New Directions in Dividing: Le Fabuleux Destin d'MISTY1 (The Case of MISTY1)

Computer Science Department
University of Haifa

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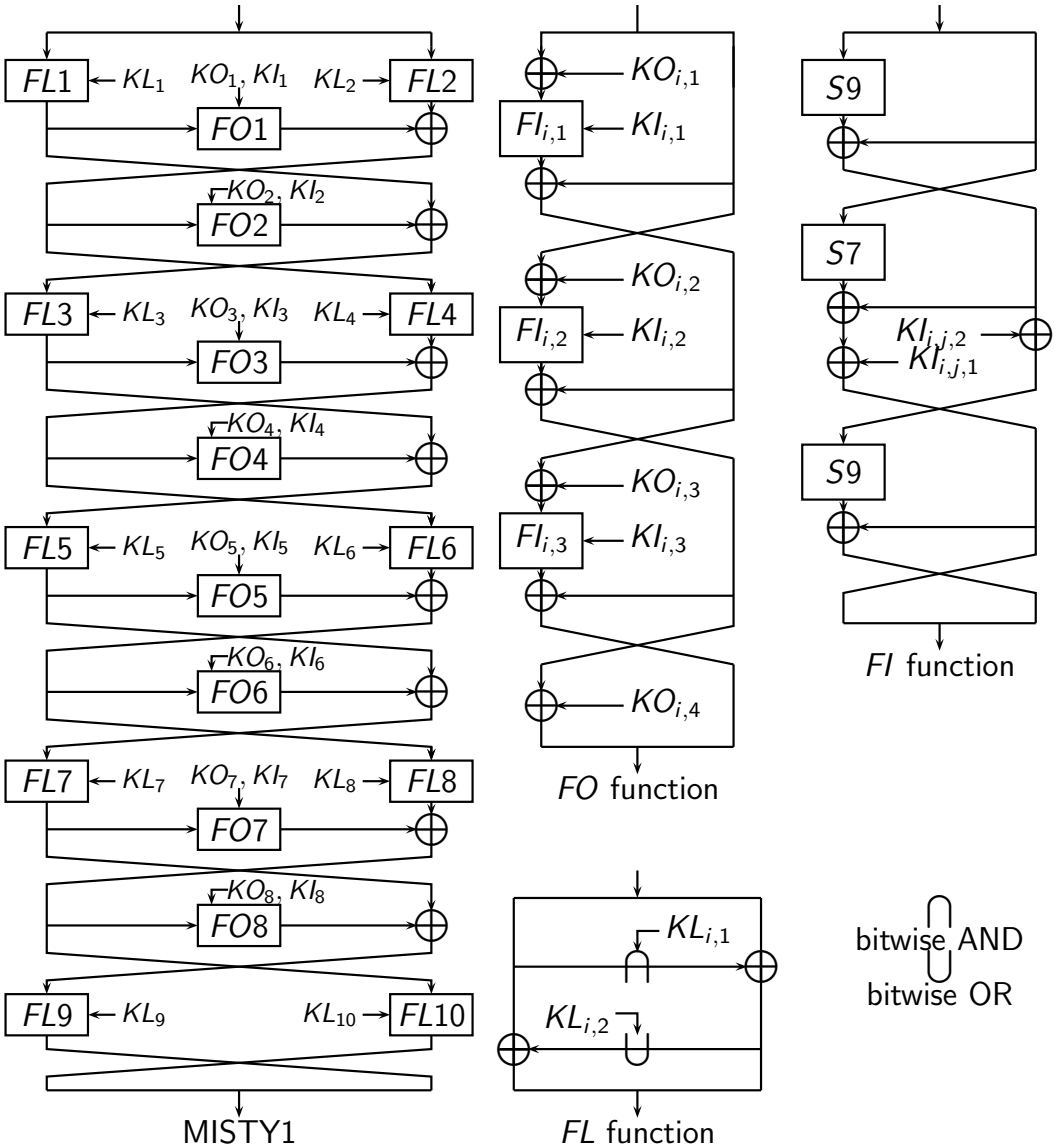
Joint work with Nathan Keller

Outline

MISTY1

- Introduced by Matsui in 1997.
- 64-bit block, 128-bit key.
- Recursive structure — 8 Feistel rounds, each round function is a 3-round Feistel function.
- Each of these semi-round functions is a 3-round Feistel on its own.
- Uses 7-bit and 9-bit S-boxes for maximal nonlinearity.
- Every two rounds there is an FL-layer.
- Cryptrec-approved, NESSIE-portfolio, RFC, ISO.
- Predecessor of KASUMI.

