A New Structural-Differential Property of 5-Round AES

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Introduction

AES is probably the most widely studied and used block cipher.

So far, non-random properties which are independent of the secret key are known for up to 4 rounds of AES.

We propose a new structural property for up to 5 rounds of AES which is independent of the secret key.

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Part I

Secret-Key Distinguisher up to 5 Rounds of AES

AES

High-level description of AES:

- block cipher based on a design principle known as *substitution-permutation network*;
- block size of 128 bits = 16 bytes, organized in a 4×4 matrix;
- key size of 128/192/256 bits;
- 10/12/14 rounds:

$$R^i(x) = k^i \oplus MC \circ SR \circ \text{S-Box}(x).$$

Secret-Key Distinguisher

Secret-Key Distinguisher: one of the weakest cryptographic attack.

Setting: *Two Oracles*:

- one simulates the block cipher for which the cryptography key has been chosen at random;
- the other simulates a truly random permutation.

Goal: distinguish the two oracles, i.e. decide which oracle is the cipher.

Secret-Key Distinguishers are usually starting points for Key-Recovery Attacks.

Secret-Key Distinguisher up to 4-round AES

Up to 4-round AES, Secret-Key Distinguisher exploits one of the following property:

- Truncated Differential;
- Integral/Zero Sum;
- Impossible Differential.

They are all independent of the secret key.

Secret-Key Distinguisher on 4-round AES - Details

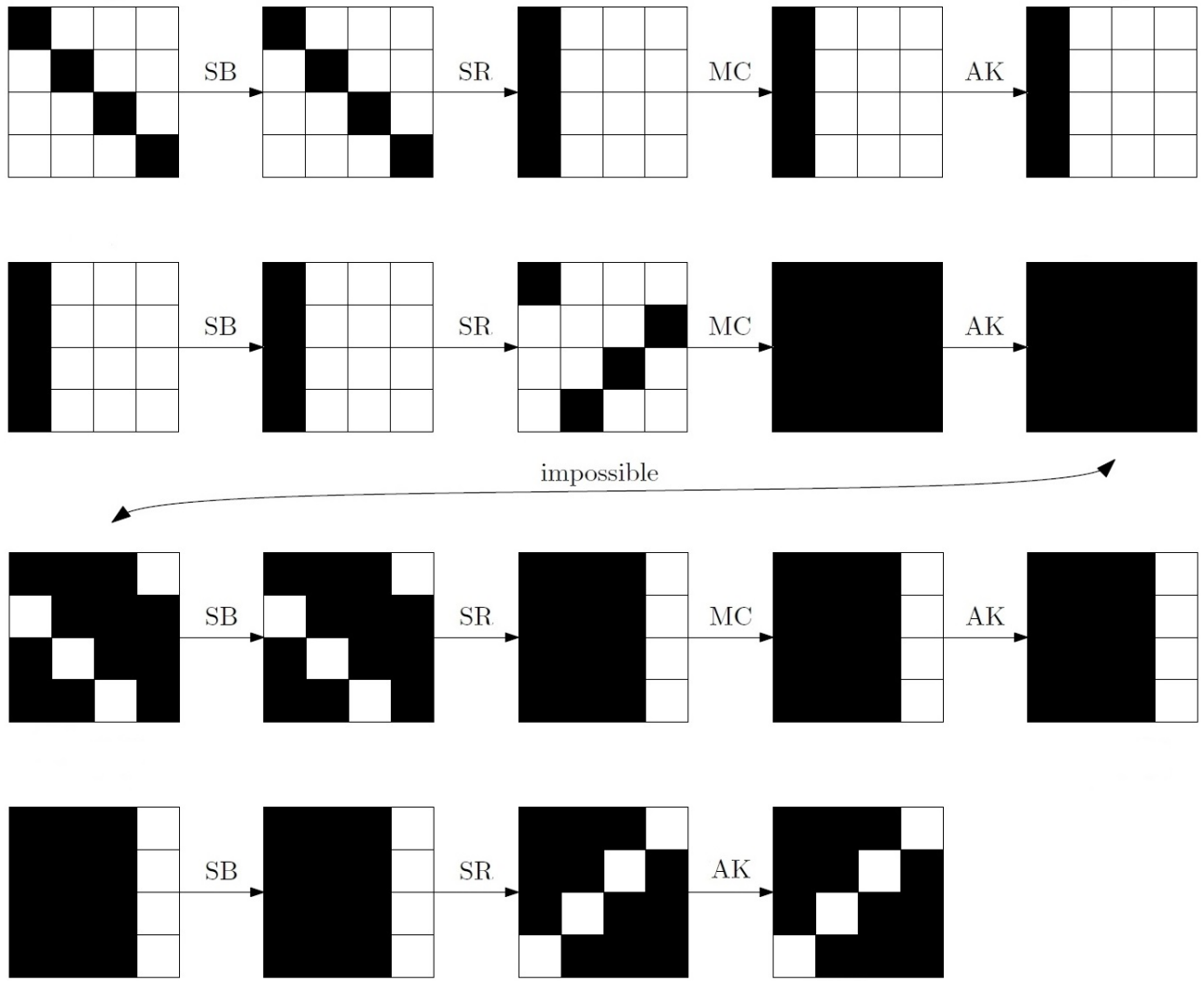
Secret-Key Distinguisher on 4-round AES:

