A Masked White-box Cryptographic Implementation for Protecting against Differential Computation Analysis

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Abstract. Recently, gray-box attacks on white-box cryptographic implementations have succeeded. These attacks are more efficient than white-box attacks because they can be performed without detailed knowledge of the target implementation. The success of the gray-box attack is due to the unbalanced encoding used to generate the white-box lookup table. In this paper, we propose a method to protect the gray-box attack against white-box implementations. The basic idea is to use Boolean masking before encoding intermediate values during the white-box lookup table generation. Compared to the existing white-box AES implementation, the lookup table size and the table lookups increase by about 1.5- and 1.6 times, respectively.

Keywords: White-box cryptography, power analysis, differential computation analysis, countermeasure.

1 Introduction

As personal devices become more diverse, the amount of data that needs to be protected has also increased. To protect this broad category of personal information, we use various encryption algorithms which are publicly known. For this reason, we should securely protect the secret key. The attack models that malicious attackers use to recover the secret key can be divided into three layers: the black-box, the gray-box, and the white-box models. As the color of the layer becomes brighter, the amount of information that the attacker can access increases. Attackers in the black-box model are given the in- and output for cryptographic primitives, but in the gray-box model they also utilize additional information leakage, i.e., side-channel information, such as timing or power consumption. As a representative example, Kocher *et al.* presented Differential Power Analysis (DPA) [14], a statistical analysis of power traces acquired during the execution of a target cryptographic primitive. In addition to all of these, attackers in the white-box model can access and modify all resources in the execution environment. Therefore, if the secret key used for the cryptographic primitive resides in memory without any protection, it may leak directly to the white-box attacker.

The white-box cryptographic implementation is intended to counter this white-box attack: the key idea behind is to embed the secret key in the implementation using precomputed lookup tables and to apply linear and non-linear encodings so that it becomes difficult for a white-box attacker to extract the secret key [9][10]. Although it is a strong point to hide the key in the software implementation, there are three main disadvantages that have been known so far. Since the table itself acts as a secret key, taking the table has the same meaning as taking the secret key. It is often called a code-lifting attack [32]. In this regard, many researchers have attempted to mitigate the code-lifting attack by significantly increasing the size of the lookup table [3][5]. The serious problem is that as the memory requirement increases, the cost of software cryptographic implementation becomes closer to the cost of hardware cryptographic one. Second, the use of lookup tables increases the memory requirement and slows down the execution speed compared to a non-white-box implementation of the same algorithm. Moreover, the size of the look-up table has increased considerably with the aforementioned anti-code-lifting technique. Finally, many white-box implementations have been practically broken by various attacks including key extraction, table-decomposition, and fault injection attacks [29]. The first two white-box implementations for DES [10] and AES [9] were shown to be vulnerable to differential cryptanalysis [12][33] as well as algebraic cryptanalytic attacks [2][18][21]. Although several further variants of white-box implementations for DES and AES have been proposed [8][34][13][16], many of them were broken [25][26]. In addition to standard ciphers, research has also been conducted on various non-standard ciphers, so-called dedicated white-box ciphers [3][5][22]. It is worth noting that these attacks have been performed in the white-box model requiring the details of the target implementation.

However, the white-box cryptography currently faces the most serious problem: the gray-box model attack on white-box implementations has succeeded. In other words, it is possible to reveal the secret key embedded in a white-box implementation using side-channel information without any detailed knowledge about it. In general, side-channel analysis, more specifically power analysis, is successful if the key hypothesis of the attacker is correct, since the intermediate value calculated from the correct hypothesis correlates to the power consumption value at particular point in the power trace. The authors of [6] have developed plugins for dynamic binary instrumentation (DBI) tools including Pin [19] and Valgrind [27] to obtain software execution traces that contain information about the memory addresses being accessed. Their so-called Differential Computation Analysis (DCA) is more effective because there is no measurement noise in software traces unlike power traces obtained using the oscilloscope in classical DPA. The main reason behind the success of DCA is due to the imbalances in linear and non-linear encodings used in the white-box implementation [30]. The authors of [6] have suggested several methods to counteract DCA including variable encodings [24], threshold implementations [28], splitting the input in multiple shares to different affine equivalence, and a masking scheme using the input data as a random source. Since DCA uses the memory address accesses available in the software traces, some obfuscation techniques including control flow obfuscation and table location randomization have been discussed.

Our Contribution. This study is to present a masked white-box implementation for protecting against DCA as well as power analysis. Boolean masking is applied during the lookup table generation unlike the existing masking techniques that are used in runtime. In other words, we do not need any random source at runtime. As a result, the runtime overhead does not increase significantly. We begin by going over the initial white-box AES (WB-AES) [9] to demonstrate its vulnerability to DCA. We apply a masking technique to this vulnerable implementation to improve security. To evaluate the security of our proposed method, we perform DCA on the masked WB-AES implementation with 128-bit key. In addition, we further validate it through the Side-channel Analysis Resistant Framework (SCARF) system and the Walsh transforms. The experimental results show that our proposed method effectively defends the attacks. Compared to the existing WB-AES implementation, the lookup table size and the number of lookups increase approximately 1.5- and 1.6 times, respectively. These become 3.68- and 1.74 times in the case that we provide additional protecting of the final round for more reliable security.

Organization of the paper. The remainder of this paper is organized as follows: Section 2 provides an overview of white-box cryptography and its vulnerabilities to the gray-box attack. We propose a white-box implementation for protecting against DCA in Section 3. We introduce a masked WB-AES implementation and analyze its performance including the lookup table size. In Section 4, we demonstrate the security of our proposed method through DCA, SCARF and the Walsh transforms. Section 5 concludes this paper.

2 Preliminaries

In this section, we introduce the basic concept of white-box cryptography and provide experimental results about its vulnerability to gray-box attacks.

2.1 Overview of White-box Cryptography

In most cases, a white-box implementation is simply a series of encoded lookup tables which replace individual computational steps of a cryptographic algorithm. Let us give a simple example. For a computational step $y = E_k(p)$, where y, p, $k \in \mathrm{GF}(2^8)$ and k is a small portion of the secret key, let $\mathcal{E}_k$ be an 8×8 lookup table to map p to y. The secret and invertible encodings are then applied to $\mathcal{E}$ in order to prevent a white-box attacker from recovering the secret key using the input and output values. Let us denote the encodings by G and F, for example. Then we have: $\mathcal{E}_k = G \circ E_k \circ F^{-1}$. It is important to remember that each encoding consists of linear and non-linear encodings.