MISTY1


FL1
KL1
KO1, KI1
KL2
FL2
FO1
KO2, KI2
FO2
FL3
KL3
KO3, KI3
KL4
FL4
FO3
KO4, KI4
FO4
FL5
KL5
KO5, KI5
KL6
FL6
FO5
KO6, KI6
FO6
FL7
KL7
KO7, KI7
KL8
FL8
FO7
KO8, KI8
FO8
FL9
KL9
KL10
FL10
MISTY1
KO_{i,1}
FI_{i,1}
KI_{i,1}
KO_{i,2}
FI_{i,2}
KI_{i,2}
KO_{i,3}
FI_{i,3}
KI_{i,3}
KO_{i,4}
FO function
S9
S7
KI_{i,j,2}
KI_{i,j,1}
S9
FI function
KL_{i,1}
KL_{i,2}
FL function
bitwise AND
bitwise OR

MISTY1 — Key Schedule

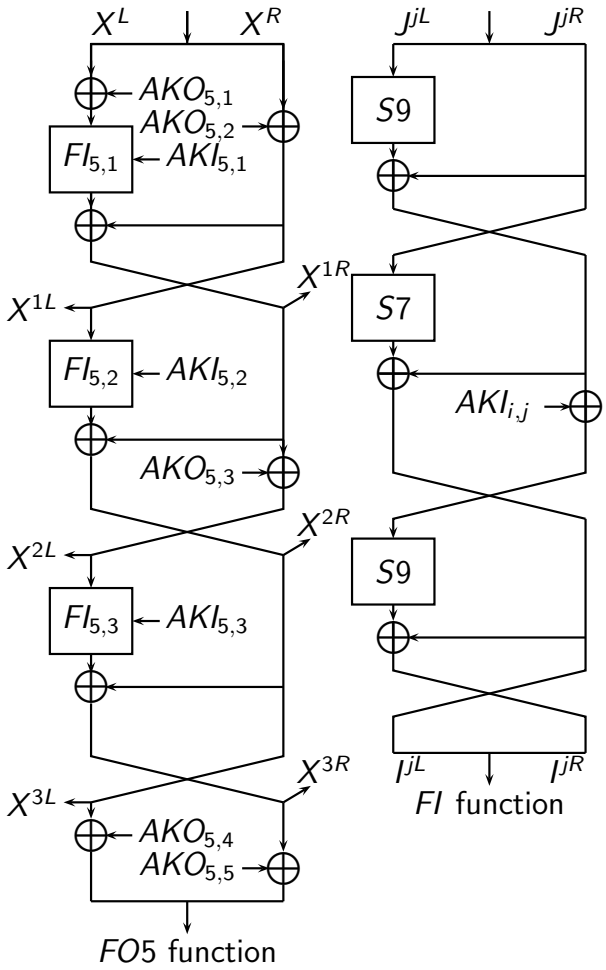
Set $K'_i = FI_{K_{i+1}}(K_i)$.

- $KO_{i,1} \leftarrow K_i$; $KO_{i,2} \leftarrow K_{i+2}$; $KO_{i,3} \leftarrow K_{i+7}$; $KO_{i,4} \leftarrow K_{i+4}$.
- $KI_{i,1} \leftarrow K'_{i+5}$; $KI_{i,2} \leftarrow K'_{i+1}$; $KI_{i+3} \leftarrow K'_{i+3}$.
- $KL_{i,1} \rightarrow i\&0x1 \ ? \ K_{\frac{i+1}{2}} : K'_{\frac{i}{2}+2}$; $KL_{i,2} \rightarrow i\&0x1 \ ? \ K'_{\frac{i+1}{2}+6} : K_{\frac{i}{2}+4}$.