- Integral Property [**DKR97**]
- Impossible Differential Property [**BK00**].

Consider a set of 2^{32} plaintexts with one active diagonal:

$$\begin{bmatrix} A & C & C & C \\ C & A & C & C \\ C & C & A & C \\ C & C & C & A \end{bmatrix}.$$

Impossible Differential Distinguisher [**BK00**]



Balance/Zero-Sum Property [**DKR97**]

$$\begin{bmatrix} A & C & C & C \\ C & A & C & C \\ C & C & A & C \\ C & C & C & A \end{bmatrix} \xrightarrow{R^4(\cdot)} \begin{bmatrix} B & B & B & B \\ B & B & B & B \\ B & B & B & B \\ B & B & B & B \end{bmatrix} \xrightarrow{R(\cdot)} ?$$

Given the same initial set of plaintexts, is there any property which is independent of the secret key after 5-round AES?

Balance/Zero-Sum Property [**DKR97**]

$$\begin{bmatrix} A & C & C & C \\ C & A & C & C \\ C & C & A & C \\ C & C & C & A \end{bmatrix} \xrightarrow{R^4(\cdot)} \begin{bmatrix} B & B & B & B \\ B & B & B & B \\ B & B & B & B \\ B & B & B & B \end{bmatrix} \xrightarrow{R(\cdot)} ?$$

Given the same initial set of plaintexts, is there any property which is independent of the secret key after 5-round AES?

Related Work on 5 rounds of AES

Key-Recovery Attack can be used as Secret-Key Distinguisher:

- the knowledge of the entire key is (usually) necessary to distinguish the block cipher from the random permutation.

At CRYPTO 2016, Sun, Liu, Gou, Qu and Rijmen [**SMG+16**] proposed a *Zero-Sum Distinguisher for 5-round AES* that

- depends on *one byte - not all - of the secret key* to distinguish 5-round AES from the random permutation;
- is independent of the S-Box but not of the MixColumns matrix;
- requires the full codebook.

Structural Property for 5 Rounds of AES

Assume 5-round AES without the final MixColumns operation.

Theorem

Consider a set of 2^{32} chosen plaintexts with one active diagonal. Let n the number of different pairs of ciphertexts which are equal in one (fixed) anti-diagonal.
The number n is a multiple of 8 with probability 1, i.e. $\exists\, n' \in \mathbb{N}$ s.t. $n = 8 \cdot n'$, ***independently of the secret key, of the details of S-Box and of MixColumns matrix*** *(assuming branch number equal to 5).*

A similar result holds also in decryption direction (i.e. using chosen ciphertexts instead of plaintexts).

Distinguisher on 5-round of AES (1/2)

Goal: Distinguish 5-round of AES from random permutation.

