Revisiting the Transferability of Chosen- to Known-plaintext Attacks and Applications to Round-reduced AES

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Abstract. Differential-based attacks represent the best known results for many block ciphers. Such attacks usually demand that the adversary can choose plaintexts (CP) or ciphertexts (CC) in subspaces to satisfy differential trails. However, many widespread modes of operation or applications prohibit the adversary from directly choosing inputs for the majority of primitive calls. While Biham and Shamir already suggested a straightforward trade-off for standard differential attacks in their work on the DES, studies on advanced differential-based types, such as impossible-differential, rectangle, or mixture attacks, have surprisingly received little attention so far.
In this work, we study applications of differential-based attacks in the random known-plaintext model (RKP) of the above. For the AES as the probably most widespread block cipher, we derive the best existing distinguishers and attacks in the RKP model on all versions, improving earlier results by at least one round. Interestingly, we show that Demirci-Selçuk meet-in-the-middle attacks with differential enumeration, which require much related data, can also be effective in that setting without approaching the full codebook too closely. For several of our attacks, we showcase differences between the models as trails that lead to the best known attack complexities under chosen data are suboptimal in the RKP model, and can be replaced by better trails. While our results do not threaten the security of the full AES, and their complexities are too high to represent any threats, we hope to inspire cryptographers to also consider attacks in the RKP for future attacks.

Keywords: Differential cryptanalysis · block cipher · AES

1 Introduction

1.1 Block-cipher Attack Settings

Block ciphers are the workhorses of symmetric-key cryptography, with various applications for manifold cryptographic goals from encryption, authentication,

integrity, or one-wayness in complex protocols. Consequently, a thorough understanding of their security against known attacks is a critical task. In particular, the security of the Advanced Encryption Standard (AES) [20,56] is of enormous practical relevance as it is probably the most widespread cipher. Unsurprisingly, since its proposal, and even more so since its standardization, it has received tremendous analysis.

In general, primitive cryptanalysis categorizes attacks by adversarial capabilities into known-plaintext, chosen-plaintext, chosen-ciphertext, and adaptively chosen-data attacks. As attacks have been focusing on maximizing the number of rounds that can be broken more efficiently than exhaustive key search and with less data than the full codebook, chosen-data attacks have become the de facto standard models. Over time, the models were further strengthened to consider also adversaries that can choose key relations. Besides, multi-user, weak-key, and even chosen-key attacks emerged. Such stronger models are relevant, as block ciphers are versatile primitives for various applications. Some settings demand strong security, e.g., the usage as a compression or one-way function. However, with the increasing adversarial capabilities, the gap between very strong models and more practically motivated ones has widened.

Known-plaintext attacks have remained relevant on many occasions, as choosing plaintexts and collecting the results is often not possible, or could lead to the adversary's detection. Additionally, many modes of operation may further restrict the inputs to the primitive compared to the theoretical models. For example, randomized variants of CTR mode [32], as employed in various AE schemes or wide-block ciphers such as AES-GCM [33] or AES-GCM-SIV [40,41], allow only forward queries and restrict the set of legitimate inputs. Moreover, various modes also encrypt previously randomized values. For example, the PRF in SIV [42,57] generates a known pseudorandom authentication tag that is then used as the initial value for CTR-mode encryption.

For the AES as the most widespread block cipher, the previous decade brought various new insights and novel techniques: the multiple-of-n property [14,39], mixture differentials [36], yoyos [59], exchange attacks [4], small-bias truncated differentials [3,38], retracing boomerangs [28,29], the combination of FFT and partial sums [27], and new representations of its key schedule [46,47]. Those have led to new records for distinguishers on up to six rounds, new attacks on seven rounds, and new improved practical attacks on five and six rounds. But how those techniques translate into attacks in the more restrictive known-plaintext model is not clear. The best attacks have remained undefeated for over a decade.

1.2 Related Work

Studying differential attacks in the known-plaintext model is as old as the public record of differential cryptanalysis itself. Biham and Shamir suggested already in their seminal analysis of the Data Encryption Standard (DES) [6,7] that a chosen-plaintext differential attack requiring 2^r pairs could be theoretically converted into a known-plaintext attack with $2^{(r+n+1)/2}$ data. However, the approach remained unexplored since then. One generation after Biham and Shamir [6,7],

Table 1: Best single-key key-recovery attacks on round-reduced AES in the random known-plaintext model. $^{(*)}$ = we argue in the full version that the data does not suffice. #Rds. = #rounds, memory in #AES states.

Version	Attack type	#Rds.	Time	Data	Memory	Reference
128	MitM	5/10	2^{120}	1	2^{96}	[13,22]
	MitM	5/10	2^{120}	1	2^{40}	[18]
	MitM	6/10	2^{120}	$2^{108.5}$	$2^{109.5}$	[12]
	Rectangle	**6/10**	$\mathbf{2^{105.8}}$	$\mathbf{2^{99.1}}$	$\mathbf{2^{103.2}}$	**Sect. 4**
	DS-MitM	**7/10**	$\mathbf{2^{125.1}}$	$\mathbf{2^{124}}$	$\mathbf{2^{125}}$	**Sect. 8**
	Imp. differential	**7/10**	$\mathbf{2^{118.1}}$	$\mathbf{2^{116.5}}$	$\mathbf{2^{117.5}}$	**Sect. 7**
192	Zero correlation	6/12	$2^{188.4}$	2^{128}	2^{128}	[10]
	MitM	7/12	2^{184}	1	2^{72}	[18]
	Imp. differential	**7/12**	$\mathbf{2^{126}}$	$\mathbf{2^{117.5}}$	$\mathbf{2^{118.5}}$	**Full version**
	DS-MitM	**8/12**	$\mathbf{2^{179}}$	$\mathbf{2^{124}}$	$\mathbf{2^{128.6}}$	**Full version**
256	Zero correlation	6/14	$2^{188.4}$	2^{128}	2^{128}	[10]
	MitM	8/14	2^{248}	1	2^{72}	[18]
	Imp. differential$^{(*)}$	8/14	2^{220}	2^{118}	2^{145}	[43]
	Imp. differential	**8/14**	$\mathbf{2^{228.5}}$	$\mathbf{2^{116.8}}$	$\mathbf{2^{217}}$	**Full version**
	DS-MitM	**9/14**	$\mathbf{2^{247.7}}$	$\mathbf{2^{124}}$	$\mathbf{2^{194.1}}$	**Full version**

Bouillaguet et al. [12, Sect. 8] proposed "an attack on 6-round AES, using a low-probability differential" that was "the best known attack on 6-round AES in the known-plaintext model", and has stood as the best attack so far. Thus, explicit studies have remained necessary to clarify the potential of transferring attacks from chosen- to known-data models. More generally, attacks with multiple (but few) related texts, such as boomerangs, or mixtures, etc., have not received attention so far. The understanding is even lower for techniques that consider sets of more text and pair relations, such as integral or Demirci-Selçuk Meet-in-the-Middle (DS-MitM) attacks. Intuitively, they seem to prohibit any straightforward transformation unless the amount of required data approaches the full codebook very closely.

Considerable work on the relations between attacks with different adversarial capabilities has also been conducted in provable security. In that direction, the focus was on deriving security guarantees against adversaries that can choose inputs from components with security guarantees only against random inputs. Maurer and Pietrzak showed compositions of weak components to PRFs [53]; Myers showed black-box compositions that did not yield adaptive security [55]. Minematsu and Tsunoo [54] proposed symmetric encryption from wPRFs. Maurer et al. [52] studied conversions of attacks on Feistel ciphers from the chosen- to the known-plaintext model by considering the applicability of attacks on PRFs to wPRFs. In contrast, we exploit the internals of the studied primitive, whereas provable security usually treats the primitives as black boxes.

1.3 Contributions

In this work, we revisit the relation of general differential-based attacks from the chosen plain-/ciphertext to the random known-plaintext (RKP) model. In the course, we study the most effective existing attack types on round-reduced AES with a single secret key, which are all in chosen-data models (or their adaptive variants). We show that impossible- and truncated-differential attacks can be effectively applied in the RKP model, although with higher data complexity. Beyond those, we generalize the approach to techniques with related pairs, such as rectangle and mixture attacks, and demonstrate new attacks in the RKP model as well. For those, we show in examples that the effectiveness of trails does not straightforwardly translate from one model to the other; preferable trails in the CP model may not produce the minimal attack complexity in the RKP model. For some of our mixture and rectangle attacks, choosing seemingly less efficient trails allows us to reduce the complexities.
We also demonstrate that DS-MitM attacks, which require many related texts, can use trade-offs that allow their use in the RKP model as well. While it would be easy with a data complexity very close to the full codebook, we strive to restrict the attack to a more meaningful factor of using at most $1/16$ of it, which demands a more sophisticated technique. For the AES-128, we show that an attack in the RKP model poses additional constraints, necessitating the use of only certain differential trails. Tables 1 and 2 compare our results with the best previous attacks on round-reduced AES in the known-plaintext model from the literature. They outline that we can add at least one round over the previous understanding.

1.4 Outline

After briefly recalling the necessary preliminaries on the AES, we study generic conversions from the CP to the RKP model for differential, impossible-differential, boomerang, and mixture attacks in Section 3. Next, we show conversions of the best known six-round distinguishers and attacks of the round-reduced AES in the follow-up sections. It includes a rectangle attack in Section 4, a mixture distinguisher in Section 5, and a truncated-differential distinguisher in Section 6. Then, it presents conversions of the seven-round impossible-differential attack in Section 7, and the seven-round DS-MitM attack in Section 8. We discuss and conclude this work in Section 9. In the extended version, we show similar applications, such as a rectangle distinguisher as well as impossible-differential and DS-MitM attacks on round-reduced AES-192 and AES-256.

2 Preliminaries

General Notations. For positive integers p, n, we denote by $\mathbb{F}_2^n$ the extension of the finite field of characteristic 2. We represent functions and variables by upper-case and indices by lower-case letters, sets by calligraphic letters (such

Table 2: Best single secret-key distinguishers on round-reduced AES in the random known-plaintext model. #Rds. = #rounds, memory in #AES states).

Attack type	#Rds.	Time	Data	Memory	Reference
Zero correlation	4	2^{128}	2^{128}	negl.	[9]
Conditional linear	4	$2^{125.6}$	$2^{125.6}$	negl.	[1,2]
Mixture differential	**6**	$\mathbf{2^{118.1}}$	$\mathbf{2^{115.5}}$	$\mathbf{2^{117.5}}$	**Sect. 5**
Rectangle	**6**	$\mathbf{2^{117.7}}$	$\mathbf{2^{113.5}}$	$\mathbf{2^{115.5}}$	**Full version**
Truncated differential	**6**	$\mathbf{2^{111.9}}$	$\mathbf{2^{106.8}}$	$\mathbf{2^{108.4}}$	**Sect. 6**

as $\mathcal{C}$). We employ typewriter font for hexadecimal values (such as `0xff`). Let $X, Y \in \mathbb{F}_p^n$ for some positive integer n in the following. Then, we denote by $X\|Y$ the concatenation of X and Y, by $X \oplus Y$ their elementwise XOR. For a non-negative integer i, we write $[i..j]$ for $\{i, i+1, \ldots, j\}$. $\langle i \rangle_m$ denotes the m-bit encoding of an integer i, e.g. $\langle 135 \rangle_8 = (10000111)$.