MISTY1 — Equivalent *FO* Representation

Each *FO* accepts 112-bit subkey.
However, one can reduce these to a 107-bit equivalent subkey:

$$
\begin{aligned}
AKO_{i,1} &= KO_{i,1} \\
AKO_{i,2} &= KO_{i,2} \\
AKO_{i,3} &= KO_{i,2} \oplus KO_{i,3} \oplus KI'_{i,1} \\
AKO_{i,4} &= KO_{i,2} \oplus KO_{i,4} \oplus KI'_{i,1} \oplus KI'_{i,2} \\
AKO_{i,5} &= KO_{i,2} \oplus KI'_{i,1} \oplus KI'_{i,2} \oplus KI'_{i,3} \\
AKI_{i,j} &= [KI_{i,j}]_{\{8,\ldots,0\}}
\end{aligned}
$$



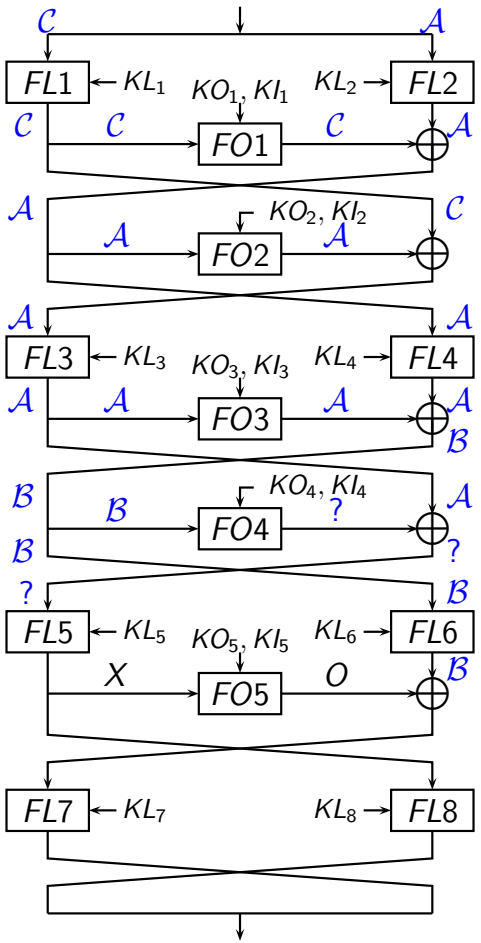
Cryptanalytic Results on MISTY1

Attack	Rounds	*FL* functions	Complexity	
			Data	Time
Impossible Differential [L+08]	6	None	2^{39} CP	2^{85}
Impossible Differential [DK08]	7	None	$2^{50.2}$ KP	$2^{114.1}$
Impossible Differential [JL12]	7	None	$2^{36.5}$ CP	$2^{92.2}$
Integral [KW02]	5	Most	2^{34} CP	2^{48}
Integral [LS09]	5	Most	2^{34} CP	$2^{27.32}$
Integral [LS09]	6	Most	2^{34} CP	$2^{108.1}$
Slicing Attack [K02]	4	All	$2^{22.25}$ CP	2^{45}
Impossible Differential [DK08]	5	All	$2^{38.6}$ CP	2^{46}
Impossible Differential [DK08]	6	All	2^{51} CP	$2^{123.4}$
Integral [LS09]	6	All	2^{32} CP	2^{126}
Impossible Differential [JL12]	6	All	$2^{52.5}$ CP	$2^{112.4}$

Practical Cryptanalytic Results on MISTY1

Attack	Rounds	*FL* functions	Complexity	
			Data	Time
Slicing Attack [K02]	4	All	$2^{22.25}$ CP	2^{45}
Higher-Order Differential [BF00]	5	None	$2^{10.5}$ CP	2^{17}
Integral [KW02]	5	Most	2^{34} CP	2^{48}
Integral [LS09]	5	Most	2^{34} CP	$2^{27.32}$
Impossible Differential [DK08]	5	All	$2^{38.6}$ CP	2^{46}
SQUARE (new)	5	All	$2^{35.6}$ CP	2^{38}
Related-Key Slide (new)	8	None	2^{18} CP	2^{18}
Related-Key Slide (new)	(any)	None	$2^{18+\epsilon}$ CP	2^{18}