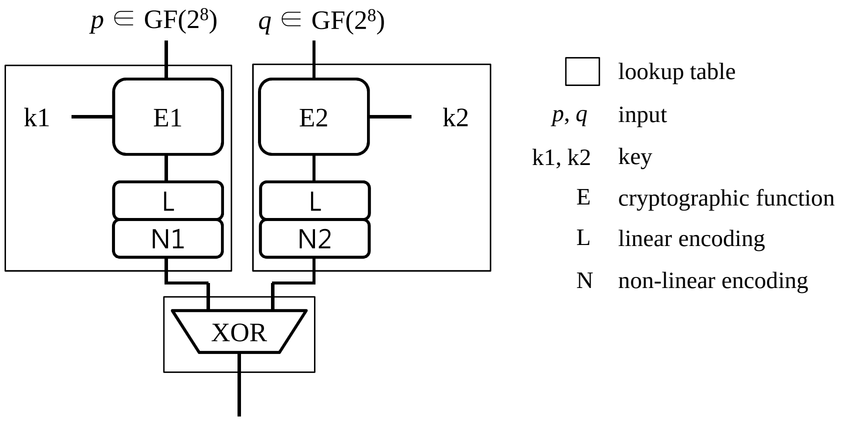


Fig. 1: Basic principle of existing white-box cryptographic implementations.

Fig.1 shows a basic principle of existing white-box implementations for a cryptographic operation, $E1(p, k1) \oplus E2(q, k2)$. If two lookup values are to be combined through an XOR operation, the XOR operation is applied during the lookup table generation after only non-linear decoding without decoding the linear encoding. This is due to the distributive property of multiplication over addition. Of course, the linear encoding applied to the two lookup values should be the same. When the above principle is extended, a ciphertext can be obtained by table lookups while hiding the secret key.

2.2 Gray-box Attacks on White-box Cryptography

For a gray-box attacker, suppose the followings:

- The underlying cryptographic algorithm is known, for example AES.
- The details about the type of the implementation and its structure are unknown.
- There is no external encoding in the target implementation; the cryptographic operation seen by the attacker is standard AES encryption (or decryption).
- The attacker can collect power traces (software traces in the case of DCA) while it is operated.

We examine the result of DCA on an unprotected WB-AES-128 implementation [9] under this gray-box attack model. We have used Valgrind, a DBI framework, to collect 200 software traces with random plaintexts and performed mono-bit Correlation Power Analysis (CPA) [7] attacks on the SubBytes output in the first round using Daredevil as introduced in [6]. The result reports two top 10 lists:

Table 1: DCA ranking for the target WB-AES implementation [9] when attacking the SubBytes output in the first round with 200 software traces.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	183	219	1	1	213	1	1	1	213	186	229	1	81	1	1
2	1	1	1	1	87	1	1	1	209	1	1	1	1	1	1	1
3	17	66	83	46	41	146	151	172	159	34	203	1	1	252	242	205
4	1	1	99	225	1	1	249	131	1	1	118	193	1	199	174	223
5	141	1	1	174	106	1	1	144	205	1	1	68	171	1	1	25
6	256	9	177	194	140	1	182	13	201	1	222	54	155	1	69	150
7	83	212	1	184	78	246	25	181	60	195	196	117	63	65	134	155
8	1	232	204	1	1	249	183	27	1	211	103	95	1	176	230	17
sum	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
highest	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

- the **sum** of the correlation coefficients for 8 mono-bit CPA attacks for each key byte candidate
- the **highest** correlation coefficient among the mono-bit CPA results for all key byte candidates

If at least one of the two lists has the correct key at the top of the list, it is assumed that the key is found (the key candidate would not be determined solely by the mono-bit CPA result for a particular bit).

As a result, all 16 correct key bytes are revealed as shown in Table 1. We have performed a total of 20 DCA attacks; DCA recovered an average of 14.3 (Standard Deviation = 2.17) key bytes with 200 software traces when attacking the unprotected WB-AES implementation; recovering the small number of missing key bytes is trivial using brute-force attacks. The attack success rate was about 89% (286/320), and the highest value average of the mono-bit CPA correlation coefficient for the correct key byte was 0.557 (S.D = 0.173). If the number of traces provided to the attack were greater, the attack success rate and correlation coefficient would be higher.

We conducted additional experiments using SCARF [31][15][17] to further investigate where and how key leaks occur. To do this, we also collected 200 software traces consisting only of *0*s and *1*s based on each bit of the target intermediate value (Fig. 2), and mounted CPA using the SubBytes output in the first round. The highest peak in the correlation plot shown in Fig. 3 was found at the point where the output of SubBytes multiplied by 01 was looked up for MixColumns operation. Even though the lookup value was encoded, CPA was possible.

Sasdrich *et al.* [30] have indicated that the main reason behind successful DCA and CPA attacks is largely due to the high imbalance in encoding used to generate white-box tables. Based on their definitions below, we demonstrate

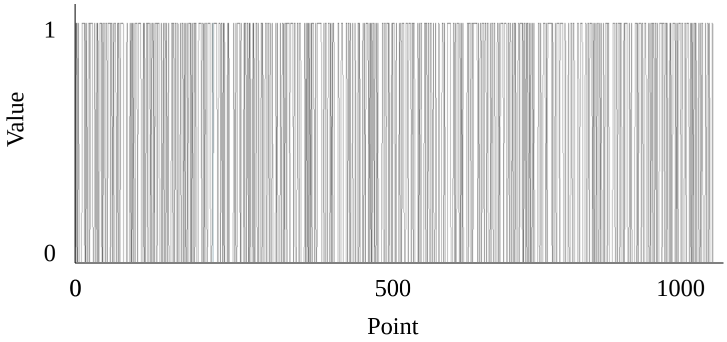


Fig. 2: SCARF software trace including only 0 or 1.

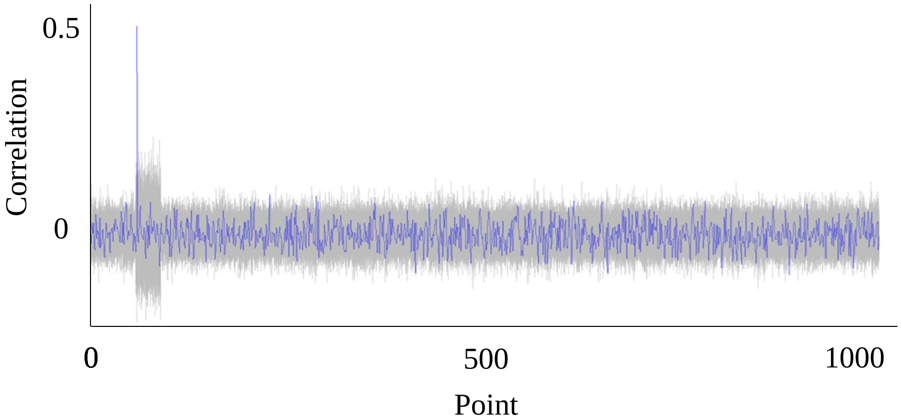


Fig. 3: A peak in the CPA result when attacking the SubBytes output in the first round. Blue line: correct key hypothesis, gray line: wrong key hypothesis.

the imbalance in the encoding used for the same lookup table that was attacked above.