Consider 2^{32} plaintexts with one active diagonal.

Count the number n of pairs of ciphertexts (after 5 rounds) which are equal in one (fixed) anti-diagonal.

If $n \bmod 8 \neq 0$, then the permutation is a random one.

Distinguisher on 5-round of AES (2/2)

To distinguish 5-round AES from a random permutation with probability of success higher than 99.5%:

- data cost: 2^{32} chosen plaintexts/ciphertexts;
- computational cost: $2^{35.6}$ table look-ups on table of size 2^{36} bytes.

Practically verified

`https://github.com/Krypto-iaik/AES_5round_SKdistinguisher`

Part II

A Formal Description

Subspace Trails for AES [**GRR16**] (FSE 2017)

We define the following subspaces:

- column space $\mathcal{C}_I$;
- *diagonal space* $\mathcal{D}_I$;
- *inverse-diagonal space* $\mathcal{ID}_I$;
- *mixed space* $\mathcal{M}_I$.

The Diagonal Space

Definition

The *diagonal spaces* $\mathcal{D}_i$ for $i \in \{0, 1, 2, 3\}$ are defined as

$$\mathcal{D}_i = \langle e_{0,i}, e_{1,(i+1)}, e_{2,(i+2)}, e_{3,(i+3)} \rangle.$$

E.g. $\mathcal{D}_0$ corresponds to symbolic matrix

$$\mathcal{D}_0 \equiv \begin{bmatrix} x_1 & 0 & 0 & 0 \\ 0 & x_2 & 0 & 0 \\ 0 & 0 & x_3 & 0 \\ 0 & 0 & 0 & x_4 \end{bmatrix}$$

for all $x_1, x_2, x_3, x_4 \in \mathbb{F}_{2^8}$.

Meaning of "$p^1 \oplus p^2 \in \mathcal{D}_i$"

Texts p^1 and p^2 belong in $\mathcal{D}_i \oplus a$ (i.e. a *coset* of $\mathcal{D}_i$)

$$p^1, p^2 \in \mathcal{D}_i \oplus a \equiv \{x \oplus a \,|\, \forall x \in \mathcal{D}_i\}$$

if and only if $p^1 \oplus p^2 \in \mathcal{D}_i$, that is p^1 and p^2 are equal in all bytes expect for ones in the i-th diagonal.

E.g. $p^1, p^2 \in \mathcal{D}_0 \oplus a$ iff $p^1 \oplus p^2 \in \mathcal{D}_0$ iff

$$p^1 \oplus p^2 \equiv \begin{bmatrix} ? & 0 & 0 & 0 \\ 0 & ? & 0 & 0 \\ 0 & 0 & ? & 0 \\ 0 & 0 & 0 & ? \end{bmatrix}$$

The Inverse-Diagonal Space

Definition

The *inverse-diagonal spaces* $\mathcal{ID}_i$ for $i \in \{0, 1, 2, 3\}$ are defined as

$$\mathcal{ID}_i = \langle e_{0,i}, e_{1,(i-1)}, e_{2,(i-2)}, e_{3,(i-3)} \rangle.$$

E.g. $\mathcal{ID}_0$ corresponds to symbolic matrix

$$\mathcal{ID}_0 \equiv \begin{bmatrix} x_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & x_2 \\ 0 & 0 & x_3 & 0 \\ 0 & x_4 & 0 & 0 \end{bmatrix}$$

for all $x_1, x_2, x_3, x_4 \in \mathbb{F}_{2^8}$.

The Mixed Space

Definition

The *i-th mixed spaces* $\mathcal{M}_i$ for $i \in \{0, 1, 2, 3\}$ are defined as

$$\mathcal{M}_i = MC(\mathcal{ID}_i).$$

E.g. $\mathcal{M}_0$ corresponds to symbolic matrix

$$\mathcal{M}_0 \equiv \begin{bmatrix} 0x02 \cdot x_1 & x_4 & x_3 & 0x03 \cdot x_2 \\ x_1 & x_4 & 0x03 \cdot x_3 & 0x02 \cdot x_2 \\ x_1 & 0x03 \cdot x_4 & 0x02 \cdot x_3 & x_2 \\ 0x03 \cdot x_1 & 0x02 \cdot x_4 & x_3 & x_2 \end{bmatrix}$$

for all $x_1, x_2, x_3, x_4 \in \mathbb{F}_{2^8}$.