A 4-Round SQUARE Property



Main Problem

- Attacking 4-round of MISTY1 using this property is straightforward.
- Attacking the fifth round when no FL is present is also quite straightforward ([KW02,LS09]).
- The problem is attacking the last round with the FL layer.
- It requires undoing the last FL layer **and** $FO5$.

Solution: Division

- Instead of checking the full SQUARE condition on 32 bits, i.e.,

$$\sum_{i=1}^{2^{32}} O_i \oplus FL7^{-1}(C_i^R) \stackrel{?}{=} 0,$$

  one can check it on a subset of the bits.
- Following Sakurai-Zheng [SZ99]:

$$\begin{aligned}\Delta O^L_{\{15,14,\ldots,9\}} &= \Delta I^{2L} \oplus \Delta X^{1R}_{\{15,14,\ldots,9\}} \\ &= \Delta I^{2L} \oplus \Delta I^{1L} \oplus \Delta X^{R}_{\{15,14,\ldots,9\}}.\end{aligned}$$

- Really useful when the last FL layer is absent ([KW02] $\leftarrow$ [LS09]).

Further Division

- The problem with the Sakurai-Zheng relation is its relying on 16 bits (I^{1L} and I^{2L} rely on AKO_1 and AKO_2, respectively).
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- This prevents successful combination with the FL-layer.
- Despite the FL-layer being easily divisible into 16 parallel functions [DK08].
- Solution: Further divide SZ into 7,9,7, and 9 bits.

Further Division (cont.)

- Actually, I^{1L} in itself, can be written as a divided property:

$$I^{1L} = S7(J^{1R}) \oplus \left(J^{1R} \oplus S9(J^{1L})\right),$$

- Similarly, we can divide I^{2L}, and obtain a more refined relation:

$$\Delta O^{L}_{\{15,14,\ldots,9\}} =$$
$$\left(J^{2R} \oplus S7(J^{2R})\right) \oplus S9(J^{2L}) \oplus \left(J^{1R} \oplus S7(J^{1R})\right) \oplus S9(J^{1L}) \oplus \Delta X^{R}_{\{15,14,\ldots,9\}}$$
$$= \underbrace{\left(S9(J^{2L}) \oplus S9(J^{1L})\right)}_{(\star)} \oplus \underbrace{\left(\left(J^{2R} \oplus S7(J^{2R})\right) \oplus \left(J^{1R} \oplus S7(J^{1R})\right)\right)}_{(\star\star)} \oplus \Delta X^{R}_{\{15,14,\ldots,9\}}$$

- One can group these into two sets — $(\star)$ and $(\star\star)$.

Further Division (cont.)

- $(\star)$ depends only on 9 leftmost bits of both halves entering $FO5$ and 9 bits of $AKO_{5,1}$ and $AKO_{5,2}$.
- Likewise $(\star\star)$ depends only on the 7 rightmost bits.
- Following the structure of the FL function, one needs to know only 18 subkey bits to evaluate $(\star)$ and 14 to evaluate $(\star\star)$.
- So we can run a MitM on the relation:

$$\underbrace{\left(\sum FL7^{-1}(C^R)\right)_{\{31,30,\ldots,25\}} \oplus \sum \left((J^{2R} \oplus S7(J^{2R})) \oplus (J^{1R} \oplus S7(J^{1R}))\right) =}_{LHS}$$
$$\underbrace{\sum \left[(S9(J^{2L}) \oplus S9(J^{1L})) \oplus \sum X^R_{\{15,14,\ldots,9\}}\right]}_{RHS}.$$