The AES. The Advanced Encryption Standard [20,56] is a substitution-permutation network that transforms 16-byte plaintexts through 10, 12, or 14 rounds for key sizes of 128, 192, or 256 bits, respectively. Each state byte is interpreted as an element of the finite field $\mathbb{F}_{2^8}$. The state itself can be viewed either as a linear array of 16 elements in $\mathbb{F}_{2^8}^{16}$ or, also commonly, as a 4×4 matrix in $\mathbb{F}_{2^8}^{4\times 4}$. Almost each round consists of the operations SubBytes (SB), ShiftRows (SR), MixColumns (MC), and AddRoundKey[K^i] (AK[K^i]), i.e. a round-key addition with a round key K^i. Before the first round, an additional whitening key K^0 is XORed to the state; the final round omits the MixColumns operation. For compactness, we will sometimes write $\overline{\mathsf{SB}}$, $\overline{\mathsf{SR}}$, and $\overline{\mathsf{MC}}$ for SB^{-1}, SB^{-1}, and MC^{-1}, respectively. We write $X[i]$ for the i-th byte of an internal state X, and we interchangeably also use $X[i][j]$ to denote the byte in the i-th row and j-th column of state X with the usual byte ordering of

$$\begin{bmatrix} 0 & 4 & 8 & 12 \\ 1 & 5 & 9 & 13 \\ 2 & 6 & 10 & 14 \\ 3 & 7 & 11 & 15 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} (0,0) & (0,1) & (0,2) & (0,3) \\ (1,0) & (1,1) & (1,2) & (1,3) \\ (2,0) & (2,1) & (2,2) & (2,3) \\ (3,0) & (3,1) & (3,2) & (3,3) \end{bmatrix}.$$

When using $X[i][j]$, we treat the indices as taken modulo four by default. Note that we will use the notation $X[i_1, i_2]$ as a short form for $X[i_1], X[i_2]$. We denote by X^i, Y^i, Z^i, and W^i the internal states in the i-th round directly after the application of AddRoundKey, SubBytes, ShiftRows, and MixColumns, respectively. We denote by $\mathsf{R}[K^i] \stackrel{\text{def}}{=} \mathsf{AK}[K^i] \circ \mathsf{MC} \circ \mathsf{SR} \circ \mathsf{SB}$ one AES round, and denote by $\widehat{\mathsf{R}}[K^i] \stackrel{\text{def}}{=} \mathsf{AK}[K^i] \circ \mathsf{SR} \circ \mathsf{SB}$ the reduced final round. We denote by $\widehat{K}^i = \mathsf{MC}^{-1}(K^i)$ an equivalent key of K^i, and denote by $\widehat{W}^i$ the state after AddRoundKey if we exchange the order of MixColumns and AddRoundKey in the i-th round. We use $\mathbf{M} = \mathsf{circ}(2, 3, 1, 1)$ to denote the circular MixColumns matrix.

3 Generic Conversions

3.1 General Setting

Leaving advanced concepts of guess-and-determine, internal-state, or internal-difference guessing aside, a general differential chosen-plaintext attack needs the following. Suppose we can split a given cipher E into parts $E : \mathbb{F}_2^k \times \mathbb{F}_2^n \to \mathbb{F}_2^n$ with k-bit key and n-bit blocks into $E = E_{\text{out}} \circ E_{\text{dist}} \circ E_{\text{in}}$. Moreover, let spaces $\mathcal{D}_{\text{in}}$, $\mathcal{D}_{\text{out}}$, $\mathcal{D}_x$, $\mathcal{D}_y \subseteq \mathbb{F}_2^n$. Further assume that there is a differential $\Delta X \xrightarrow{E_{\text{dist}}} \Delta Y$ through E_{dist}. Let the adversary gather $D = 2^d$ plaintexts that can be partitioned into 2^s structures of texts such that for each pair of distinct texts P, P' in a structure, $P \oplus P' \in \mathcal{D}_{\text{in}}$. They are influenced by k_{in} key bits from a key space $\mathcal{K}_{\text{in}}$ through E_{in}. The goal is to find pairs in a difference space $\mathcal{D}_x$ that serves as inputs to a distinguisher through E_{dist}, and is mapped probabilistically to output pairs in an output-difference space $\mathcal{D}_y$ after E_{dist} that allows to distinguish E_{dist} with non-negligible advantage from a random permutation. At the ciphertext side, the adversary filters all pairs except those whose ciphertext differences lie in a certain space $\mathcal{D}_{\text{out}}$. Those pairs are influenced by k_{out} key bits from a key space $\mathcal{K}_{\text{out}}$ through E_{out}. The adversary searches for keys in $\mathcal{K}_{\text{in}} \cup \mathcal{K}_{\text{out}}$ that map plaintext pairs from $\mathcal{D}_{\text{in}}$ and their corresponding ciphertext pairs from $\mathcal{D}_{\text{out}}$ to pairs with difference in $\mathcal{D}_x$ through E_{in} and to pairs with difference in $\mathcal{D}_y$ through E_{out}^{-1}.
Let $\delta_{\text{in}} =^{\text{def}} \log_2(|\mathcal{D}_{\text{in}}|)$, $\delta_{\text{out}} =^{\text{def}} \log_2(|\mathcal{D}_{\text{out}}|)$ and assume that for random nonzero $\Delta P \in \mathcal{D}_{\text{in}}$, and $\Delta C \in \mathcal{D}_{\text{out}}$, and over the random choice of the key K, we define c_{in} and c_{out} for the number of bit conditions (cf. [16,15]) that have to be fulfilled for a plaintext pair to form a difference in $\mathcal{D}_x$ and for a ciphertext pair to form a difference in $\mathcal{D}_y$, respectively:

$$\Pr\left[K \twoheadleftarrow \mathbb{F}_2^k : E_{\text{in}}(K, P) \oplus E_{\text{in}}(K, P \oplus \Delta P) \in \mathcal{D}_x\right] \approx 2^{-c_{\text{in}}} \quad \text{and}$$
$$\Pr\left[K \twoheadleftarrow \mathbb{F}_2^k : E_{\text{out}}^{-1}(K, C) \oplus E_{\text{out}}^{-1}(K, C \oplus \Delta C) \in \mathcal{D}_y\right] \approx 2^{-c_{\text{out}}}.$$

3.2 Standard, Truncated-, and Impossible-differential Attacks

For a differential, truncated-differential, or impossible-differential attack, we assume that there is a nontrivial (i.e., nonzero) differential $\Delta X \xrightarrow{E_{\text{dist}}} \Delta Y$ through E_{dist} with probability 2^{-p}. We assume that $\Delta X \in \mathcal{D}_x$ and $\Delta Y \in \mathcal{D}_y$:

$$\Pr\left[K \twoheadleftarrow \mathbb{F}_2^k : E_{\text{dist}}(K, X) \oplus E_{\text{dist}}(K, X \oplus \Delta X) \in \mathcal{D}_y, \Delta X \in \mathcal{D}_x\right] = 2^{-p}.$$

Chosen-plaintext Model. In a chosen-plaintext attack, the adversary can form up to $\binom{D}{2} \approx 2^{2d-1}$ pairs from $D =^{\text{def}} 2^d$ plaintexts. However, given $|\mathcal{D}_{\text{in}}| = 2^{\delta_{\text{in}}}$, the number of pairs whose input difference is in $\mathcal{D}_{\text{in}}$, N_{CP}, is limited to

$$N_{\text{CP}} \approx 2^{d+\min(d,\delta_{\text{in}})-1} = 2^{d+d'-1} = \begin{cases} 2^{2d-1} & \text{if } |\mathcal{D}_{\text{in}}| \geq 2^d \\ 2^{d+\delta_{\text{in}}-1} & \text{otherwise}, \end{cases}$$

where we define $d' =^{\text{def}} \min(d, \delta_{\text{in}})$. The number of pairs that survive the initial filter, #SP, i.e., the pairs whose ciphertext pairs satisfy $C \oplus C' \in \mathcal{D}_{\text{out}}$, is approximately

$$\mathbb{E}\left[\#\mathsf{SP}_{\text{CP}}^{\text{Diff}}\right] = N_{\text{CP}} \cdot \left(\frac{|\mathcal{D}_{\text{out}}|}{2^n - 1} \cdot (1 - 2^{-p}) + 2^{-p}\right) \approx \frac{2^{d+d'}}{2} \cdot \left(\frac{2^{\delta_{\text{out}}}}{2^n} + 2^{-p}\right). \tag{1}$$

Random Known-plaintext Model. In the distinct RKP model, the adversary can use all data and obtain $N_{\text{RKP}} \approx 2^{2d-1}$ pairs from $D = 2^d$ texts. Thereupon, it has to discard all but those pairs $((P, C), (P', C'))$ that satisfy $P \oplus P' \in \mathcal{D}_{\text{in}}$ and $C \oplus C' \in \mathcal{D}_{\text{out}}$. Thus, one can expect that the number of surviving pairs averages

$$\begin{aligned}\mathbb{E}\left[\#\mathsf{SP}_{\text{RKP}}^{\text{Diff}}\right] &= \frac{|\mathcal{D}_{\text{in}}|}{2^n - 1} \cdot N_{\text{RKP}} \cdot \left(\frac{|\mathcal{D}_{\text{out}}|}{2^n - 1} \cdot (1 - 2^{-p}) + 2^{-p}\right) \\ &\approx \frac{2^{2d+\delta_{\text{in}}}}{2^{n+1}} \cdot \left(\frac{2^{\delta_{\text{out}}}}{2^n} + 2^{-p}\right).\end{aligned} \tag{2}$$

Remark 1. This reflects the conversion proposed in [6,7], where a differential attack requiring 2^r pairs in the chosen-plaintext model could be transformed into an attack with $2^{n/2} \cdot \sqrt{2^{r+1}}$ random known plaintexts (cf. [8]).

We can derive a ratio for the expected number of surviving pairs from 2^d texts between the chosen-plaintext and the random known-plaintext model:

$$\frac{\mathbb{E}\left[\#\mathsf{SP}_{\text{CP}}^{\text{Diff}}\right]}{\mathbb{E}\left[\#\mathsf{SP}_{\text{RKP}}^{\text{Diff}}\right]} = \frac{(1)}{(2)} \approx \frac{2^{d+\min(d,\delta_{\text{in}})-1}}{2^{2d-1+\delta_{\text{in}}-n}} = 2^{n-\max(d,\delta_{\text{in}})}. \tag{3}$$

Thus, given an attack of that type in the CP model, the corresponding reduction to a random known-plaintext attack differs mainly in the data that the adversary has to collect (but also to store, filter, and process) for obtaining the same number of required pairs. Let $2^{d_{\text{CP}}}$ and $2^{d_{\text{RKP}}}$ be the number of plaintext-ciphertext pairs that are required in the corresponding models to acquire N pairs. Then, the data complexity of an RKP attack must satisfy

$$d_{\text{RKP}}^{\text{Diff}} \geq d_{\text{CP}}^{\text{Diff}} + \frac{n - \max\left(d_{\text{CP}}^{\text{Diff}}, \delta_{\text{in}}\right)}{2} \tag{4}$$

to apply an attack that was defined for the chosen-plaintext model.