Definition 1. *Let $x = \langle x_1, \ldots, x_n \rangle$, $\omega = \langle \omega_1, \ldots, \omega_n \rangle$ be elements of $\{0,1\}^n$ and $x \cdot \omega = x_1\omega_1 \oplus \ldots \oplus x_n\omega_n$. Let $f(x)$ be a Boolean function of n variables. Then the Walsh transform of the function $f(x)$ is a real valued function over $\{0,1\}^n$ that can be defined as $W_f(\omega) = \Sigma_{x \in \{0,1\}^n} (-1)^{f(x) \oplus x \cdot \omega}$.*

Definition 2. *Iff the Walsh transform W_f of a Boolean function $f(x_1, \ldots, x_n)$ satisfies $W_f(\omega) = 0$, for $0 \leq HW(\omega) \leq m$, it is called a balanced m-th order correlation immune (CI) function or an m-resilient function, where HW stands for the Hamming weight.*

Let us denote the output of SubBytes by x and the combination of MixColumns, linear and non-linear encodings by 32 Boolean functions $f_{i \in \{1,\ldots,32\}}(x)$: $\{0,1\}^8 \rightarrow$

$\{0,1\}$. For all key candidates k^* and for all ω we calculated the Walsh transforms W_{f_i} and summed up all the imbalances for each key candidate as follows:

$$\Delta_{k\in\{0,1\}^8} = \sum_{\forall\omega\in\{0,1\}^8} \sum_{i=1,\ldots,32} |W_{f_i}(\omega)|; k^* = k.$$

Then this gives us as shown in Fig. 4 that Δ_k of the correct key candidate (*0x*88, 136) is obviously distinguishable from that of other key candidates. Based on this fact, it can be said that DCA and power analysis would be protected if for all ω the distribution of the Walsh transforms of all f_i is not distinguishable from that of other key candidates. In the next section, we propose our masked white-box implementation. We conduct DCA to evaluate its security. Also, we use the Walsh transforms to see if there is still a problematic correlation between the lookup values and the secret key, although there is no difference in the encoding used.

3 Proposed Method

In this section, we propose a masked white-box implementation to depend against DCA. As aforementioned, the vulnerability to DCA of the white-box implementation is due to the imbalanced encoding. Our goal is to reduce the correlation to the key at the intermediate values before encoding them in the process of generating the white-box lookup table. To achieve this, we use masking with a balanced distribution at the key-sensitive intermediate value. Originally, the masking techniques [1][4][11][20] have been used to force the power consumption signals to be uncorrelated with the secret key and the input and output. We apply this technique, in particular Boolean masking, during the lookup table generation. Before going into more depth, we provide an overview.

Fig. 5 shows an example of the proposed method applied to $E1(p, k1) \oplus E2(q, k2)$ used in Section 2. The key idea behind is to apply masking before encoding the outputs of $E1$ and $E2$ while generating lookup tables. Let us denote the lookup tables for $E1$ and $E2$ by $\mathcal{E}1$ and $\mathcal{E}2$, respectively. An example

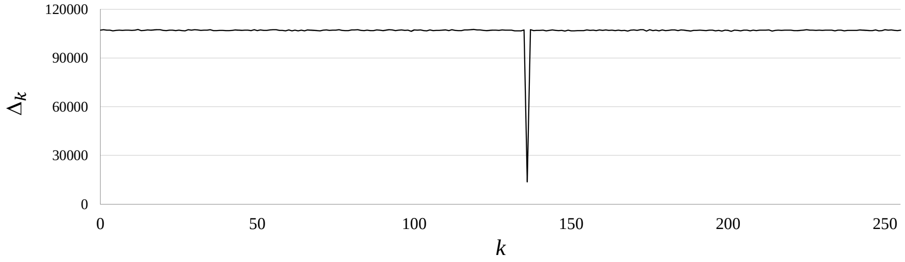


Fig. 4: Sum of all imbalances Δ_k for all key candidates of the previous WB-AES implementation.

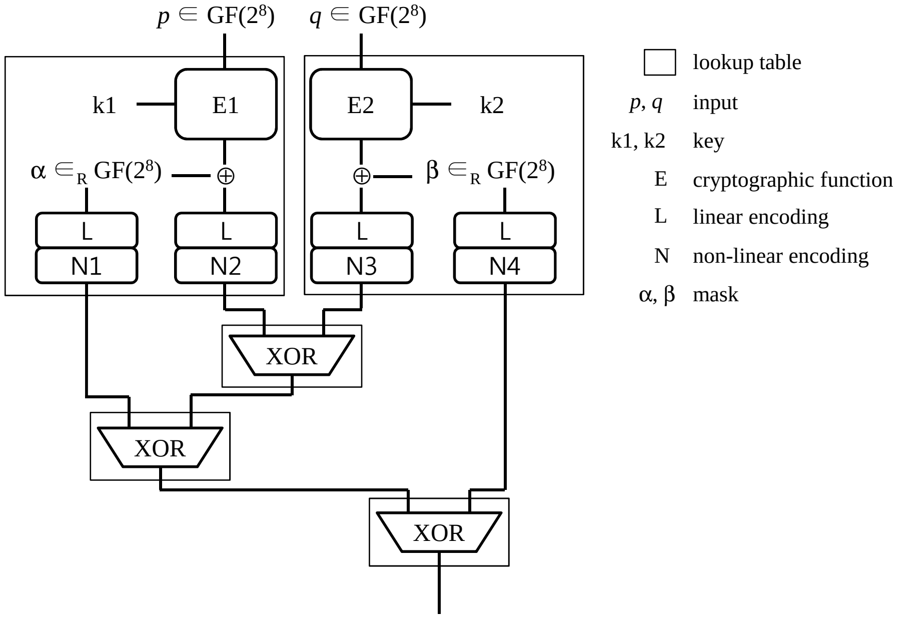


Fig. 5: Basic principle of the proposed white-box cryptographic implementation.

of $\mathcal{E}1$-generating code might look like this:

```
for $p = 0$ to 255 do
    pick random $m \in \{0,1\}^8$
    $y \leftarrow E1(p, k1) \oplus m$
    $\mathcal{E}1[0][p] \leftarrow \mathrm{N1}(\mathrm{L}(m))$
    $\mathcal{E}1[1][p] \leftarrow \mathrm{N2}(\mathrm{L}(y))$,
```

where the decoding of the input p is not considered. The most important point over here is that the mask should be selected uniformly at random regardless of the input value. Then 256 different masks are used to generate $\mathcal{E}1$ (or $\mathcal{E}2$). The lookup values for an input p (resp. q) to $\mathcal{E}1$ (resp. $\mathcal{E}2$) are the following two values: an encoded key-sensitive intermediate value which is masked, and an encoded mask. To cancel out the masks, they are XORed by the following XOR lookup tables as shown in Fig. 5. We implement a WB-AES implementation with 128-bit key using this principle.