Attack on 5-Round MISTY1

- A naïve implementation would need 2^{36} trials for each structure.
- This results in time of about $2^{36} \cdot 2^{32} \cdot 12 = 2^{71.6}$ operations.
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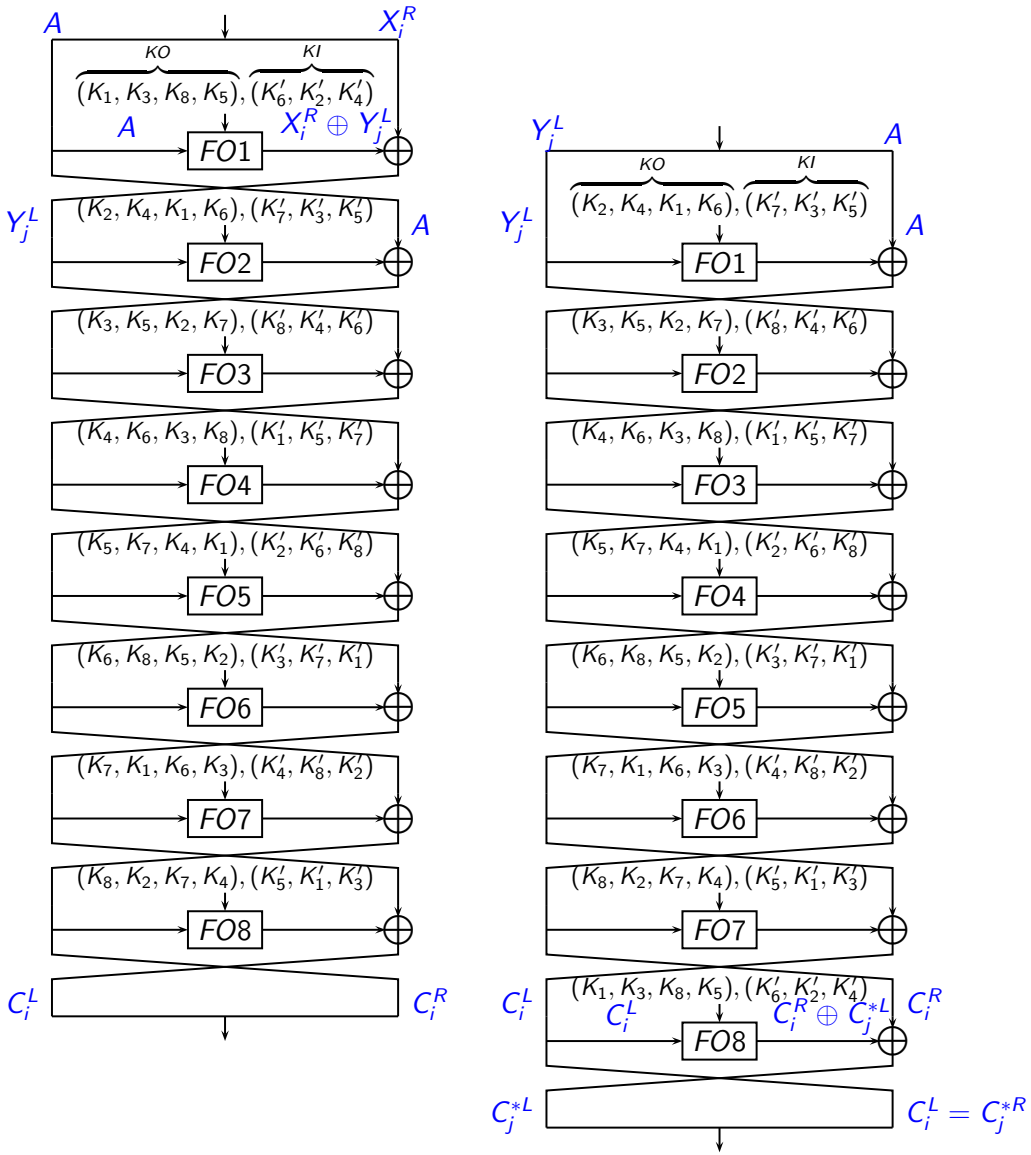
- Outcome: 71-key bits are found using $2^{35.6}$ CPs, 2^{38} time and $2^{36.6}$ 64-bit blocks of memory.
- The remaining key bits can be easily found practically for free.