Subspace Trail for AES

For $I \subseteq \{0, 1, 2, 3\}$, let $\mathcal{D}_I$, $\mathcal{ID}_I$ and $\mathcal{M}_I$ defined as:

$$\mathcal{D}_I = \bigoplus_{i \in I} \mathcal{D}_i, \qquad \mathcal{ID}_I = \bigoplus_{i \in I} \mathcal{ID}_i, \qquad \mathcal{M}_I = \bigoplus_{i \in I} \mathcal{M}_i.$$

Theorem

For each $a \in \mathcal{D}_I$, there exists (unique) $b \in \mathcal{M}_I$ s.t.

$$R^2(\mathcal{D}_I \oplus a) = \mathcal{M}_I \oplus b.$$

Equivalently, for each x, y:

$$Prob(R^2(x) \oplus R^2(y) \in \mathcal{M}_I \mid x \oplus y \in \mathcal{D}_I) = 1.$$

Subspace Trail for AES

For $I \subseteq \{0, 1, 2, 3\}$, let $\mathcal{D}_I$, $\mathcal{ID}_I$ and $\mathcal{M}_I$ defined as:

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Equivalently, for each x, y:

$$Prob(R^2(x) \oplus R^2(y) \in \mathcal{M}_I \,|\, x \oplus y \in \mathcal{D}_I) = 1.$$

Structural Property for 5 Rounds of AES

Given $\mathcal{D}_I \oplus a$ (i.e. a coset of $\mathcal{D}_I$), consider all the $2^{32\cdot|I|}$ plaintexts and the corresponding ciphertexts after 5 rounds, i.e. $(p^i, c^i \equiv R^5(p^i))$ for $i = 0, ..., 2^{32\cdot|I|} - 1$ where $p^i \in \mathcal{D}_I \oplus a$.

Theorem

For a fixed $J \subseteq \{0, 1, 2, 3\}$, let n the number of different pairs of ciphertexts (c^i, c^j) for $i \neq j$ such that $c^i \oplus c^j \in \mathcal{M}_J$

$$n := |\{(p^i, c^i), (p^j, c^j) \,|\, \forall p^i, p^j \in \mathcal{D}_I \oplus a,\ p^i < p^j \text{ and } c^i \oplus c^j \in \mathcal{M}_J\}|.$$

The number n is a multiple of 8, i.e. $\exists\, n' \in \mathbb{N}$ s.t. $n = 8 \cdot n'$, ***independently of the secret key, of the details of S-Box and of MixColumns matrix*** *(assuming branch number equal to 5).*

Part III

Sketch of the Proof

Reduction to a Single Round (1/2)

Remember:

$$R^2(\mathcal{D}_I \oplus a) = \mathcal{M}_I \oplus b$$

and for each x, y:

$$Prob(R^2(x) \oplus R^2(y) \in \mathcal{M}_I \,|\, x \oplus y \in \mathcal{D}_I) = 1.$$

Since

$$\mathcal{D}_I \oplus a \xrightarrow[\text{prob. 1}]{R^2(\cdot)} \mathcal{M}_I \oplus b \xrightarrow{R(\cdot)} \mathcal{D}_J \oplus a' \xrightarrow[\text{prob. 1}]{R^2(\cdot)} \mathcal{M}_J \oplus b',$$

we can focus only on the middle round!

Reduction to a Single Round (1/2)

Remember:

$$R^2(\mathcal{D}_I \oplus a) = \mathcal{M}_I \oplus b$$

and for each x, y:

$$Prob(R^2(x) \oplus R^2(y) \in \mathcal{M}_I \,|\, x \oplus y \in \mathcal{D}_I) = 1.$$

Since

$$\mathcal{D}_I \oplus a \xrightarrow[\text{prob. 1}]{R^2(\cdot)} \mathcal{M}_I \oplus b \xrightarrow{R(\cdot)} \mathcal{D}_J \oplus a' \xrightarrow[\text{prob. 1}]{R^2(\cdot)} \mathcal{M}_J \oplus b',$$

we can focus only on the middle round!