3.3 Mixture-differential Attacks

Conditional-differential attacks were first introduced for the cryptanalysis of stream ciphers [45], but are well-known in the analysis of block ciphers, hash functions, or compression functions. The adversary constructs (at least) two pairs (X_0, X_0') and (X_1, X_1'), and studies the conditional probability that the

latter will be mapped to (Y_1, Y_1') with $Y_1 \oplus Y_1' \in \mathcal{D}_y'$ through E_{dist} for a certain difference space $\mathcal{D}_y'$ if the former pair (X_0, X_0') was mapped to a pair (Y_0, Y_0') through E_{dist} with $Y_0 \oplus Y_0' \in \mathcal{D}_y$:

$$\Pr\left[K \twoheadleftarrow \mathbb{F}_2^k : E_{\text{dist}}(X_1) \oplus E_{\text{dist}}(X_1') \in \mathcal{D}_y' | E_{\text{dist}}(X_0) \oplus E_{\text{dist}}(X_0') \in \mathcal{D}_y\right] .$$

Mixture differentials [36] are variants of conditional differentials, where related pairs (X_i, X_i') are constructed from an initial pair (X_0, X_0') by an exchange function. In this context, the n-bit strings X_i are interpreted as m w-bit words such that $n = m \cdot w$. The exchange function $\rho : \mathbb{F}_2^m \times \mathbb{F}_{2^w}^m \to \mathbb{F}_{2^w}^m$ takes a bit vector $\alpha \in \mathbb{F}_2^m$ and two elements X_0, $X_1 \in \mathbb{F}_{2^w}^m$ and outputs

$$\rho_\alpha(X_0, X_1) \stackrel{\text{def}}{=} (X_{\alpha[0]}[0], \ldots, X_{\alpha_{m-1}}[m-1]) .$$

For all mixture pairs $(X_i, X_i') = (\rho_{\alpha_i}(X_0, X_0'), \rho_{\alpha_i}(X_0', X_0))$, it holds that $X_i \oplus X_i' = X_0 \oplus X_0'$ for some exchange vector α_i. Define $\delta_y' =^{\text{def}} \log_2(|\mathcal{D}_y'|)$ and $\delta_{\text{out}}' =^{\text{def}} \log_2(|\mathcal{D}_{\text{out}}'|)$, and let $\mathsf{E}_Y =^{\text{def}} E_{\text{dist}}(K, X) \oplus E_{\text{dist}}(K, X \oplus \Delta X) \in \mathcal{D}_y$. We define $2^{-p'}$ as the probability for an average related pair

$$\Pr\left[K \twoheadleftarrow \mathbb{F}_2^k : E_{\text{dist}}(K, X_i) \oplus E_{\text{dist}}(K, X_i \oplus \Delta X) \in \mathcal{D}_y' | \mathsf{E}_Y\right] = 2^{-p'} .$$

Chosen-plaintext Model. In the following, we restrict our attention to attacks where structures are quartets, i.e., they contain two pairs, an initial pair and a conditional pair. In a chosen-plaintext mixture attack with two pairs, the adversary collects $D = 2^d$ texts that can produce $N_{\text{CP}} \approx 2^{d+d'-1}/4$ structures. The number of structures that survive the initial filter, i.e., whose ciphertext differences are in $\mathcal{D}_{\text{out}}$ and $\mathcal{D}_{\text{out}}'$, respectively, is approximately

$$\begin{aligned}\mathbb{E}\left[\#\mathsf{SQ}_{\text{CP}}^{\text{Mix2}}\right] &= N_{\text{CP}} \cdot \left(\frac{|\mathcal{D}_{\text{out}}| \cdot |\mathcal{D}_{\text{out}}'|}{(2^n-1)\cdot(2^n-3)} \cdot (1 - 2^{-(p+p')}) + 2^{-(p+p')}\right) \\ &\approx \frac{2^{d+d'}}{2^2} \cdot \left(\frac{2^{\delta_{\text{out}}+\delta_{\text{out}}'}}{2^{2n}} + 2^{-(p+p')}\right) . \end{aligned} \tag{5}$$

Random Known-plaintext Model. In the RKP model, the adversary can use all pairs and obtain $N_{\text{RKP}} = 2 \cdot 3 \cdot \binom{2^d}{4} \approx 2^{4d-2}$ pairs of pairs from $D = 2^d$ texts. The factors arise as there are three ways of combining the texts into pairs, and two ways of mixing a pair with a fixed exchange vector or its bitwise inverse. Here, the adversary searches for pairs of pairs $((P, C), (P', C'))$ and $((P_1, C_1), (P_1', C_1'))$ such that the first pair $P \oplus P' = \mathcal{D}_{\text{in}}$ is in the desired input space and (P_1, P_1') is a mixture of (P, P'). We obtain

$$\begin{aligned}\mathbb{E}\left[\#\mathsf{SP}_{\text{RKP}}^{\text{Mix2}}\right] &= \frac{|\mathcal{D}_{\text{in}}| \cdot N_{\text{RKP}}}{(2^n-1)_3} \cdot \left(\frac{|\mathcal{D}_{\text{out}}| \cdot |\mathcal{D}_{\text{out}}'|}{(2^n-1)\cdot(2^n-3)} \cdot \left(1 - 2^{-(p+p')}\right) + 2^{-(p+p')}\right) \\ &\approx \frac{2^{4d+\delta_{\text{in}}}}{2^{3n+2}} \cdot \left(\frac{2^{\delta_{\text{out}}+\delta_{\text{out}}'}}{2^{2n}} + 2^{-(p+p')}\right) . \end{aligned} \tag{6}$$

As a result, the ratio for the expected number of surviving pairs from 2^d texts between the CP and the RKP model for mixtures with two pairs becomes

$$\frac{\mathbb{E}\left[\#\mathsf{SP}_{\mathrm{CP}}^{\mathrm{Mix2}}\right]}{\mathbb{E}\left[\#\mathsf{SP}_{\mathrm{RKP}}^{\mathrm{Mix2}}\right]} = \frac{(5)}{(6)} \approx \frac{2^{d+\min(d,\delta_{\mathrm{in}})-2}}{2^{4d+\delta_{\mathrm{in}}-3n-2}} = 2^{3n-2d-\max(d,\delta_{\mathrm{in}})}\,. \tag{7}$$

The data complexity of an RKP mixture-differential attack with two pairs must therefore satisfy

$$d_{\mathrm{RKP}}^{\mathrm{Mix2}} \geq \frac{2d_{\mathrm{CP}}^{\mathrm{Mix2}} + 3n - \max\left(d_{\mathrm{CP}}^{\mathrm{Mix2}}, \delta_{\mathrm{in}}\right)}{4} \tag{8}$$

to apply an attack that was defined for the chosen-plaintext model.

3.4 Rectangle Attacks

Boomerang attacks [60] are adaptive plain-and-ciphertext attacks that trace quartets of plaintexts through a (partial) cipher, shift their ciphertexts by differences, and trace the so-shifted ciphertexts back through the inverse cipher. They were subsequently refined by multiple differentials in the middle [5], and adding a transition in the middle part [19,30]. The adversary splits the cipher $E_{\mathrm{dist}} = E_2 \circ E_m \circ E_1$, and exploits the existence of two trails $\Delta_x \xrightarrow{E_1} \Delta_u$ and $\Delta_v \xrightarrow{E_2} \Delta_y$, where the middle part undergoes a more precise evaluation of the map $\Delta_u \xrightarrow{E_m} \Delta_v$ for both pairs through the middle. The probability through the first part is usually approximated by

$$\Pr\left[E_1(K,X) \oplus E_1(K,X') \in \mathcal{D}_u\right] = 2^{-p}\,.$$

Amplified-boomerang [44] and rectangle attacks [5] turned adaptive two-way boomerangs into chosen-plaintext (or chosen-ciphertext) attacks. Given two input pairs (X,X') and $(\overline{X},\overline{X}')$ with $X \oplus X' \in \mathcal{D}_x$ that are mapped to (U,U') and $(\overline{U},\overline{U}')$ through E_1, the probability through the second part of a rectangle is usually approximated by

$$\Pr\left[E_2(K,U) \oplus E_2(K,\overline{U}) \in \mathcal{D}_y\right] = 2^{-q}\,.$$

When $\mathcal{D}_u$ and $\mathcal{D}_v$ are subspaces, the probability that $U, U', \overline{U}$, and $\overline{U}'$ are mapped to $V, V', \overline{V}$, and $\overline{V}'$, respectively, such that $V \oplus \overline{V} \in \mathcal{D}_v$ and $V' \oplus \overline{V}' \in \mathcal{D}_v$, is usually approximated as $2 \cdot |\mathcal{D}_v| \cdot 2^{-n}$ (there are two quartet options). Thus, the probability is approximated by

$$\Pr\left[K \twoheadleftarrow \mathbb{F}_2^k : \begin{cases} E_{\mathrm{dist}}(K,X) \oplus E_{\mathrm{dist}}(K,\overline{X}) \in \mathcal{D}_y, \\ E_{\mathrm{dist}}(K,X \oplus \Delta X) \oplus E_{\mathrm{dist}}(K,\overline{X} \oplus \Delta\overline{X}) \in \mathcal{D}'_y, \\ \Delta X, \Delta\overline{X} \in \mathcal{D}_x \end{cases}\right] \approx \frac{1}{2^{n+2(p+q)}}\,.$$

Chosen-plaintext Model. The adversary can partition the $D = 2^d$ plaintexts into structures. Define $2^{-\widehat{p}} =^{\text{def}} 2^{-2(p+q)}$. The number of quartets whose ciphertexts satisfy $C \oplus \overline{C} \in \mathcal{D}_{\text{out}}$ and $C' \oplus \overline{C'} \in \mathcal{D}'_{\text{out}}$ #SQ is approximately

$$\begin{aligned}\mathbb{E}\left[\#\mathsf{SQ}_{\text{CP}}^{\text{Rect}}\right] &= N_{\text{CP}} \cdot \left(\frac{|\mathcal{D}_{\text{out}}| \cdot |\mathcal{D}'_{\text{out}}|}{(2^n-1)\cdot(2^n-3)} \cdot (1-2^{-\widehat{p}}) + 2^{-\widehat{p}}\right) \\ &\approx \frac{2^{2(d+d')}}{4} \cdot \left(\frac{2^{\delta_{\text{out}}+\delta'_{\text{out}}}}{2^{2n}} + 2^{-\widehat{p}}\right). \end{aligned} \tag{9}$$

Random Known-plaintext Model. In the RKP model, the adversary can again combine all data and obtain $N_{\text{RKP}} = 2 \cdot 3 \cdot \binom{2^d}{4} \approx 2^{4d-2}$ rectangle quartets from $D = 2^d$ texts. There are three ways of combining plaintexts into pairs and two ways of combining the ciphertexts into two pairs each. In contrast to mixtures, the pairs may employ different input-difference spaces $\mathcal{D}_{\text{in}}$ and $\mathcal{D}'_{\text{in}}$, where we define $\delta'_{\text{in}} = |\mathcal{D}'_{\text{in}}|$. One can expect that the number of surviving quartets with the initial filters on the plaintext side is

$$\begin{aligned}\mathbb{E}\left[\#\mathsf{SQ}_{\text{RKP}}^{\text{Rect}}\right] &= \frac{|\mathcal{D}_{\text{in}}| \cdot |\mathcal{D}'_{\text{in}}| \cdot N_{\text{RKP}}}{(2^n-1)\cdot(2^n-3)} \cdot \left(\frac{|\mathcal{D}_{\text{out}}| \cdot |\mathcal{D}'_{\text{out}}|}{(2^n-1)\cdot(2^n-3)} \cdot (1-2^{-\widehat{p}}) + 2^{-\widehat{p}}\right) \\ &\approx \frac{2^{\delta_{\text{in}}+\delta'_{\text{in}}+4d}}{2^{2n+2}} \cdot \left(\frac{2^{\delta_{\text{out}}+\delta'_{\text{out}}}}{2^{2n}} + 2^{-\widehat{p}}\right). \end{aligned} \tag{10}$$

In the case of $\delta'_{\text{in}} = \delta_{\text{in}}$, it must hold in an RKP rectangle attack that

$$d_{\text{RKP}}^{\text{Rect}} \geq \frac{2d_{\text{CP}}^{\text{Rect}} + 2n + 2 - (\delta_{\text{in}} + \max\left(d_{\text{CP}}^{\text{Rect}}, \delta_{\text{in}}\right))}{4} \tag{11}$$

to apply an attack that was defined for the chosen-plaintext model.