The Related-Key Relation



Some Basic Problems

- By picking 2^{18} CPs, one expects 4 "slid" pairs, and 4 wrong pairs to pass basic filtering.
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- By picking 2^{18} CPs, one expects 4 "slid" pairs, and 4 wrong pairs to pass basic filtering.
- One needs to attack 107-bit subkey, so the standard approach yields attacks of 2^{111} operations or so.
- However, we can (almost certainly) identify the "slid" pairs.
- Same input to first round $\Rightarrow$ same output.
- Sort these pairs according to the suggested output of the first round.

Attack Algorithm

- Assume at least three "slid" pairs exist (probability 76%).
- We obtain four input-output pairs to $FO1$.
- And we apply our divided Sakurai-Zheng relation, retrieving $AKO_{1,1}$ and $AKO_{1,2}$ in MitM.
- For the remaining candidates — apply the full Sakurai-Zheng relation (using the other 9 bits) to retrieve $AKI_{1,1}$ and $AKI_{1,2}$.
- Follow with similar analysis to retrieve $AKI_{1,3}$, and deduce $AKO_{1,4}$ and $AKO_{1,5}$.
- One solution is expected to exist.
- This approach yields 107 bits of the key in 2^{18} time.

Partial Experimental Verification

- We started by verifying we get the right "slid" pairs proportions.
- We run the experiment with MISTY1 code submitted to NESSIE by Mitsubishi.
- 1,000,000 keys, 2^{18} plaintexts (4 expected "slid" pairs).
- We expected that the number of "slid" pairs follows a Poisson distribution with a mean value of 4.

Partial Experimental Verification (cont.)

"Slid" Pairs	0	1	2	3	4	5
Theory ($Poi(4)$)	18,316	73,263	146,525	195,367	195,367	156,293
Experiment	18,324	73,461	146,699	195,390	194,541	156,609
"Slid" Pairs	6	7	8	9	10	11
Theory ($Poi(4)$)	104,196	59,540	29,770	13,231	5,292	1,925
Experiment	104,266	59,338	29,860	13,330	5,348	1,916
"Slid" Pairs	12	13	14	15	16	17
Theory ($Poi(4)$)	641	197	56	15	4	1
Experiment	657	190	54	15	2	0

Application to Other Variants of MISTY1

- Any number of rounds (may need to increase number of "slid" pairs to 4, in exchange full key is recovered).
- *FL* after each round — either combine with previous attack for a 2^{68} attack or use [BDK08] and 8 related keys (at most) for an attack of 2^{36} time and 2^{24} ACPCs (worst case).
- Does not apply to KASUMI (round constants in key schedule).

Three Identified Weaknesses in MISTY1

1. The 3-round Feistel structure of the *FO* and *FI* functions: admits division of *FO* into four smaller parts of $7, 9, 7, 9$ bits each with limited interaction.
2. The *FL* function can be divided into sixteen 2-bit functions applied in parallel. (same holds for a sequential application of several *FL* functions).
3. The key schedule of *MISTY*1 without the *FL* functions lacks round constants, and hence, makes this variant susceptible to related-key slide attacks.

In Comparison — KASUMI

1. The *FI* function was strengthened by adding a fourth round to the Feistel structure, while the *FO* function remained with a 3-round structure. (5-round SQUARE attack is now 2^{68}).
2. A rotation by one bit was added to the *FL* function, thus making it impossible to divide it into 16 independent functions.
3. Round constants were inserted into the round subkeys, thwarting the related-key slide attack completely.
4. On the other hand, the key schedule was simplified, which led to a practical-time related-key attack on the full KASUMI, which does not apply to MISTY1.

Conclusions

- New practical attack on 5-round MISTY1.
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- New practical attack on 5-round MISTY1.
- New (very practical) related-key attack on 8-round MISTY1 with no *FL* functions.
- First case of a related-key attack on a "reasonable" cipher which is practical.
- TODO: Finalize the verification of the attack.

Questions?

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