3.1 Masked White-box AES Implementation

Since we protect a particular part of the implementation presented in [9][23] we focus on the protected part and briefly describe the rest. With AES-128 written below, AddRoundKey, SubBytes, and part of MixColumns are combined into a series of lookup tables, where $\hat{k}_r$ indicates that ShiftRows is applied to k_r.

```
state ← $plaintext$
for $r = 1$ to 9 do
    ShiftRows(state)
    AddRoundKey(state, $\hat{k}_{r-1}$)
    SubBytes(state)
    MixColumns(state)
ShiftRows(state)
AddRoundKey (state, $\hat{k}_9$)
SubBytes(state)
AddRoundKey(state, $k_{10}$)
$ciphertext$ ← state
```

At first, *T-boxes*, a series of 160 (one per cell per round) 8×8 lookup tables, combines AddRoundKey and SubBytes as follows:

$$\begin{aligned} T^r_{i,j}(x) &= S(x \oplus \hat{k}^{r-1}_{i,j}), \qquad \text{for } 0 \leq i,j \leq 3, \text{ and } 1 \leq r \leq 9, \\ T^{10}_{i,j}(x) &= S(x \oplus \hat{k}^{9}_{i,j}) \oplus k^{10}_{i,j}, \text{ for } 0 \leq i,j \leq 3. \end{aligned}$$

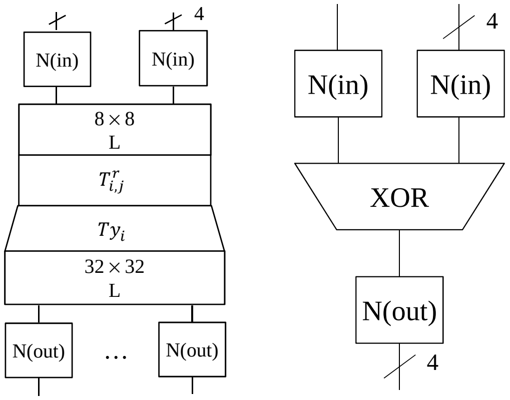
Let us denote (x_0, x_1, x_2, x_3) a column of four bytes to be multiplied with the MixColumns matrix. The multiplication is then decomposed as follows:

$$\begin{pmatrix} 02\ 03\ 01\ 01 \\ 01\ 02\ 03\ 01 \\ 01\ 01\ 02\ 03 \\ 03\ 01\ 01\ 02 \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \end{pmatrix} = x_0 \begin{pmatrix} 02 \\ 01 \\ 01 \\ 03 \end{pmatrix} \oplus x_1 \begin{pmatrix} 03 \\ 02 \\ 01 \\ 01 \end{pmatrix} \oplus x_2 \begin{pmatrix} 01 \\ 03 \\ 02 \\ 01 \end{pmatrix} \oplus x_3 \begin{pmatrix} 01 \\ 01 \\ 03 \\ 02 \end{pmatrix}.$$

For the right-hand side (say y_0, y_1, y_2, y_3), the so-called Ty_i tables are defined as follows:

$$\begin{aligned} Ty_0(x) &= x \cdot [02\ 01\ 01\ 03]^T \\ Ty_1(x) &= x \cdot [03\ 02\ 01\ 01]^T \\ Ty_2(x) &= x \cdot [01\ 03\ 02\ 01]^T \\ Ty_3(x) &= x \cdot [01\ 01\ 03\ 02]^T. \end{aligned}$$

The 32-bit result of $y_0 \oplus y_1 \oplus y_2 \oplus y_3$ can be computed via the XOR table lookups. An XOR lookup table takes two 4-bit inputs and maps them to their XOR value. The XOR of two 32-bit values is then obtained using 8 copies of the XOR lookup tables, and thus twelve 32-bit XORs are required to compute the MixColumns result for each round. This gives us that the previous WB-AES implementation requires 96 copies of the XOR lookup tables per round, a total of 864 copies. Fig. 6 simply illustrates the so-called TypeII and TypeIV tables; TypeII is the composition of *T-boxes* and Ty_i that are encoded [9], and TypeIV is the XOR lookup tables. The remaining part of the tables includes the so-called TypeIII and another copy of TypeIV (TypeIV_III). They remove the transformation applied in TypeII and apply the necessary 8-bit linear transformations



(a) TypeII (b) TypeIV

Fig. 6: TypeII and TypeIV tables in the previous WB-AES implementation [9].

for the next round. In addition, the lookup table for the final round, say TypeV, is generated from T^{10} without Ty_i because MixColumns is not included in the final round. However, this is not an important part of this study and therefore is not discussed in detail.

What we want to protect is the output of Ty_i; previously, the linear and non-linear encodings were directly applied to them. Let (z_0, z_1, z_2, z_3) denote the four-byte output of Ty_i. Each byte of them is to be masked using M defined in Algorithm 1.

Algorithm 1 Masking function M

```
procedure M($z$)                    ▷ Choose a random mask and apply it to $z$
    $m \in_R \{0,1\}^8$
    $\hat{z} \leftarrow z \oplus m$
    return $(\hat{z}, m)$           ▷ masked $z$ and the mask used
```

To unmask later, the used masks are also encoded and stored in TypeII illustrated in Fig. 7. As pointed out previously, the linear encoding applied to (z_0, z_1, z_2, z_3) and the masks should be the same. We prepare TypeIV_IIA and TypeIV_IIB tables to perform the XOR operations on the masked values and to unmask them using the encoded masks, respectively, as shown in Fig. 8. In this sense, TypeIV_IIA consists of 864 (=9×96) copies of the XOR table, but TypeIV_IIB contains 1152 (=9×128) copies. The rest of the implementation including TypeIII and TypeIV_III tables is identical to the previous one [9].