Reduction to a Single Round (2/2)

Given $\mathcal{M}_I \oplus a$, consider all the $2^{32\cdot|I|}$ plaintexts and the corresponding ciphertexts after 1 round, i.e. $(p^i, c^i \equiv R(p^i))$ for $i = 0, ..., 2^{32\cdot|I|} - 1$ where $p^i \in \mathcal{M}_I \oplus a$.

Lemma

Let n the number of different pairs of ciphertexts (c^i, c^j) *for* $i \neq j$ *such that* $c^i \oplus c^j \in \mathcal{D}_J$

$$n := |\{(p^i, c^i), (p^j, c^j) \,|\, \forall p^i, p^j \in \mathcal{M}_I \oplus a,\ p^i < p^j \text{ and } c^i \oplus c^j \in \mathcal{D}_J\}|.$$

The number n is a multiple of 8*, independently of the secret key, of the details of S-Box and of MixColumns matrix (assuming branch number equal to 5).*

Sketch of the Proof

W.l.o.g. $I = \{0\}$.

Given $p^1, p^2 \in \mathcal{M}_0 \oplus a$, there exist $x^1, y^1, z^1, w^1 \in \mathbb{F}_{2^8}$ and $x^2, y^2, z^2, w^2 \in \mathbb{F}_{2^8}$ s.t.:

$$p^i = a \oplus \begin{bmatrix} 2 \cdot x^i & y^i & z^i & 3 \cdot w^i \\ x^i & y^i & 3 \cdot z^i & 2 \cdot w^i \\ x^i & 3 \cdot y^i & 2 \cdot z^i & w^i \\ 3 \cdot x^i & 2 \cdot y^i & z^i & w^i \end{bmatrix},$$

for $i = 1, 2$ and where $2 \equiv 0\text{x}02$ and $3 \equiv 0\text{x}03$.

For the following: p^1 "$\equiv$" $\langle x^1, y^1, z^1, w^1 \rangle$ and p^2 "$\equiv$" $\langle x^2, y^2, z^2, w^2 \rangle$.

Sketch of the Proof

Study the following cases:

- 3 variables are equal, e.g. $x^1 \neq x^2$ and $y^1 = y^2$, $z^1 = z^2$, $w^1 = w^2$;
- 2 variables are equal, e.g. $x^1 \neq x^2$,$y^1 \neq y^2$ and $z^1 = z^2$, $w^1 = w^2$;
- 1 variable is equal, e.g. $x^1 \neq x^2$, $y^1 \neq y^2$, $z^1 \neq z^2$ and $w^1 = w^2$;
- all variables are different, e.g. $x^1 \neq x^2$, $y^1 \neq y^2$, $z^1 \neq z^2$, $w^1 \neq w^2$.

If 3 variables are equal, then $R(p^1) \oplus R(p^2) = c^1 \oplus c^2 \notin \mathcal{D}_J$ with prob. 1.

Sketch of the Proof

Study the following cases:

- 3 variables are equal, e.g. $x^1 \neq x^2$ and $y^1 = y^2$, $z^1 = z^2$, $w^1 = w^2$;
- 2 variables are equal, e.g. $x^1 \neq x^2$,$y^1 \neq y^2$ and $z^1 = z^2$, $w^1 = w^2$;
- 1 variable is equal, e.g. $x^1 \neq x^2$, $y^1 \neq y^2$, $z^1 \neq z^2$ and $w^1 = w^2$;
- all variables are different, e.g. $x^1 \neq x^2$, $y^1 \neq y^2$, $z^1 \neq z^2$, $w^1 \neq w^2$.

If 3 variables are equal, then $R(p^1) \oplus R(p^2) = c^1 \oplus c^2 \notin \mathcal{D}_J$ with prob. 1.