3.5 DS-MitM Attacks

DS-MitM attacks [21] are key-recovery variants based on an observation from [35]. A sequence of partial outputs derived from a set of related texts can take considerably fewer values than a random sequence. An adversary maps a set of related texts through the distinguishing part of a cipher by guessing the required internal state and key variables, and stores the possible output sequences or sets in a table. From [31], the number of variables could be further reduced if the set is formed in relation to a pair that follows a differential trail. For round-reduced AES, attacks often start from a δ-set, with a set of 2^8 texts differing only in a single active byte. The adversary is interested in recovering the values or differences of the set in a byte or a linear combination of several bytes after the distinguisher [23,24,26,48,50]. The number of related texts, m, must be chosen such that the number of random matched byte sequences between entries in the offline table and candidates from the online phase is sufficiently small to filter the involved key bytes. More precisely, it should be lower than the product of the

number of surviving pairs and 2^b for b guessed key bits in the steps around the distinguisher. In the attacks above on round-reduced AES, this often required more than 16 related texts, and up to 256 texts in a δ-set that iterated over all values in a single input byte, as in [23,24,31,26].

Chosen-plaintext Model. The resulting chosen-plaintext attacks were efficient. An adversary could form up to $\binom{D}{2} \approx 2^{2d-1}$ pairs from $D =^{\text{def}} 2^d$ plaintexts. Given $|\mathcal{D}_{\text{in}}| = 2^{\delta_{\text{in}}}$, the number of pairs whose input difference is in $\mathcal{D}_{\text{in}}$, is calculated as for standard (truncated) differential attacks. Let $\mathcal{D}_{\text{out}}$ be an output difference space. For attacks that consider a distinguisher based on differential enumeration [31], $\mathcal{D}_{\text{out}} \subset \mathbb{F}_2^n$; otherwise, as in low-data chosen-plaintext attacks, $\mathcal{D}_{\text{out}}$ may equal $\mathbb{F}_2^n \setminus \{0^n\}$. Similarly to differential attacks, the number of pairs that survive the initial filter, #SP, i.e., the pairs whose ciphertext pairs satisfy $C \oplus C' \in \mathcal{D}_{\text{out}}$ for some space $\mathcal{D}_{\text{out}}$, can be calculated as:

$$\mathbb{E}\left[\#\mathsf{SP}_{\text{CP}}^{\text{DS}}\right] = \mathbb{E}\left[\#\mathsf{SP}_{\text{CP}}^{\text{Diff}}\right] . \tag{12}$$

Random Known-plaintext Model. For finding the initial pairs that satisfy the desired differential through the distinguisher, the adversary can use all data and obtain $N_{\text{RKP}} \approx 2^{2d-1}$ pairs from $D = 2^d$ texts. However, collecting the related data becomes significantly more challenging in the RKP model. Using 2^d random known plaintexts, the probability for a text to be in the available data is approximately 2^{d-n}. To ensure a high probability that sufficiently many related texts for a pair of plaintexts and ciphertexts that follow the trail in the middle rounds are available, 2^{d-n} must not be too small. However, we strive to avoid data complexities too close to the codebook (e.g. the one from the seven-round attack in [34], which was valuable as a pioneering result on AES) and set $d \leq n-4$ as an upper bound, which is challenging as the data has to be collected, stored, and more data lowers the meaningfulness of even academic attacks.
Using random data, the increasing data complexity will result in significantly more wrong pairs that must be tested, i.e., whose ciphertext difference lies in $\mathcal{D}_{\text{out}}$ when using differential enumeration. From an analysis of the configurations of the number of in- and output bytes in the offline trails, the complexity for testing the number of surviving pairs can more easily become the bottleneck of the attack. Thus, using only differential trails that reduce the number of surviving pairs may be beneficial for RKP attacks.
We introduce a time-data trade-off from a set of parameters θ_k-out-of-m related texts. In the offline phase, the adversary gathers the possible matches for m related texts, and computes and stores all $\binom{m}{\theta_k}$ sets. In the online phase, for every candidate pair that may satisfy the differential through the distinguishing part of the cipher, the adversary guesses the key material for one part of the cipher, usually at the beginning. Then, it derives the first m related texts, traces them back to their would-be plaintexts, and looks up which of them exists in the available collected data. If k texts for $k \geq \theta_k$ are available, the adversary constructs the set of the lexicographically first θ_k texts from them, and conducts

the attack on that subset of related texts. Thus, the attack requires that at least θ_k among m related texts are available in the given data, whose probability is

$$q_{\text{succ}} \stackrel{\text{def}}{=} 1 - \left(\sum_{k=0}^{\theta_k - 1} \binom{m}{k} \cdot (2^{d-n})^k \cdot (1 - 2^{d-n})^{m-k} \right) ,$$

which must be chosen to be non-negligible. As an alternative, the adversary could conduct the online phase first, as in [11,25]. The potential disadvantage of this approach is higher memory complexity if the number of surviving pairs in the online phase exceeds the number of entries to be stored in the offline phase. In the CP model, given a differential through the distinguisher with probability 2^{-p}, the adversary collects $2^{d_{\text{CP}}}$ texts that can be combined to $2^{d+d'-1} \geq 2^p$ pairs, so that at least one of them fulfills the differential, and approximately $2^{d+d'-1+\delta_{\text{out}}-n}$ survive on average. In the RKP model, it must hold

$$d_{\text{RKP}} \geq \frac{p + 1 + \delta_{\text{in}} - n}{2} . \tag{13}$$

However, the data complexity is determined mainly by the goal of obtaining a non-negligible probability that the related texts are available with respect to a pair that satisfies the differential through the distinguisher.

4 Six-round Rectangle Key-recovery Attack

We can formulate a six-round rectangle attack, as shown in Figure 1.

4.1 Attack in the Chosen-plaintext Model

When using the trails in a chosen-plaintext attack, the adversary can start from plaintext structures of two fixed active diagonals. The adversary searches for pairs $((P, C), (\overline{P}, \overline{C}))$ such that $C \oplus \overline{C}$ is active in only one inverse diagonal, cf. Figure 1. Eventually, it will search for pairs of such pairs, i.e., to combine them with other pairs $((P', C'), (\overline{P}', \overline{C}'))$ to form quartets.

The probability that a pair has only a single active diagonal after the first round in ΔW^1 is approximately $4 \cdot 2^{-48-48} \approx 2^{-94}$ for two pairs. Two such pairs are each mapped to a single active inverse diagonal in ΔZ^3. With a probability of approximately 2^{-32}, it holds that ΔZ^3 is the same for both pairs. From there, if $X^4 \oplus \overline{X}^4$ is active in only a single diagonal, which has probability $4 \cdot 2^{-96}$, the same difference holds automatically for $X'^4 \oplus \overline{X}'^4$. Then, both pairs are mapped to a difference ΔW^4 with a single active byte with probability $4 \cdot 2^{-24-24}$, which is guaranteed to be mapped to $C \oplus \overline{C}$ and $C' \oplus \overline{C}'$ having a single active inverse diagonal. Thus, the probability for a good quartet is approximately $2^{-46-48} \cdot 2^{-32} \cdot 2^{-94} \cdot 2^{-22-24} = 2^{-266}$, whereas it is $4 \cdot 2^{-96 \cdot 2} \approx 2^{-190}$ for a random pair. Given 2^7 plaintext structures of 2^{64} plaintexts yields $2^7 \cdot \binom{2^{64}}{2} \approx 2^{134}$ pairs (P, P') in total. Those can be combined to approximately

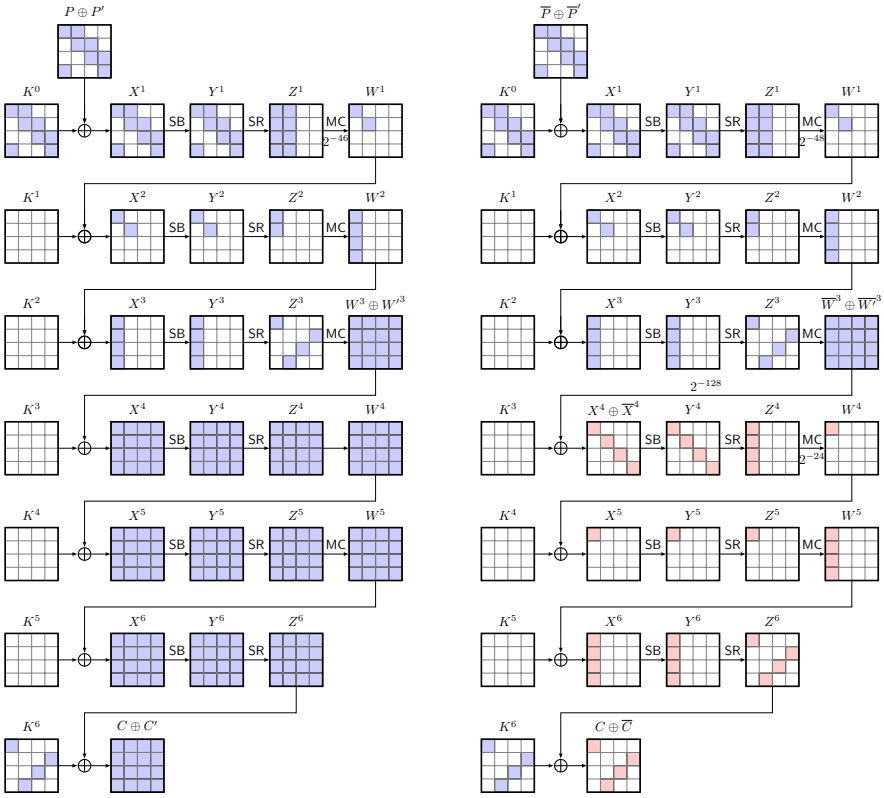


Fig. 1: Six-round rectangle key-recovery attack. Left: The trail between pairs (P, P') to (C, C') (blue). Right: The trail between $(\overline{P}, \overline{P}')$ to $(W^3, \overline{W}^3)$ at the top (blue) and the trail from $(X^3, \overline{X}^3)$ to $(C, \overline{C})$ (red). Colored bytes of plaintext states are active in the differential trails. Colored key bytes are guessed.

$2 \cdot \binom{2^{134}}{2} \approx 2^{268}$ quartets $(P, \overline{P}, P', \overline{P'})$. We expect 2^2 good quartets among $2^{268-190} = 2^{78}$ surviving quartets on average.

The attack starts with collecting the 2^{71} plaintext-ciphertext pairs and storing them four times into a table $\mathcal{T}$ indexed by the 96-bit values from all except one inverse ciphertext diagonal, which costs 2^{71} encryptions and $4 \cdot 2^{71} = 2^{73}$ lookups. Note that the memory can be reused and $2 \cdot 2^{71}$ states in one table suffice. Then, the adversay finds $4 \cdot \binom{2^{71}}{2} \cdot 2^{-96} \approx 2^{47}$ pairs $((P, C), (\overline{P}, \overline{C})$.