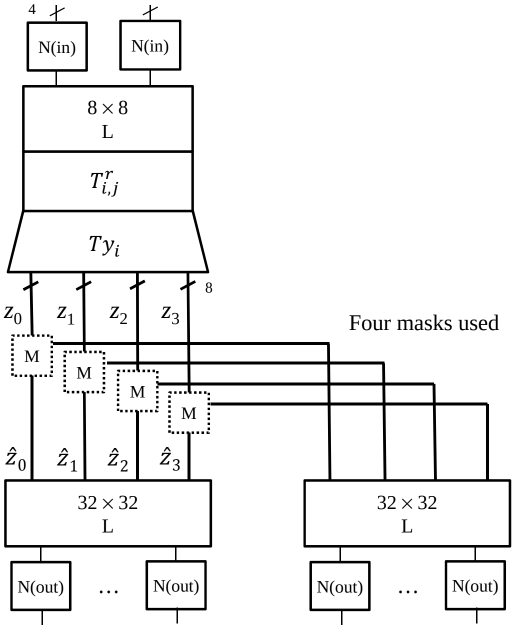


Fig. 7: Protected TypeII tables in our WB-AES implementation.

Fig. 9 shows the memory accesses performed by our implementation on the stack. One can see repeated memory access patterns from round 1 to round 9. In the final round, memory access is relatively small due to the absence of MixColumns.

3.2 Size and Performance

We now have a masked white-box implementation of AES-128. Compared to [9], the modified lookup tables are TypeII and TypeIV_II (TypeIV_IIA and TypeIV_IIB). Because we excluded the external encoding in this study as aforementioned, we compare the total size of the lookup tables including TypeII, TypeIV_II, TypeIII, TypeIV_III, and TypeV (we named it above). The size of the unmodified lookup tables is computed as follows:

- TypeIII : 9×4×4×256×4 = 147456 bytes.
- TypeIV_III : 9×4×4×3×2×128 = 110592 bytes.
- TypeV : 4×4×256 = 4096 bytes.

In the case of [9], the sizes of TypeII and TypeIV_II are equal to the sizes of TypeIII and TypeIV_III, respectively. Thus their total size is 520192 bytes. In contrast, the sizes of TypeII and TypeIV_II in our case are given by

- TypeII : 9×4×4×256×2×4 = 294912 bytes.
- TypeIV : 9×4×4×(3×2×128 + 4×2×128) = 258048 bytes.

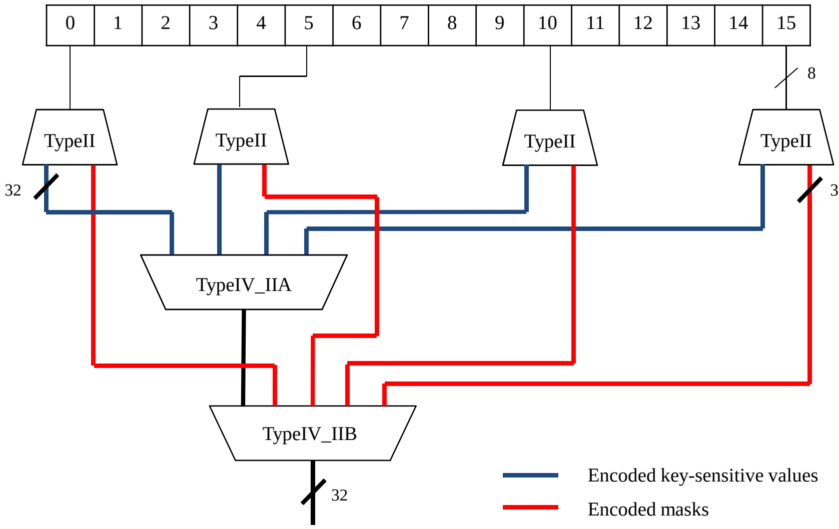


Fig. 8: TypeIV_II tables to XOR and unmask.

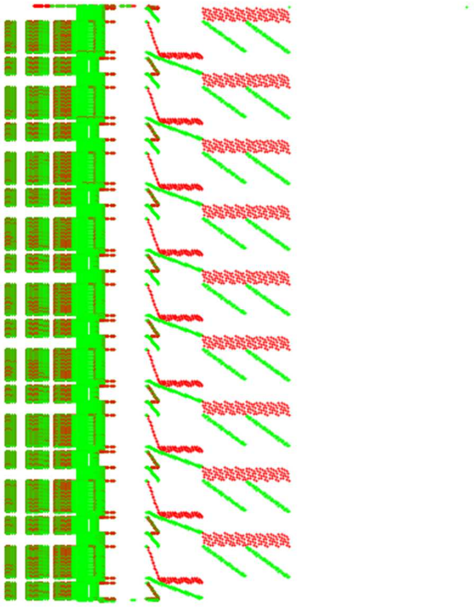


Fig. 9: Visualization of a software execution trace of our WB-AES implementation.

Then, the total size of the lookup tables is 815104 bytes. In comparison, the lookup table size increases 1.56 times.
Since most of operations are table lookups except for ShiftRows, we compare the number of lookups. During each execution, the lookups for each table in the previous WB-AES-128 implementation are counted as follows.

- TypeII : 9×4×4 = 144.
- TypeIV_II : 9×4×4×3×2 = 864.
- TypeIII : 9×4×4 = 144.
- TypeIV_II : 9×4×4×3×2 = 864.
- TypeV : 4×4 = 16.

Then, there are 2032 lookups in total. Compared to this, the only differences in our case are

- TypeII : 9×4×4×2 = 288.
- TypeIV_II : 9×4×4×(3×2 + 4×2) = 2016.

Then 3328 lookups are performed during each execution of our masked WB-AES-128 implementation. Consequently, the number of table lookups increases by 1.63 times.

4 Security Analysis and Experimental Results

Because we remain the final round, say round 10, table unprotected, each subbyte of the 9^{th} round output might be attacked if an attacker can guess 2^{16} key byte candidates (two subkeys, $\hat{k}^9_{i,j}$ $k^{10}_{i,j}$) for the final round where two subkeys are integrated. This is because these is no MixColumns in the final round. This attack might be not impossible due to the fact that the encoding to protect the round output is imbalanced. But the attack complexity increases significantly. In the case of protecting the final round for this reason, we can provide an additional mask for each byte of the Ty_i output like a higher-order masking. These additional masks are combined together via TypeIV_IIC (Fig. 10) and given as an input to the final round to provide a proper ciphertext. The final round lookup table TypeV is then extended to include 256 copies satisfying the following for each mask m:

$$T^{10}_{i,j}(x, m) = S(x \oplus m \oplus \hat{k}^9_{i,j}) \oplus k^{10}_{i,j}, \text{ for } m \in \{0,1\}^8,$$

where x is a masked input to the final round. In this case, the size and performance are recomputed at the last two rounds. In the round 9, 16384 (= 4×4×256×4) bytes are added to the TypeII table, 12288 (=4×4×3×2×128) bytes are added to the newly defined TypeIV_IIC, and 16384 and 12288 bytes are added to the TypeIII and TypeIV_III tables, respectively. Also, the size of TypeV increases to 1048576 bytes (1MB). Consequently, the size of the lookup tables and the number of lookups, compared to [9], increase by about 3.68- and 1.74 times, respectively.