Sketch of the Proof (2 variables are different)

W.l.o.g. consider $p^1 \equiv \langle x^1, y^1, z, w \rangle$ and $p^2 \equiv \langle x^2, y^2, z, w \rangle$.
$R(p^1) \oplus R(p^2) \in \mathcal{D}_J$ if and only if

$$R(\hat{p}^1) \oplus R(\hat{p}^2) \in \mathcal{D}_J$$

where

$$\hat{p}^1 \equiv \langle x^1, y^2, z, w \rangle, \qquad \hat{p}^2 \equiv \langle x^2, y^1, z, w \rangle.$$

It is sufficient to prove that $R(p^1) \oplus R(p^2) = R(\hat{p}^1) \oplus R(\hat{p}^2)$.

$$\begin{aligned}
&(R(p^1) \oplus R(p^2))_{0,0} = \\
=&2 \cdot [\text{S-Box}(2 \cdot x^1 \oplus a_{0,0}) \oplus \text{S-Box}(2 \cdot x^2 \oplus a_{0,0})] \oplus \\
&\oplus 3 \cdot [\text{S-Box}(y^1 \oplus a_{1,1}) \oplus \text{S-Box}(y^2 \oplus a_{1,1})] = \\
=&(R(\hat{p}^1) \oplus R(\hat{p}^2))_{0,0}.
\end{aligned}$$

Sketch of the Proof (2 variables are different)

Given $p^1 \equiv \langle x^1, y^1, z, w \rangle$ and $p^2 \equiv \langle x^2, y^2, z, w \rangle$,
$R(p^1) \oplus R(p^2) \in \mathcal{D}_J$ if and only if

$$R(\hat{p}^1) \oplus R(\hat{p}^2) \in \mathcal{D}_J$$

where

$$\hat{p}^1 \equiv \langle x^1, y^1, z, w \rangle, \qquad \hat{p}^2 \equiv \langle x^2, y^2, z, w \rangle$$

or

$$\hat{p}^1 \equiv \langle x^1, y^2, z, w \rangle, \qquad \hat{p}^2 \equiv \langle x^2, y^1, z, w \rangle$$

for all $z, w \in \mathbb{F}_{2^8}$.

Note: $p^1 \equiv \langle x^1, y^1, z, w \rangle$ and $p^2 \equiv \langle x^2, y^2, z, w \rangle$ such that
$R(p^1) \oplus R(p^2) \in \mathcal{D}_J$ can exist if and only if $|J| \geq 3$.

Sketch of the Proof (3 variables are different)

W.l.o.g. consider $p^1 \equiv \langle x^1, y^1, z^1, w \rangle$ and $p^2 \equiv \langle x^2, y^2, z^2, w \rangle$.
$R(p^1) \oplus R(p^2) \in \mathcal{D}_J$ if and only if $R(\hat{p}^1) \oplus R(\hat{p}^2) \in \mathcal{D}_J$ where

$$\begin{aligned}
\hat{p}^1 &\equiv \langle x^1, y^1, z^1, w \rangle, & \hat{p}^2 &\equiv \langle x^2, y^2, z^2, w \rangle \\
\hat{p}^1 &\equiv \langle x^2, y^1, z^1, w \rangle, & \hat{p}^2 &\equiv \langle x^1, y^2, z^2, w \rangle \\
\hat{p}^1 &\equiv \langle x^1, y^2, z^1, w \rangle, & \hat{p}^2 &\equiv \langle x^2, y^1, z^2, w \rangle \\
\hat{p}^1 &\equiv \langle x^1, y^1, z^2, w \rangle, & \hat{p}^2 &\equiv \langle x^2, y^2, z^1, w \rangle
\end{aligned}$$

for each $w \in \mathbb{F}_{2^8}$.

Note: $p^1 \equiv \langle x^1, y^1, z^1, w \rangle$ and $p^2 \equiv \langle x^2, y^2, z^2, w \rangle$ such that $R(p^1) \oplus R(p^2) \in \mathcal{D}_J$ can exist if and only if $|J| \geq 2$.