Among pairs that share the same single active inverse ciphertext diagonal, the adversary can search for quartets. It can discard quartets whose pairs do not suggest the same used bytes in K^6 and do not share the same plaintext structures. A good quartet consists of two pairs, so that the plaintexts in each pair originate from the same one of 2^7 plaintext structures. For all pairs, the adversary looks up $4 \cdot 2^8$ candidates K^6 that can lead to a single active byte in $Z^5 \oplus \overline{Z}^5$, and

stores the results in a table indexed by the keys and structure indices. This costs about $4 \cdot 2^{45} \cdot 4 \cdot 2^8 = 2^{58}$ memory accesses, and can reuse previous memory.
The probability that two random pairs suggest the same key K^6 is about $4 \cdot 2^8 \cdot 2^8 \cdot 2^{-32} = 2^{-14}$, and $2^{-7-7} = 2^{-14}$ that they share the same structure indices. Given four options for inverse ciphertext diagonals and four options for the active byte in ΔZ^5, we expect approximately $4 \cdot \binom{2^{45}}{2} \cdot 2 \cdot 4 \cdot 2^8 \cdot 2^8 \cdot 2^{-32} \cdot 2^{-7-7} = 2^{64}$ quartets. The factor two represents the fact that a quartet can be built by $((P, P'), (\overline{P}, \overline{P}'))$ and $((P, \overline{P}'), (\overline{P}, P'))$, which differ only in the structure indices. Identifying both needs one memory access when storing the seven-bit structure indices in order.
For each quartet, the adversary looks up the $4 \cdot 2^8$ keys $K^0[0, 5, 10, 15]$ that produce a single active byte in ΔW^1 with $2 \cdot 4 \cdot 2^{64} = 2^{67}$ lookups to a precomputed hash table. The number of surviving quartets is approximately $4 \cdot 2^8 \cdot 2^8 \cdot 2^{64} \cdot 2^{-32} = 2^{50}$. The adversary can repeat the procedure for the surviving quartets with $2 \cdot 2^{50} = 2^{51}$ lookups, and obtain $2^8 \cdot 2^8 \cdot 2^{50} \cdot 2^{-32} = 2^{34}$ mostly false-positive quartets on average, while preserving all good quartets.
Each surviving quartet produces a 96-bit key candidate. However, the positions of only the plaintext diagonals are fixed. Thus, quartets must suggest the same 64-bit key candidates $K^0[0, 3, 4, 5, 9, 10, 14, 15]$ from the active plaintext-difference diagonals. The correct key can usually be identified among a few key candidates (if any) suggested at least twice, with $\binom{2^{34}}{2} \cdot 2^{-64} \approx 2^3$ random collisions on average. The costs are 2^{34} encryption equivalents. For those, the adversary can guess 2^{64} options for the missing key bits of K^0, compute the key schedule to check if they transfer to the known values of K^6, and test the surviving candidates. This costs at most 2^{64} encryptions.
The attack complexity is dominated $2^{71} + 2^{64}$ encryption equivalents, and $2^{73} + 2^{58} + 2^{67} + 2^{51} + 2^{34} \approx 2^{73}$ memory accesses. Approximating the latter by a full encryption equivalent each yields $2^{73.4}$ encryption equivalents in total. It needs 2^{71} chosen plaintexts, and memory for 2^{72} AES states.

4.2 Conversion to the Random Known-plaintext Model

We use the same trails in the corresponding RKP attack. Here, the plaintext pair (P, P') can have two active diagonals. Thus, the probability that a pair (P, P') lies in $\mathcal{D}_{\text{in}}$ is approximately $6 \cdot 2^{64}/2^{128} \approx 2^{-61.4}$. The probability that two random ciphertexts $(C, \overline{C})$ have a difference in $\mathcal{D}_{\text{out}}$ is approximately $4 \cdot 2^{32}/2^{128} = 2^{-94}$. Given 2^d plaintexts, we can build $3 \cdot 2 \cdot \binom{2^d}{4} = 2^{4d-2}$ quartets to find a right quartet, given three options of combining plaintexts to pairs, and two options for forming a quartet from two ciphertext pairs. The probability of desired plaintexts to form quartets $(P, P', \overline{P}, \overline{P'})$ with both $P \oplus P'$ and $\overline{P} \oplus \overline{P}'$ to have the same two diagonals active is $6 \cdot 2^{64} \cdot 2^{64}/2^{2 \cdot 128} \approx 2^{-125.4}$. Since the probability of a right quartet is 2^{-266}, to obtain on average 2^3 right quartets, the adversary needs

$$d \geq (125.4 + 266 + 3 + 2)/4 \approx 99.1\,. \tag{14}$$

With $2^{99.1}$ random known plaintexts P, the adversary can form $2^{197.2}$ pairs $((P, C), (\overline{P}, \overline{C}))$. At the ciphertext side, it uses the four options for the single

active inverse diagonal to have a 94-bit filter, and therefore reduces the pairs $((P, C), (\overline{P}, \overline{C}))$ to $2^{103.2}$. Such pairs can be combined to $2 \cdot \binom{2^{103.2}}{2} = 2^{206.4}$ quartets; using the plaintext filter reduces this number to $2^{206.4} \cdot 2^{-61.4-64} \approx 2^{81}$ surviving quartets on average. For each such surviving quartet, the adversary can further filter whether the ciphertexts share the same (out of four options) single active inverse diagonal for reducing them to 2^{79}. The adversary identifies candidate keys K^0 and K^6, and discards quartets whose pairs do not suggest at least one shared key. This allows wrong quartets to survive with probability only approximately $4 \cdot 2^{8+8-32} \cdot 4 \cdot 2^{16+16-64} = 2^{-44}$, as before, to reduce them to 2^{35}. On average, the adversary can expect 2^3 good quartets.
In contrast to the CP attack, the active diagonals between quartets may also differ on the plaintext side. Thus, good quartets do not necessarily overlap in any active plaintext diagonals. However, approximating the number of good quartets as a random variable following a binomial distribution $\mathcal{B}(N, 2^{-p})$ with $N \approx 2^{269}$ and $2^{-p} \approx 2^{266}$, the cumulative probability for at least $k \geq 6$ good quartets is greater than 0.808. Since there exist only six options for the two active plaintext diagonals, there will be at least one collision of good quartets that suggest the same values for K^0. Over all quartets, we can expect $\binom{2^{35}}{2} \cdot 2^{-64} \cdot 1/6 \approx 2^{2.4}$ key collisions. For those, the adversary can guess 2^{64} options for the missing key bits of K^0, compute the key schedule to check if they transfer to the known values of K^6, and test the surviving candidates. Then, the adversary can guess 2^{32} options for the 32 missing key bits and test each key with one encryption each. The detailed steps are given in the full version. The attack needs

- $4 \cdot 2^{32+8} = 2^{42}$ memory accesses to get precomputed $4 \cdot 2^8$ key candidates $K^0[0, 5, 10, 15]$ for a given input diagonal difference, corresponding to the four possible positions of a single active byte in ΔW^1.
- $4 \cdot 2^{32+8} = 2^{42}$ memory accesses to get precomputed $4 \cdot 2^8$ key candidates $K^6[0, 7, 10, 13]$ for a given input diagonal difference, corresponding to the four possible positions of a single active byte in ΔZ^5.
- $2^{99.1}$ encryptions by the oracle.
- $4 \cdot 2^{99.1} = 2^{101.1}$ memory accesses to store the texts into four tables for the four options of a single active inverse diagonal in ΔZ^6, and to find $4 \cdot 2^{101.2}$ pairs $(P, \overline{P}, C, \overline{C})$. Note that the four options can define an outer loop.
- Furthermore, it uses in total $6 \cdot 4 \cdot 2^{101.2} \approx 2^{105.8}$ memory accesses to store the pairs into six tables, where a table uses the same two diagonals of both plaintexts from a pair as index, and the tables differ in the diagonal indices they use. For each position of the active inverse ciphertext diagonal, we expect $6 \cdot 2 \cdot \binom{2^{101.2}}{2} \cdot 2^{-64-64} \approx 2^{77}$ quartets, and 2^{79} quartets in total.
- $4 \cdot (2^{79+8} + 2^{79+8}) = 2^{90}$ memory accesses to get precomputed key candidates K^6 for the four options of the active byte, and two pairs of 2^{79} quartets. We expect $4 \cdot 2^{79+16-32} = 2^{65}$ surviving quartets.
- $4 \cdot (2^{65+8} + 2^{65+8}) = 2^{76}$ memory accesses to get key candidates for the first active plaintext diagonal, filtering the quartets down to $4 \cdot 2^{65+16-32} = 2^{51}$.
- $2 \cdot 2^{51+8} = 2^{60}$ memory accesses to get key candidates for the second active plaintext diagonal, filtering the quartets down to $2^{51+16-32} = 2^{35}$.

- 2^{35} memory accesses to find colliding key candidates at the plaintext side. For each surviving pair of quartets, the adversary guesses the missing 64-bit key with $2^{2.4} \cdot 2^{64} = 2^{66.4}$ encryptions on average.

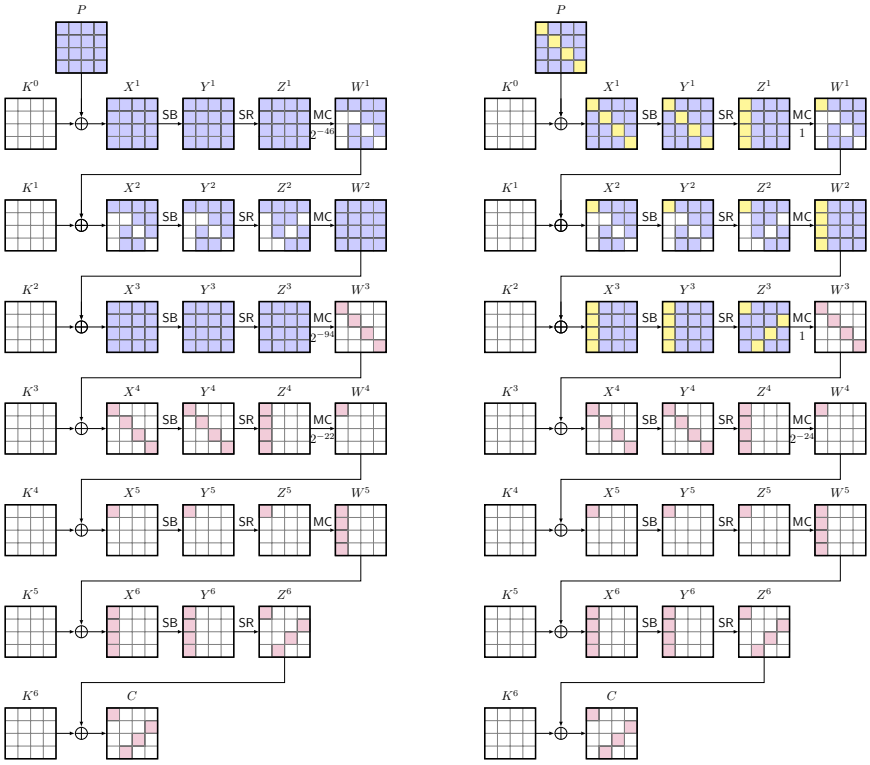
Randomized accesses to huge tables are considerably slower than to small tables that can be cached. We follow earlier works and approximate each memory access to huge tables with a full (here, six-round) encryption equivalent. The time complexity is $2^{42} + 2^{99.1} + 2^{105.8} + 2^{81} + 2^{90} + 2^{76} + 2^{60} + 2^{35} + 2^{66.4} \approx 2^{105.8}$ encryption equivalents. The data complexity is $2^{99.1}$ random known plaintext-ciphertext pairs, and the memory at most $2^{101.2} \cdot 4 = 2^{103.2}$ AES states.

5 Six-round Mixture Distinguisher

Next, we illustrate the transformation of a mixture-differential distinguisher to the random known-plaintext model. If we started from the six-round distinguisher by Bardeh and Rønjom from [4], which starts from pairs with three active plaintext diagonals, and is recalled in the full version the resulting time, data, and memory complexities would be 2^{126} encryption equivalents, $2^{117.5}$ random known plaintexts, and $2^{118.5}$ state equivalents of memory. By choosing a different distinguisher, which is illustrated in Figure 2 and would require more time and data than the original result from [4] in the CP model, we can reduce time and data complexities in the RKP model.