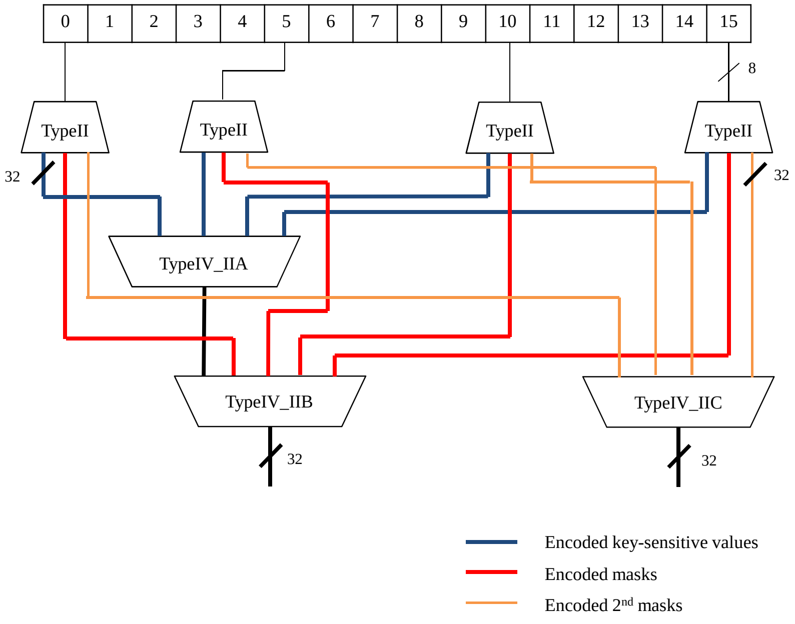


Fig. 10: Additional masking in the 9^{th} round for protecting the final round.

Additionally, there is a difference between the maskings that we used before and that we apply now. To be specific, we mask the intermediate value of four bytes with four 1-byte masks, which are generated for each round, for each cell of the state, and for each input value. This gives us that 1-byte masks are generated 147456 (=9×4×4×256×4) times in total for generating WB-AES lookup tables. This also gives us another point of view that for fixed values $x \in \mathrm{GF}(2^8)$, round $\in [1,9]$, row and column $\in [0, 3]$, TypeII[round][row][column][x] outputs the same value for each execution of the algorithm.

In this section, we demonstrate the security of our proposed method. Let $z[j]$ denote the j^{th} bit of z. If the mask m is uniformly distributed, we know that $\Pr[z_i[j] = \hat{z}_i[j]]$=1/2, where $0 \leq i \leq 3$, and $0 \leq j \leq 7$. Then the masking results in the reduced correlation of the Ty_i output to the secret key byte. One might choose random masks with the Hamming weight of 4, but the number of masks is reduced compared to using a full range of masks. We have generated 20 target instances of our implementation to be attacked by DCA. As the number of traces given to the DCA attacker increases, the attack accuracy increases. For this reason, 10000 software traces were generated with random plaintexts for each target instance. DCA was performed with mono-bit CPA attacks on the SubBytes output in the first round. The entire first round was observed in order to check whether the key is leaked in the masked values or in the process of unmasking them. As described in Section 2, the result is given by

Table 2: DCA ranking of ATK #1. If the correct key is not in the top 10, we leave it blank.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	53	62	138	179	245	167	214	146	85	57	223	244	32	38	169	152
2	36	12	70	17	160	241	244	19	148	184	113	119	68	195	96	20
3	190	238	226	76	80	250	183	58	10	4	193	113	49	252	232	85
4	52	168	234	153	235	92	20	177	70	19	232	84	213	245	193	187
5	223	113	193	239	44	253	241	69	134	34	93	123	158	163	151	165
6	42	75	168	256	199	39	120	181	57	122	43	194	205	176	170	89
7	179	170	236	215	230	98	152	82	52	250	124	122	206	79	88	234
8	198	111	149	158	79	97	81	55	107	153	87	96	219	240	166	18
sum																
highest																

two top 10 lists. Due to the limited space, we provide the DCA ranking tables in Appendix. As a result, only four correct key bytes were ranked at the top in at least one list. Thus, the probability of attack success is 1.25% (4/320). The highest value average of the mono-bit CPA correlation coefficient for the correct key byte was just 0.206 (S.D = 0.022). We note that the expected value of an attacker guessing a key byte by using a random number is 1.25 (= 320/256), and the success probability of him is 0.39%. More importantly, the correlation coefficient of the correct key is much lower than that of the unprotected white-box implementation; the highest coefficient average for the correct key byte was 0.557. Remember that we provided the DCA attacker with only 200 traces at that time. If we supplied more traces in Section 2, this average of correlation coefficients would have been bigger.

Let's call our 20 attacks ATK #1, . . . , ATK #20. We have analyzed the instance (ATK #1) that did not leak key bytes and the instance (ATK #12) that leaked a key byte. We used the Walsh transform introduced in Section 2 to examine the change in the correlation between the output x of SubBytes and the value encoded by our proposed method. In ATK #1 as shown in Table 2, no key leak occurred at all. Fig. 11 shows $\varDelta_k$, the sum of the imbalances in ATK #1, and it can be confirmed that the correct key is not distinguished from the other key candidates at all. Even though encoding is still imbalanced, the correlation to the key is drastically reduced through Boolean masking applied before encoding.

Table 3: DCA ranking of ATK #12.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	20	19	156	151	228	101	158	89	78	232	199	110	141	210	58	64
2	169	1	41	30	188	189	24	149	196	162	101	237	103	38	1	118
3	218	113	51	138	166	63	97	2	237	53	227	138	163	227	55	2
4	190	53	33	65	55	212	146	177	2	152	225	119	9	230	30	253
5	138	142	62	3	16	4	184	121	107	170	23	253	97	143	151	160
6	137	99	206	184	165	44	111	73	27	148	119	247	52	152	29	71
7	61	137	43	108	223	197	172	223	199	71	70	131	84	84	149	240
8	106	202	102	4	200	58	254	156	65	51	84	178	138	238	14	83
sum		5		5											1	
highest		3													1	2

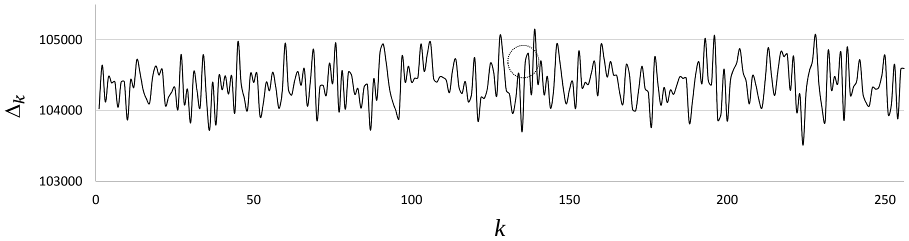


Fig. 11: Sum of all imbalances Δ_k for all key candidates in ATK #1. Dotted circle: Δ for the correct key.