Sketch of the Proof (4 variables are different)

W.l.o.g. consider $p^1 \equiv \langle x^1, y^1, z^1, w^1 \rangle$ and $p^2 \equiv \langle x^2, y^2, z^2, w^2 \rangle$.
$R(p^1) \oplus R(p^2) \in \mathcal{D}_J$ if and only if $R(\hat{p}^1) \oplus R(\hat{p}^2) \in \mathcal{D}_J$ where

$$\hat{p}^1 \equiv \langle x^2, y^1, z^1, w^1 \rangle, \quad \hat{p}^2 \equiv \langle x^1, y^2, z^2, w^2 \rangle;$$
$$\hat{p}^1 \equiv \langle x^1, y^2, z^1, w^1 \rangle, \quad \hat{p}^2 \equiv \langle x^2, y^1, z^2, w^2 \rangle;$$
$$\hat{p}^1 \equiv \langle x^1, y^1, z^2, w^1 \rangle, \quad \hat{p}^2 \equiv \langle x^2, y^2, z^1, w^2 \rangle;$$
$$\hat{p}^1 \equiv \langle x^1, y^1, z^1, w^2 \rangle, \quad \hat{p}^2 \equiv \langle x^2, y^2, z^2, w^1 \rangle;$$
$$\hat{p}^1 \equiv \langle x^1, y^1, z^2, w^2 \rangle, \quad \hat{p}^2 \equiv \langle x^2, y^2, z^1, w^1 \rangle;$$
$$\hat{p}^1 \equiv \langle x^1, y^2, z^1, w^2 \rangle, \quad \hat{p}^2 \equiv \langle x^2, y^1, z^2, w^1 \rangle;$$
$$\hat{p}^1 \equiv \langle x^1, y^2, z^2, w^1 \rangle, \quad \hat{p}^2 \equiv \langle x^2, y^1, z^1, w^2 \rangle.$$

Note: $p^1 \equiv \langle x^1, y^1, z^1, w^1 \rangle$ and $p^2 \equiv \langle x^2, y^2, z^2, w^2 \rangle$ such that $R(p^1) \oplus R(p^2) \in \mathcal{D}_J$ can exist if and only if $|J| \geq 1$.

Sketch of the Proof

$$n := |\{(p^i, c^i), (p^j, c^j) \,|\, \forall p^i, p^j \in \mathcal{M}_I \oplus a,\ p^i < p^j \text{ and } c^i \oplus c^j \in \mathcal{D}_J\}|.$$

- If $|J| = 1$, then $n = 8 \cdot n'$;
- If $|J| = 2$, then $n = 8 \cdot n' + 4 \cdot 2^8 \cdot n''$;
- If $|J| = 3$, then $n = 8 \cdot n' + 4 \cdot 2^8 \cdot n'' + 2 \cdot 2^{16} \cdot n'''$.

The number of collisions n is a multiple of 8 independently of I, J, the secret key, the details of the S-Box and the MixColumns operation (expect for the branch number equal to 5).

Part IV

Open Problems

Open Problems

First 5-round Secret-Key Distinguisher for AES independent of the secret key.

Open Problems:

- Set up a *6-round Secret-Key Distinguisher for AES* independent of the secret key;
- Set up a *key recovery attack that exploits this 5-round secret key distinguisher* (or a modified version of it);
- Apply “similar” distinguisher to other constructions.

Thanks for your attention!

Questions?

Comments?

Partial Order of the Plaintexts

Definition

Given two different texts t^1 and t^2, we say that $t^1 \leq t^2$ if $t^1 = t^2$ or if there exists $i, j \in \{0, 1, 2, 3\}$ such that

1. $t^1_{k,l} = t^2_{k,l}$ for all $k, l \in \{0, 1, 2, 3\}$ with $k + 4 \cdot l < i + 4 \cdot j$
2. $t^1_{i,j} < t^2_{i,j}$.

If $t^1 \leq t^2$ and $t^1 \neq t^2$, then $t^1 < t^2$.

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