5.1 Parameters in the Chosen-plaintext Model

In the chosen-plaintext model, the attack can start from plaintext structures that iterate over a fixed number of pairwise distinct random values (drawn with replacement) in each plaintext diagonal. In a structure, pairs require all plaintext-difference diagonals to be active. First, the adversary searched for pairs $((P, C), (P', C'))$ that follow the trail of Figure 2, i.e., whose ciphertext difference $C \oplus C'$ has only a single active inverse diagonal. Among those, it restricts its attention to those pairs (P, P') whose mixture pairs $(\overline{P}, \overline{P}')$, generated from exchanging the first plaintext diagonal of P and P', such that the difference $\overline{C} \oplus \overline{C}'$ had only a single active inverse diagonal. The probability that the first pair has only a single active diagonal after the first round is approximately $4 \cdot 2^{-48}$, and approximately $4 \cdot 2^{-96}$ to lead to a single active diagonal with $W^3 \oplus W'^3$ after three rounds. If that is the case, the mixed pair would follow the truncated differential trail having the same difference $\overline{W}^3 \oplus \overline{W'}^3$ with probability one. If the difference of both pairs reduces to a single active byte after the fourth round with probability about 2^{-22-22}, both are mapped to a ciphertext difference with a single active inverse diagonal after six rounds without a final MixColumns operation. Thus, the probability is approximately $2^{-46-94-44} = 2^{-184}$ for a pair and its mixture pair for the real six-round AES, and $2^{-94 \cdot 2} = 2^{-188}$ for a random permutation. The cardinalities of the plaintext- and ciphertext-difference spaces are $|\mathcal{D}_{\text{in}}| \approx 2^{128}$ and $|\mathcal{D}_{\text{out}}| \approx 4 \cdot 2^{32} = 2^{34}$, respectively. The attack needs 2^{93} chosen plaintexts to form approximately 2^{185} pairs in 2^{184} mixture structures.



(a) The first trail of the six-round mixture distinguisher.

(b) The related second trail of the six-round mixture distinguisher.

Fig. 2: The mixture trails on six-round AES. Colored bytes are active in the differential trails. Both figures show two differentials between two related pairs: one differential with all active bytes for one pair, and a differential where one diagonal (colored in red) is exchanged to form a second pair.

5.2 Parameters in the Random Known-plaintext Model

In the RKP model, 2^d plaintexts can form $\binom{2^d}{4} \approx 2^{4d}/24$ quartets, that can be partitioned into two pairs in three distinct ways, with the single exchanged plaintext diagonal could be in either of the two plaintexts in the second pair, yielding approximately 2^{4d-2} mixture quartets $(P, P', \overline{P}, \overline{P}')$. We have expanded the plaintext-difference space to $|\mathcal{D}_{\text{in}}| = 2^{128}$. The probability that $\overline{P}, \overline{P}'$ is a diagonal mixture from (P, P') exchanging the first diagonal is approximately $2^{-128} \cdot 2^{-128} = 2^{-256}$. Moreover, we consider only pairs with $b = 20$ plaintext bits at fixed (choosable by the adversary) positions in the three non-exchanged diagonals to be equal in P and P', which then automatically holds also in $\overline{P}, \overline{P}'$ when they are a mixture pair of (P, P'). To have 2^{184} mixture quartets, we need $d \geq (2 + 256 + 20 + 184)/4$, which yields $d \geq 115.5$.

Algorithm 1 Six-round RKP mixture distinguisher.

function $\mathcal{A}$
  Collect $2^{115.5}$ known plaintext-ciphertext pairs (P, C)
  Store them into a table $\mathcal{Q}$
  for all active inverse ciphertext diagonal indices $j \in \{0, 1, 2, 3\}$ **do**
    Store the pairs into a new table $\mathcal{C}$ indexed by the inverse diagonals of C except for the i-th diagonal and the 20 fixed bits in P
    Identify the approximately $4 \cdot \binom{2^{115.5}}{2} \cdot 2^{-116} \approx 2^{116}$ pairs $((P, C), (P', C'))$
    for all pairs **do**
      for all plaintext diagonal indices $j \in \{0, 1, 2, 3\}$ **do**
        if mixture pair $(\overline{P}, \overline{P}')$ with the j-th plaintext diagonal is in $\mathcal{Q}$ **then**
          if $\overline{C} \oplus \overline{C}'$ has only one active inverse diagonal **then**
            return "real"
  return "random"

The attack steps are detailed in Algorithm 1. The attack can use a table $\mathcal{Q}$ to store the $2^{115.5}$ plaintext-ciphertext pairs (P, C), and then re-index them by the 20 selected bits in P and the values in C in all but the j-th inverse diagonal for all j. Hence, the adversary can identify $4 \cdot \binom{2^{115.5}}{2} \cdot 2^{-20-96} \approx 2^{116}$ pairs $((P, C), (P', C'))$, and look up in $\mathcal{Q}$ whether the mixture pair is also given. Since this covers two ways of matching P, P' to $\overline{P}, \overline{P}'$ or the latter pair in reverse order, and since 20 fixed bits are equal between $\overline{P}$ and $\overline{P}'$ and can be used only once for matching, the adversary can find approximately $\binom{2^{116}}{2} \cdot 2 \cdot 2^{-128-128+20} \approx 2^{-4}$ wrong quartets, but one correct quartet following the trail on average. The attack requires $2^{115.5}$ encryptions and $4 \cdot 2^{115.5} + 2^{116} = 2^{117.94}$ memory accesses to huge tables. Approximating the latter by one six-round encryption equivalent, this yields $2^{118.1}$ encryption equivalents. The attack requires $2^{115.5}$ random known plaintexts and $2^{115.5} \cdot 2 \cdot 2 = 2^{117.5}$ state equivalents of memory.

6 Six-round Truncated-differential Distinguisher

Bao et al. [3] as well as Grassi and Rechberger [37,38] developed truncated-differential distinguishers with very small bias. The works differed in their perspective: the latter two works laid out statistical foundations and focused on many angles of the probabilities of truncated differentials through five-round AES. In contrast, Bao et al. came from the perspective of extending the integral attack to a probabilistic four-round differential, which they extended to five and six rounds thereafter. Rønjom [58] developed a generic framework that uses iterated transition matrices to compute the sum of probabilities over all possible trails, which matched the theoretical results. All those works approximated the AES to have an ideal S-box. Chang et al. [17] refined Bao et al.'s results by studying the distribution of trails with the AES S-box, showing that the bias for the real AES (under random-key assumptions) was larger than assumed in [3].

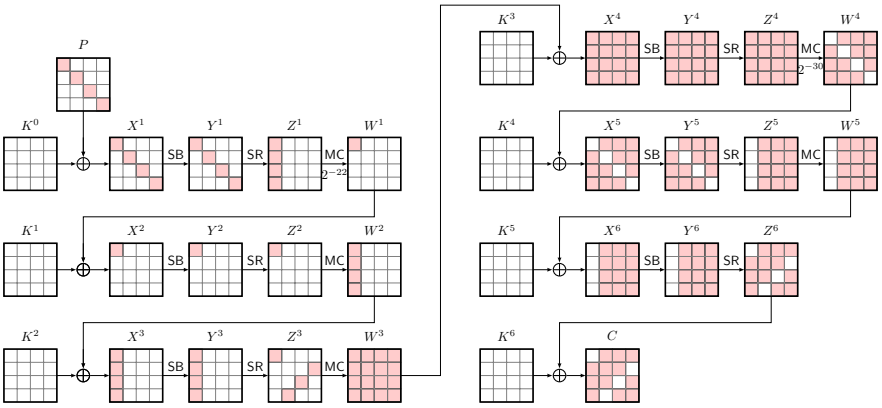


Fig. 3: The six-round truncated-differential distinguisher [3,17] that we transfer to the RKP model. Colored state cells represent active bytes in the trails.

6.1 Evaluating the Probability

Chang et al. derived separate average probabilities p_{i_s,i_e} for all combinations of a starting-byte index i_s to an ending inactive byte index i_e that take the internals of the AES S-box into account. Under the simplifying assumption that inactive bytes in different columns were independent, we can derive the probabilities that a pair with a single active byte in the first column is mapped to a pair through four rounds of AES with the first inverse diagonal being inactive is approximately

$$\begin{aligned}&(2^{-8}+2^{-31.982})\cdot(2^{-8}+2^{-31.774})\cdot(2^{-8}+2^{-31.988})\cdot(2^{-8}+2^{-31.816})\\ \approx\ &2^{-32}+2^{-53.887}\,.\end{aligned}$$

The probability of having the output diagonals 1, 2, or 3 inactive, is approximately $2^{-32}+2^{-53.797}$, $2^{-32}+2^{-53.868}$, and $2^{-32}+2^{-53.792}$, respectively. Moreover, the probabilities of starting from other input diagonals are permutations of those four probabilities. In contrast, for a random permutation, the probability of an inactive inverse diagonal in the ciphertexts is approximately

$$p_{\text{rand}} = (2^{96}-1)/(2^{128}-1) \approx 2^{-32}-2^{-128}\,.$$

6.2 Statistical Framework

We use the statistical framework used in [3,37,38]. Assuming that the normal distribution approximates the binomial distribution sufficiently well for large values of N, the number of independent Bernoulli trials (corresponding to the number of pairs in a truncated-differential attack) N has to satisfy

$$N \geq \frac{2\left(p_{\text{real}}(1-p_{\text{real}}) + \frac{\sigma_{\text{real}}}{\sigma_{\text{rand}}}\cdot p_{\text{rand}}(1-p_{\text{rand}})\right)}{(p_{\text{real}}-p_{\text{rand}})^2}\cdot \mathsf{erfinv}(2p_{\text{succ}}-1)^2\,, \qquad (15)$$

where erfinv denotes the inverse error function and p_{succ} the desired success probability; for $p_{\text{succ}} = 0.95$, it holds that $\mathsf{erfinv}(2 \cdot p_{\text{succ}} - 1)^2 \approx 1.353$. When considering all pairs from all values of a single input diagonal as in [3,37,38], the variance ratio of real five-round AES to a random permutation is beyond one, and up to $\frac{\sigma_{\text{real}}}{\sigma_{\text{rand}}} \approx 16$ when starting from mixture structures as in [37,38]. However, this ratio is approximately one when random pairs are considered.

6.3 Attack Parameters in the Chosen-plaintext Model

Each structure of 2^{32} texts guaranteed a ratio of approximately $4 \cdot (2^8 - 1)/(2^{32} - 1)$ pairs with a single active byte after the first round that are assumed to follow the differential, whereas the remaining pairs were assumed to follow the transition with the probability of a random permutation. Thus, the probability through six rounds of AES could be approximated by

$$p_{\mathsf{AES},6} \approx \left(4 \cdot \frac{2^8 - 1}{2^{32} - 1}\right) \cdot p_{\mathsf{AES},5} + \left(1 - 4 \cdot \frac{2^8 - 1}{2^{32} - 1}\right) \cdot p_{\text{rand}} \,.$$

When we consider random pairs close to uniformly distributed over all input diagonals and output inverse diagonals, we obtain an average probability

$$p_{\mathsf{AES},5} \approx 2^{-32} + 2^{-53.835} \,.$$

When considering any active inverse diagonal in the output, we obtain approximately $p_{\mathsf{AES},5} \approx 2^{-30} + 2^{-51.833}$ in contrast to $p_{\text{rand}} \approx 2^{-30} - 2^{-61.415}$. Then,

$$p_{\mathsf{AES},6} \approx 2^{-30} + 2^{-74.058} \,.$$

For $\frac{\sigma_{\text{real}}}{\sigma_{\text{rand}}} \approx 16$, one obtains $N \geq 2^{121.64}$ pairs, yielding $2^{58.64}$ structures of 2^{32} chosen plaintexts each, or $2^{90.64}$ chosen plaintexts. For $\frac{\sigma_{\text{real}}}{\sigma_{\text{rand}}} \approx 1$, $N \geq 2^{118.55}$ pairs, yielding $2^{55.55}$ structures of 2^{32} plaintexts each, or $2^{87.55}$ chosen plaintexts.