On the other hand, ATK #12 revealed the 15^{th} secret key byte in the both lists (Table 3). To analyze in more detail, we have collected 30000 software traces using the same target table via SCARF and analyzed the tendency of the CPA correlation coefficients. As a result, the correct key byte was found to be in the top 1 from the roughly 1000^{th} trace analysis to the end (Fig. 12).

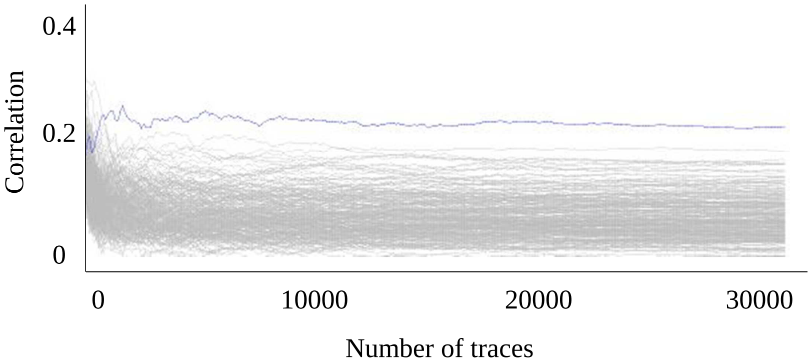
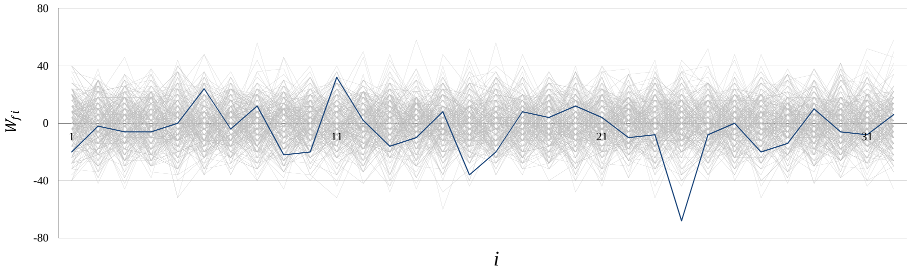
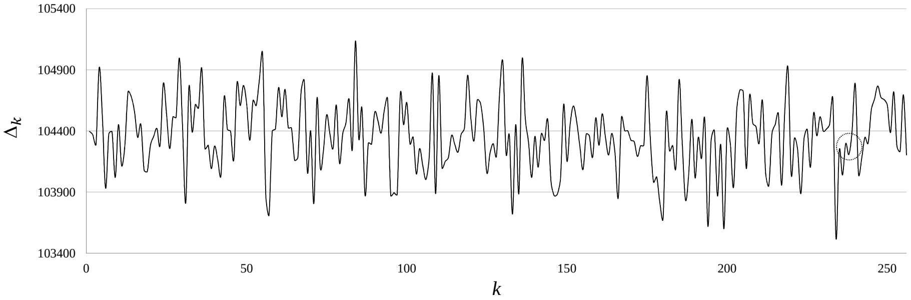


Fig. 12: Correlation coefficient tendency of the correct key byte for ATK #12.



(a) Walsh transforms for $f_{i \in \{1,\ldots,32\}}(\cdot)$ with $\omega = 2$ for all key candidates. Blue line: correct key, gray line: wrong key candidates.



(b) Sum of all imbalances Δ_k for all key candidates. Dotted circle: Δ for the correct key.

Fig. 13: Walsh transforms for ATK #12.

Table 3 shows that the correlation is high in the case of the mono-bit CPA using the 2^{nd} bit. As shown by Fig. 13a, for $\omega = 2$, $f_{24}(\cdot)$ is not first-order correlation immune; the imbalance of $f_{24}(\cdot)$ for the correct key can be detected among that for other key candidates. However, the correct key is still not distinguishable in Δ_k for all key candidates as shown in Fig. 13b. This is because the correlation coefficient of the correct key is not much higher than that of the other key candidates. In fact, the difference in the correlation coefficients between the first and the second key candidates for the 15^{th} key byte in ATK #12 was only 0.0005. In conclusion, our method can be used as an efficient countermeasure against DCA and power analysis by significantly mitigating key leakage caused by the encoding imbalance. The defense success rate is as high as 98%.

5 Conclusion

In this paper, we proposed a masked white-box cryptographic implementation to protect DCA attacks. First, we generated 20 target instances according to the unprotected WB-AES implementation and performed DCA on the SubBytes output in the first round with 200 software traces. As a result, an average of 14.3 key bytes were leaked and the average of the highest CPA correlation coefficient for the correct key byte was 0.557. In order to testify the problematic encoding imbalance we provided the sum of all imbalances that distinguishes the correct key from other key candidates.

To solve this problem, we applied Boolean masking to the intermediate value before applying the encoding during the white-box table generation. Based on this basic idea, a design method of masked WB-AES implementation was suggested. DCA was performed with 10000 software traces for each of 20 instances. As a result, only four of the 320 key bytes were leaked, and the highest CPA correlation coefficient of the correct key byte was 0.206 in average. We also reverified through the Walsh transforms that the correlation between the intermediate value and the secret key is significantly reduced. Compared to the unprotected WB-AES implementation, the lookup table size increased by approximately 1.5 times, the number of lookups by 1.6 times. In the case of protecting of the final round with additional masks, these become 3.68- and 1.74 times, respectively. An additional attractive point is that there is no need for a random source at runtime. Based on these facts, we can conclude that our proposed method can practically defend DCA and power analysis on white-box cryptographic implementations.

Directions for future work include developing various designs of other block ciphers and combining additional techniques to provide resistance to white-box attacks. Another interesting direction is to examine the attack for the final round indicated in Section 4.

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A DCA Ranking Tables

The following tables represent the DCA results for ATK #1 - ATK #20, except for ATK #1 and ATK #12 that were provided in Section 4. If the correct key is not in the top 10, we leave it blank.

