	0.18 μm
PRESENT-80	64	80	1000	N/A	11.4	0.35 μm
Grain	1	80	1294	7.25	100	0.13 μm
Trivium	1	80	749	2$^\diamondsuit$	100‡	0.35 μm
KATAN32	32	80	802	6.25	12.5	0.13 μm
KATAN48	48	80	902	6.25	18.8	0.13 μm
KATAN64	64	80	1008	6.25	25.1	0.13 μm
KTANTAN32	32	80	462	6.25	12.5	0.13 μm
KTANTAN48	48	80	562	6.25	18.8	0.13 μm
KTANTAN64	64	80	662	6.25	25.1	0.13 μm

Implementation Results (cont.)

Cipher	Block	Key	Area	GE/bit	Throughput	Logic
KATAN32	32	80	802	6.25	12.5	0.13 μm
KATAN32	32	80	846	6.25	25	0.13 μm
KATAN32	32	80	898	6.25	37.5	0.13 μm
KATAN48†	48	80	916	6.25	9.4	0.13 μm
KATAN48	48	80	927	6.25	18.8	0.13 μm
KATAN48	48	80	1002	6.25	37.6	0.13 μm
KATAN48	48	80	1080	6.25	56.4	0.13 μm
KATAN64†	64	80	1027	6.25	8.4	0.13 μm
KATAN64	64	80	1054	6.25	25.1	0.13 μm
KATAN64	64	80	1189	6.25	50.2	0.13 μm
KATAN64	64	80	1269	6.25	75.3	0.13 μm

Implementation Results (cont.)

Cipher	Block	Key	Area	GE/bit	Throughput	Logic
KTANTAN32	32	80	462	6.25	12.5	0.13 μm
KTANTAN32	32	80	673	6.25	25	0.13 μm
KTANTAN32	32	80	890	6.25	37.5	0.13 μm
KTANTAN48†	48	80	571	6.25	9.4	0.13 μm
KTANTAN48	48	80	588	6.25	18.8	0.13 μm
KTANTAN48	48	80	827	6.25	37.6	0.13 μm
KTANTAN48	48	80	1070	6.25	56.4	0.13 μm
KTANTAN64†	64	80	684	6.25	8.4	0.13 μm
KTANTAN64	64	80	688	6.25	25.1	0.13 μm
KTANTAN64	64	80	927	6.25	50.2	0.13 μm
KTANTAN64	64	80	1168	6.25	75.3	0.13 μm

Security Analysis — Security Targets

- Differential cryptanalysis — no differential characteristics with probability 2^{-n} for 127 rounds.
- Linear cryptanalysis — no approximation with bias $2^{-n/2}$ for 127 rounds.
- No related-key/slide attacks.
- No related-key differentials (probability at most 2^{-n} for the entire cipher).
- No algebraic-based attacks.

Security Analysis — Differential Cryptanalysis

- Computer-aided search for the various round combinations and all block sizes.
- KATAN32: Best 42-round char. has prob. at most 2^{-11}.
- KATAN48: Best 43-round char. has prob. at most 2^{-18}.
- KATAN64: Best 37-round char. has prob. at most 2^{-20}.

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- KATAN64: Best 37-round char. has prob. at most 2^{-20}.
- This also proves that all the differential-based attacks fail (boomerang, rectangle).

Security Analysis — Linear Cryptanalysis

- Computer-aided search for the various round combinations and all block sizes.
- KATAN32: Best 42-round approx. has prob. at most 2^{-6}.
- KATAN48: Best 43-round char. has prob. at most 2^{-10}.
- KATAN64: Best 37-round char. has prob. at most 2^{-11}.
- This also proves that differential-linear attacks fail.

Security Analysis — Slide/Related-Key Attacks

- Usually these are prevented using constants.
- In the case of KATAN/KTANTAN — solved by the irregular function use.
- In KATAN — the key "changes" (no slide).
- In KTANTAN — order of subkey bits not linear.

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- So if there are 76 key bits active — there are at least 16 quintuples, each with probability 2^{-2}.
- The key expansion is linear, so check minimal hamming weight in the code.
- Current result: lower bound: 72, upper bound: 84.

Security Analysis — Related-Key Differentials (cont.)

- In KATAN48 — each key bit difference must enter (at least) four linear operations and four non-linear ones.
- Hence, an active bit induces probability of 2^{-4}, and cancels four other bits (or probability of 2^{-8} and 6).
- Need 61 active bits in the expanded key. We have them.
- For KATAN64 — need 56.

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- Conclusion: no related-key differential in KATAN family.
- KTANTAN family: still checking computer simulations.

Questions?

Thank you for your attention!