6.4 Parameters in the Random Known-plaintext Model

The cardinalities of the plaintext- and ciphertext-difference spaces of the adapted attack are $|\mathcal{D}_{\text{in}}| \approx 2^{34}$ and $|\mathcal{D}_{\text{out}}| \approx 2^{98}$. In the RKP model, we obtain $2^{2d-1-n+\delta_{\text{in}}}$ pairs in the desired plaintext space from 2^d plaintexts. That is, we can use a slightly larger plaintext space than in the original chosen-plaintext attack, as all plaintext pairs with a single active diagonal can lead to a single active byte. To have $N \geq 2^{118.55}$ pairs that start from a single active diagonal, we need

$$2^{2d-1-n+\delta_{\text{in}}} = 2^{118.55} \,,$$

which yields $d = 106.8$, i.e., $2^{106.8}$ random known plaintexts that can form approximately $2^{212.6} \geq 2^{118.55+94}$ pairs, as in the original attack. The steps of the attack are given in Algorithm 2. The computational complexity consists of

- $2^{106.8}$ encryptions,

Algorithm 2 Six-round RKP truncated-differential distinguisher.

function $\mathcal{A}$
  Collect $2^{106.8}$ known plaintext-ciphertext pairs (P, C)
  Store them into a table $\mathcal{Q}$
  count $\leftarrow 0$
  for all active plaintext diagonal indices $i \in \{0, 1, 2, 3\}$ **do**
    for all active inverse ciphertext diagonal indices $j \in \{0, 1, 2, 3\}$ **do**
      Store the plaintext-ciphertext pairs (P, C) in a second table $\mathcal{T}$ indexed by all but the i-th diagonals of P and the j-th inverse diagonals of C
      for all colliding pairs **do**
        count $\leftarrow$ count $+ 1$
  if count $\geq 2^{88.6} - 2^{56.2}$ **then**
    return "real" ▷ We expect count $\approx 2^{88.6} + 2^{44.6}$ on average
  return "random" ▷ We expect count $\approx 2^{88.6} - 2^{57.2}$ for a random permutation

- $2 \cdot 4 \cdot 4 \cdot 2^{106.8} \approx 2^{111.8}$ memory accesses to tables, and
- $2^{88.6} + 2^{44.6}$ increment operations on average for six-round AES.

Approximating each lookup into a huge table as a full encryption equivalent, we obtain $2^{106.8} + 2^{111.8} + 2^{88.6} + 2^{44.6} \approx 2^{111.9}$ encryption equivalents. The memory complexity is given by $2^{106.8} \cdot 3 \approx 2^{108.4}$ state equivalents.

7 Impossible-differential Attack on Seven-round AES-128

Here, we consider the attack by Leurent and Pernot [46,47], who slightly improved the attack by Boura et al. [15,16].

7.1 Original Attack Parameters

The cardinalities of plaintext- and ciphertext-difference spaces are $|\mathcal{D}_{\text{in}}| \approx 2^{64}$ and $|\mathcal{D}_{\text{out}}| \approx 2^{32}$ as the key-recovery procedure fixes the spaces of interests. The attack uses structures of 2^{64} chosen plaintexts that produced approximately $2^{2\delta_{\text{in}}-1} \approx 2^{127}$ pairs. Given an initial filter of $2^{\delta_{\text{out}}-n} \approx 2^{-96}$, there are on average

$$2^{s_p} = 2^{2\delta_{\text{in}}-1+\delta_{\text{out}}-n} \approx 2^{31}$$

surviving pairs per structure. There are $c_{\text{in}} = 46$ bit conditions on the plaintext-side guessing trail and $c_{\text{out}} = 22$ bit conditions on the ciphertext-side guessing trail. Moreover, there are $k_{\text{in}} = 80$ key bits and $k_{\text{out}} = 32$ key bits involved, with a union of $k_{\text{atk}} = k_{\text{in}} \cup k_{\text{out}} = 112$ key bits, which has a gap of $a = k - k_{\text{atk}} = 128 - 112 = 16$ bits. Therefore, the number of surviving pairs 2^d must satisfy

$$\left(1 - 2^{-c_{\text{in}}+c_{\text{out}}}\right)^{2^d} \leq 2^{-a}$$

which yields $2^d \geq 2^{71.5}$ and thus $2^s = 2^d/2^{s_p} = 2^{71.5-31} = 2^{40.5}$ structures. This corresponds to $2^{s+\delta_{\text{in}}} = 2^{40.5+64} = 2^{104.5}$ chosen plaintexts to have a bits of

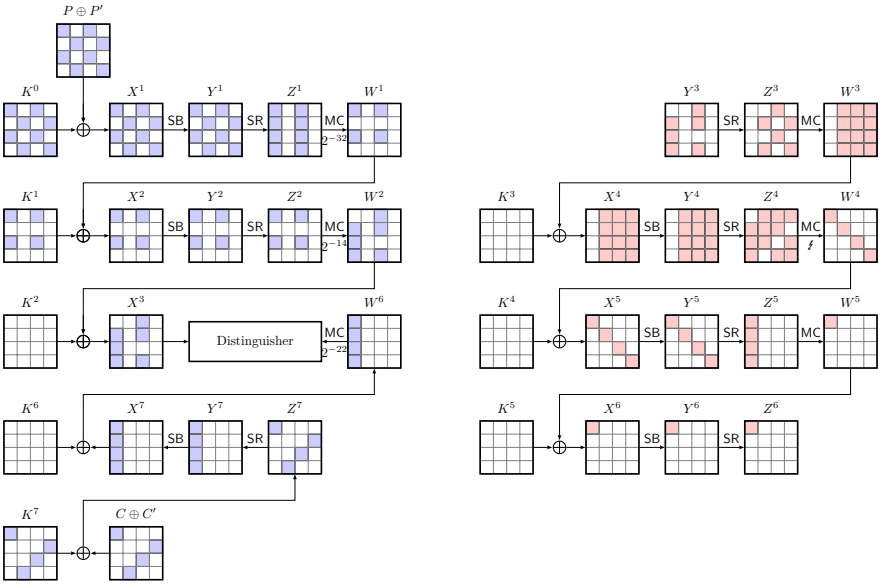


Fig. 4: Seven-round impossible-differential attack on AES-128. Left: The online key-recovery phase. Right: The impossible-differential distinguisher. Colored state bytes are active in the differential trails. Colored key bytes are filtered.

advantage. Finally, the attack can guess the remaining a bits not covered in the attack to recover the full key with one encryption per remaining full candidate in $2^{k-a} = 2^{112}$ encryptions on average.

7.2 Parameters in the Random Known-plaintext Model

In the RKP model, pairs occur randomly in the desired plaintext space. Given 2^p plaintexts, we can form 2^{2p-1} pairs. From those, approximately

$$2^{2p-1+\delta_{\text{in}}+\delta_{\text{out}}-2n} = 2^{2(p-n)-1+\delta_{\text{in}}+\delta_{\text{out}}}$$

pairs are surviving pairs, i.e., lie in the desired plain- and ciphertext spaces. Thus, to have the same number of surviving pairs 2^d as before, we need

$$\begin{aligned} 2(p-n) - 1 + \delta_{\text{in}} + \delta_{\text{out}} &= d \\ ((2n+1) - \delta_{\text{in}} - \delta_{\text{out}} + d)/2 &= p\,, \end{aligned}$$

which yields $p = (257 - 96 + 72)/2 = 116.5$. Therefore, the attack needs $2^{116.5}$ random known plaintext-ciphertext pairs on average.
The attack collects and stores them, that is $2^{117.5}$ plaintext-ciphertext states, and identifies approximately $\binom{2^{116.5}}{2} \cdot 2^{-64-96} = 2^{72}$ surviving pairs. For each, it can use a few table lookups to identify $2^{112} \cdot 2^{-68} = 2^{44}$ keys that it can discard on average. For that purpose, it has a table $\mathcal{K}$ of 2^{112} bits that represent the key candidates, or 2^{105} AES state equivalents. Thus, the time complexity consists of

- $2^{116.5}$ encryptions,
- $2^{116.5}$ lookup and store accesses each into a huge table,
- $2^{72} \cdot 8$ lookups into smaller tables whose size is negligible,
- $2^{72} \cdot 2^{44}$ bit sets into the huge table $\mathcal{K}$,
- 2^{112} sequential lookups to find surviving keys,
- and at most 2^{100} final encryptions,

which can be upper bounded by $2^{116.5}+2^{100} \approx 2^{116.5}$ encryptions and $2^{117.5}+2^{72} \cdot 8+2^{72+44}+2^{112} \approx 2^{117.5}$ memory accesses into huge tables. Approximating one lookup by one encryption equivalent produces a total of $2^{116.5}+2^{117.5} \approx 2^{118.1}$ encryption equivalents. The memory complexity is at most $2^{117.5}+2^{105} \approx 2^{117.5}$ state equivalents.

7.3 Further Applications to Round-reduced AES-192 and AES-256

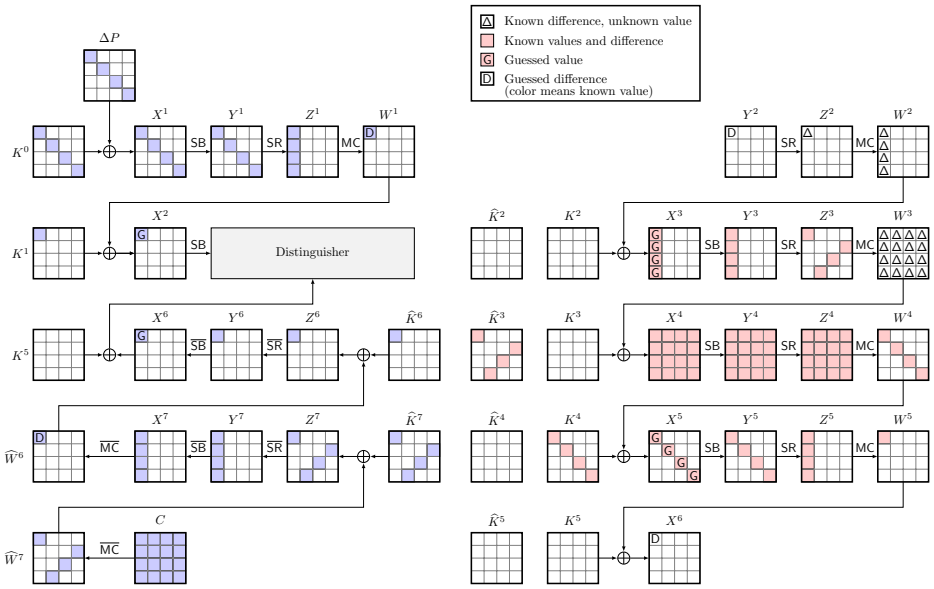
In the full version, we provide two further impossible-differential attacks in the RKP model on seven rounds of AES-192 and eight rounds of AES-256, respectively. Both improve over the decade-old six-round zero-correlation attack from [10] and the six-round meet-in-the-middle attack from [12] that, to the best of our knowledge, have remained the best attacks on those AES variants in the RKP model so far. The attack on seven-round AES-192 uses a similar trail as the attack on seven rounds of AES-128, which led to lower overall complexities compared to the earlier results from [49].
For AES-256, Kara had proposed an updated eight-round attack in the RKP model [43]. We remark on the complexity estimation in the full version arguing that the data complexity seems not to suffice. There, we also note that his attack may be salvaged straightforwardly but leads to higher data and time complexities than our result, as we can replace its trail with the better one from [51].

8 DS-MitM Attack on Seven-round AES-128

In the following, we illustrate with an adaptation of the attack on seven-round AES-128 that also attacks with various related texts, such as DS-MitM attacks, can be transformed to the RKP model.

8.1 Attack in the Chosen-plaintext Model

The original attack uses several differential trails: from two active bytes after the first round to a single active byte after five rounds, and from one active byte after the first round to two active bytes in the same column after five rounds. We expect the reader to be familiar with the attack on seven-round AES-128 from [24] or refer to it for details.



(a) The outer rounds of the online filtering and key-recovery phase.

(b) Distinguisher trail.

Fig. 5: Key-recovery rounds and distinguisher for one of 2^6 differential trails in the distinguisher from the DS-MitM attack on seven-round AES-128. Colored and marked bytes are active (different between texts).

8.2 Attack in the Random Known-plaintext Model

In contrast to the original attack, in the RKP model, the related texts are not guaranteed to be part of the available data. We conduct the online phase first and store the results before conducting the offline phase. From an analysis of the configurations of the number of in- and output bytes in the offline trails, the complexity for testing the number of surviving pairs easily becomes the bottleneck. Dong et al.'s value constraints can be used at the end to reduce the number of available pairs. Since the adversary must keep track of plaintext-ciphertext pairs, storing and testing for pairs of 2-to-1 trails can easily become the bottleneck of the attack. Thus, we consider only 1-to-1 trails, i.e., truncated differentials from a single active byte in ΔY^2 to a single active byte in ΔX^6.

Online Phase. The online phase differs from that in [24] in several aspects:

1. There are no plaintext structures.
2. It uses only trails from a single active byte to a single active byte.
3. It further restricts the attack to trails from a single active byte to a single active byte from the first active plaintext diagonal and the first column of $\Delta\widehat{W}^7 = \mathsf{MC}^{-1}(\Delta C)$.

The adversary observes 2^d plaintext-ciphertext known pairs and stores them in a table corresponding to the values of the plaintexts in all diagonals except the fixed (e.g., the first) diagonal and the values of ciphertexts without the fixed inverse diagonal of $\widehat{W}^7$. It identifies $\binom{2^d}{2} \cdot 2^{-96-96} \approx 2^{2d-193}$ pairs of plaintext-ciphertext pairs. For each pair, the adversary guesses all possible indices of the single active byte position after the first round and after six rounds, and its approximately 2^8 possible differences. It uses precomputed hash tables to obtain the approximately 2^{10} corresponding possible keys.
We constrain the active byte in $\Delta Y^2 = Y^2 \oplus Y'^2$ to α differences, in the manner introduced by Dong et al. [26]. If the constraint is not satisfied, we discard the current pair-key combination. Similarly, we restrict the 255 options to β values for the difference in the active byte in $\Delta X^6 = X^6 \oplus X'^6$.
From ΔY^2, the adversary iterates over the first m nonzero differences of the active byte, computes backwards to their corresponding plaintexts, looks up the available plaintexts in the data, and identifies the lexicographically first k available ciphertexts among those. If $k < \theta_k$, i.e., the number of available plain- and ciphertexts among the first m nonzero differences is below a threshold, it discards the current pair. Then, for the first k found plaintexts among the first m plaintexts, it looks up the corresponding ciphertexts. It guesses the difference in the possible single active byte in $\Delta\widehat{W}^6$, and looks up the 2^{10} would-be values of the corresponding active inverse diagonal of Z^7 from precomputed hash tables to derive the bytes of $\widehat{K}^7$. It guesses the 2^8 key candidates for the active byte in ΔX^6. For all pairs with $k \geq \theta_k$, the adversary computes from the ciphertexts to the active byte in X^6 for the current key guess and derives the differences to the fixed text for all k further texts. It uses the differences of the lead pair at ΔX^6 as well as the differences of the texts at $X_i^6[j] \oplus X^6[j]$ for the first $i = 1..k$ texts at the active byte into a table $\mathcal{T}_{\mathsf{online}}$, indexed by that vector and the indices of the first available k texts, $i_1, \ldots, i_k$, and stores a reference to the plaintext pair, and the induced keys, and all other given byte differences ΔX_i^6 for $i > k$ and their indices into the table entry.

Offline Phase. The offline phase works similarly as in the attack from [24] with several differences: Using row-wise rotational symmetry that was not observed by [24], the procedure needs only 16 tables and trail computations instead of 2^6 to capture all $4 \cdot 4$ combinations of active byte positions in the first column of X^2 and positions in the first diagonal of X^6.
The adversary restricts the difference in the active byte of ΔY^2 to $\alpha \geq 1$ fixed chosen non-zero eight-bit constants. Similarly, it restricts the difference in the active byte in ΔX^6 to $\beta \geq 1$ fixed chosen non-zero eight-bit constants. The adversary traces the approximately 2^8 related texts through the offline phase. Afterwards, it first extracts all $\binom{m}{k}$ combinations of k out of the first m differences to the first text. Let $i_1, \ldots, i_k$ be the k out of $\{1, \ldots, m\}$ indices. For all those combinations, it looks up the string of $\Delta X^6, \Delta X_1^6, \ldots, \Delta X_k^6, i_1, \ldots, i_k$ if it is stored in $\mathcal{T}_{\mathsf{offline}}$. For all matches, it uses the remaining available texts in the table entry to further filter matches. All matches that survive this stage produce a key candidate: 32 bits of $K^0[0, 5, 10, 15]$, 32 bits of $\widehat{K}^7[0, 7, 10, 13]$, eight bits

of K^1, eight bits of $\widehat{K}^6$, as well as 32 bits of $\widehat{K}^3$, and 32 bits of K^4. Even with the key-schedule representations by [46,47], it is not easy to filter them further. However, the adversary can collect them in a table and count the occurrences. Finally, it outputs the key candidates with the highest counts. The detailed steps are provided in the full version.

Online-phase Complexity. The probability of pairs to fulfill the trails from one active plaintext diagonal to a single active ciphertext diagonal is approximately $2^{-96} \cdot 2^{-96} = 2^{-192}$. Given 2^d data, we expect 2^{2d-193} pairs that fulfill this filter. The probability of having a single active byte in the first diagonal after the first round and in the first column after five rounds is $4 \cdot 2^{-120} \cdot 4 \cdot 2^{-120} = 2^{-236}$. We expect 2^{2d-237} correct pairs, i.e., pairs that follow the offline-phase trail, and to have a fraction of approximately 2^{-44} of correct pairs that satisfy the first filter. The complexity of the online phase consists of 2^d encryptions and 2^d lookup-and-store memory accesses into a huge table. Next, the adversary identifies 2^{2d-193} pairs. For each of them, it guesses $4 \cdot 255 \approx 2^{10}$ keys on average, or analogously the α differences in ΔW^1, and encrypts the pairs through the first two rounds. For the non-discarded pairs, it derives 2^8 texts and traces them backwards through the inverse first two rounds. Using 2^{-4} seven-round encryption equivalents as [24] did, this yields $\alpha \cdot 2^{2d-193+10-4} = \alpha \cdot 2^{2d-187}$ encryption equivalents. For each, it computes up to $\alpha \cdot 2^{2d-187} \cdot 2^8 \cdot 2^{-4} = \alpha \cdot 2^{2d-183}$ re-decryptions and needs up to $\alpha \cdot 2^{2d-179}$ memory accesses to a large table to obtain the plaintexts and their corresponding ciphertexts. Next, the adversary takes the $\alpha \cdot 2^{2d-187}$ entries, obtains 2^{10} keys from hash tables for $\widehat{K}^6$, and traces the up to 2^8 texts two rounds backwards to the β differences of ΔX^6 and derives the differences. This costs at most $\alpha \cdot \beta \cdot 2^{2d-187} \cdot 2^{10} \cdot 2^8 \cdot 2^{-4} = \alpha \cdot \beta \cdot 2^{2d-173}$ encryptions, and $\alpha \cdot \beta \cdot 2^{2d-169}$ accesses for the $\alpha \cdot \beta \cdot 2^{2d-169}$ entries on average.
For $d = 124$, $k = 9$, and $m = 144$, we obtain 2^{11} correct pairs and 2^{55} wrong pairs after the first filter, and can expect $2^{11-3} = 2^3$ correct pairs when $\alpha = 1$ and $\beta = 255$, i.e., we have an eight-bit constraint at ΔY^2 and none at ΔX^6. The online phase needs approximately

$$2^d + 2^{2d-187} + 2^{2d-183} + 2^{2d-165} = 2^{124} + 2^{61} + 2^{65} + 2^{83} \approx 2^{124}$$

encryption equivalents and

$$2^d + 2^{2d-179} + 2^{2d-187} + 2^{2d-161} = 2^{124} + 2^{69} + 2^{61} + 2^{87} \approx 2^{124}$$

memory accesses.

Offline-phase Complexity. The offline phase computes 16 tables, and traces up to 2^8 texts for $\alpha \cdot \beta \cdot 2^{8 \cdot 8}$ guesses of internal values with 2^{-4} encryption equivalents per text, i.e., $\alpha \cdot \beta \cdot 2^{72}$ encryption equivalents for $\alpha \cdot \beta \cdot 2^{68}$ table entries in total. For each, it extracts the first $\binom{m}{k}$ options with 2^{-4} matches of the table options with $\alpha \cdot \beta \cdot 2^{68} \cdot \binom{m}{k}$ lookups. For $\alpha = 1$ and $\beta = 255$, we have 2^{76} table entries, out of which a fraction of 2^{-4} applies to a position (i, i') in ΔY^2 and ΔX^6

$$(2^{2d-169-4} \cdot 2^{76-4}) \cdot 2^{-4 \cdot (k+1)} \cdot \binom{m}{k} \quad \text{matches} \tag{16}$$

on average. Here, the $k+1$ indicates the difference in a byte in $\Delta X^6[i']$ for the reference pair and k further texts. For each match, it uses the remaining matches to filter the options further. $d = 124$, $k = 9$, and $m = 144$, $\binom{m}{k} \approx 2^{45.7}$, so that the offline phase needs approximately 2^{80} encryptions as well as $2^{76} \cdot 2^{45.7} \approx 2^{121.7}$ memory accesses. From Equation (16), the adversary can expect

$$2^{2 \cdot 124 - 169 - 4} \cdot 2^{76-4} \cdot 2^{-10 \cdot 8} \cdot 2^{45.7} \approx 2^{112.7} \quad \text{matches.}$$

Given 2^{124} distinct random plaintexts, the probability for any text to be available is 2^{-4}. From 256 texts in a δ-sequence, the adversary can expect $256 \cdot 2^{-4} = 16$ texts on average, i.e., seven further bytes in the 2^8 related texts to be available that have not been used before, with another filter of 2^{-56} to obtain $2^{112.7-56} \approx 2^{56.7}$ surviving matches. For each, it stores the union of key information from K^0 and $\widehat{K}^7$ into a table. Given 2^3 correct pairs on average, we can expect the correct key candidate of the 64 bits of K^0 and K^7 to be the only one that is suggested at least four or more times.
To sum up, the phases of the attack combined need 2^{124} random known plaintexts, negligible memory for the hash tables and keys, but memory for 2^{124} plaintext-ciphertext pairs, and 16 would-betables with 2^{64} entries at a time each, or 2^{76} entries. Thus, the memory is dominated by 2^{125} state equivalents for finding ciphertext pairs in the online phase. The attack requires $2^{124} + 2^{80} \approx 2^{124}$ encryption equivalents and $2^{124} + 2^{121.7} + 2^{112.7} + 2^{56.7} \approx 2^{124.3}$ memory accesses. Approximating each memory access to huge tables by one seven-round encryption, the complexity is $2^{124} + 2^{124.2} \approx 2^{125.1}$ encryption equivalents.

9 Conclusion

We revisited and extended the set of relations between differential-based attacks on block ciphers in the chosen- and in the random known-data model. With the AES as probably the most widely deployed and used block cipher and therefore a highly relevant example, we showed explicit adaptations of some of the best distinguishers and attacks to the RKP model, improving over the best attacks on all versions of the AES in that model. The number of required related texts in DS-MitM attacks had made conversions from the CP to the RKP model seem impractical, up to the use of (almost) the full codebook. However, we demonstrated that a probabilistic approach allows for mounting DS-MitM attacks in the RKP model. Our attacks may seem similar to statistical methods, such as statistical integrals [61]. However, while they allowed for reducing the data complexity of integral attacks, their technique still assumed chosen-data adversaries. Naturally, the high complexities render all our attacks purely academic and no threat to the security of the full-round AES, but demonstrate that they may remain applicable in the known-plaintext setting. We leave the study of further implications to other ciphers and techniques as interesting future work.

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