Table 4: DCA ranking of ATK #2.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	44	229	36	54	233	67	37	74	23	47	71	160	203	195	208	87
2	15	223	161	247	229	211	76	165	205	188	78	179	45	188	61	169
3	171	219	117	156	171	82	176	127	113	90	41	64	138	125	108	129
4	81	184	62	202	56	50	211	108	198	53	217	71	76	41	155	115
5	186	31	161	19	76	61	206	32	202	71	33	102	123	131	15	177
6	256	238	49	80	16	232	185	34	73	236	130	110	178	242	2	32
7	87	64	4	59	157	76	225	30	106	171	253	99	34	27	254	29
8	186	148	164	29	166	98	18	2	7	113	202	45	115	63	118	54
sum	2															
highest	5															

Table 5: DCA ranking of ATK #3.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	252	90	243	76	164	242	174	236	251	179	171	2	55	225	128	210
2	154	114	193	230	57	77	119	231	185	155	125	2	46	167	77	248
3	21	242	235	206	127	55	247	256	77	38	199	52	174	247	121	99
4	80	52	73	208	35	211	178	50	79	86	230	147	18	135	31	61
5	220	7	108	110	7	80	24	208	255	99	4	157	237	225	213	45
6	229	189	140	60	8	30	222	33	113	46	37	255	189	115	204	35
7	189	13	52	128	205	193	129	175	96	39	24	123	171	133	82	127
8	70	200	122	204	213	166	235	6	13	240	27	110	37	50	23	203
sum																
highest																

Table 6: DCA ranking of ATK #4.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	230	44	114	119	100	13	4	130	140	185	84	213	32	78	51	139
2	15	229	171	220	248	131	225	127	223	69	200	178	104	33	131	170
3	93	16	254	254	180	36	249	208	12	188	217	191	194	252	158	140
4	236	162	250	37	215	50	240	140	25	190	31	78	192	84	191	3
5	22	121	217	239	181	24	199	12	249	213	225	15	248	219	41	152
6	187	163	51	148	185	18	123	218	181	63	204	13	223	144	89	114
7	190	183	128	59	39	189	4	219	65	125	48	59	254	214	26	234
8	220	76	110	143	250	208	168	212	64	25	15	85	182	141	41	135
sum																
highest																

Table 7: DCA ranking of ATK #5.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	256	31	195	189	210	39	18	192	147	35	150	246	239	190	75	72
2	183	238	88	185	212	105	91	64	210	244	45	95	129	253	196	74
3	110	41	68	116	133	67	119	203	203	188	204	181	106	165	85	219
4	169	171	18	20	25	91	124	252	91	184	111	175	95	143	93	179
5	41	220	155	35	147	30	115	73	16	106	58	142	136	146	32	161
6	57	231	174	103	21	235	227	94	180	61	44	190	31	127	240	199
7	40	179	174	74	139	129	59	24	67	1	24	134	65	94	204	213
8	227	222	81	201	164	72	96	116	199	151	238	36	14	179	113	46
sum																
highest																

Table 8: DCA ranking of ATK #6.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	114	102	69	21	109	115	107	53	191	36	183	31	147	137	155	142
2	113	253	168	36	160	244	19	242	171	224	20	235	231	47	15	98
3	249	74	138	13	19	35	169	62	249	189	214	94	95	247	106	197
4	63	12	84	210	200	77	160	24	244	229	104	215	128	59	21	72
5	65	235	66	1	173	189	192	191	63	71	104	156	101	113	156	46
6	27	244	188	211	97	212	215	159	22	106	230	127	54	163	196	209
7	5	212	73	117	170	46	174	127	249	60	158	37	10	250	219	95
8	78	66	117	252	123	130	75	203	5	22	164	97	147	136	138	28
sum				8												
highest				4												

Table 9: DCA ranking of ATK #7.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	215	221	253	175	255	255	177	238	175	43	111	131	247	174	86	79
2	73	30	242	15	28	84	64	73	86	215	148	240	155	46	38	95
3	116	115	217	47	207	20	7	106	76	167	2	192	67	245	148	218
4	94	32	230	106	242	77	139	78	256	22	125	23	164	41	214	55
5	174	110	145	246	105	15	85	34	154	57	31	151	61	48	118	12
6	252	109	155	95	187	144	249	85	164	82	236	41	221	191	181	142
7	134	241	71	166	256	237	184	26	72	241	171	205	144	164	190	50
8	199	87	86	238	40	132	152	77	33	73	157	19	223	143	155	208
sum																
highest																

Table 10: DCA ranking of ATK #8.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	27	214	75	143	120	75	210	5	71	241	62	92	109	108	54	16
2	140	80	18	219	232	147	18	17	214	52	58	169	61	14	196	12
3	157	208	153	91	28	204	138	25	77	212	51	100	98	221	220	235
4	190	189	185	27	236	143	125	166	7	240	223	249	106	15	161	12
5	146	111	46	28	213	70	102	217	91	35	2	75	30	114	54	114
6	145	230	48	195	151	136	225	206	15	50	219	3	9	56	129	104
7	8	43	60	229	80	57	187	15	213	199	245	10	216	176	147	201
8	130	224	249	155	159	44	167	30	125	121	77	109	54	176	146	44
sum								3								
highest											6					

Table 11: DCA ranking of ATK #9.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	187	224	96	237	34	254	86	246	74	107	175	80	40	117	227	159
2	74	164	132	181	232	112	71	7	122	54	31	150	7	231	71	241
3	118	77	41	122	112	135	2	97	151	210	34	221	27	20	44	147
4	149	227	134	91	27	244	139	30	228	106	123	2	154	106	24	87
5	170	154	229	186	23	37	68	93	7	73	220	171	139	130	4	151
6	252	171	31	168	234	160	212	197	38	93	226	36	223	168	140	120
7	10	26	200	211	116	193	237	227	175	194	256	83	97	256	28	87
8	205	179	217	47	1	240	249	51	184	126	41	167	4	140	167	46
sum					5								7			
highest					3							6				

Table 12: DCA ranking of ATK #10.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	18	109	75	207	123	197	124	249	95	3	101	169	206	146	122	19
2	180	179	95	223	12	110	217	113	179	201	183	106	206	64	49	166
3	170	173	204	49	24	245	72	153	115	121	84	122	162	96	158	163
4	25	205	140	237	183	102	227	111	82	208	86	212	169	175	105	7
5	225	155	131	227	18	217	116	191	168	110	49	16	123	138	227	57
6	138	29	52	242	180	27	206	151	100	87	15	236	2	202	213	214
7	115	177	173	171	211	51	166	211	211	202	26	211	132	139	138	91
8	68	150	50	49	158	62	218	27	239	240	34	143	6	57	25	19
sum											9					
highest													3			

Table 13: DCA ranking of ATK #11.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	38	94	170	176	215	90	50	27	231	249	13	108	64	14	134	12
2	237	49	159	51	54	183	119	123	187	20	177	217	133	253	23	207
3	169	34	253	113	129	25	38	225	111	187	144	58	131	220	88	71
4	197	80	68	45	212	97	139	218	89	211	78	242	81	176	107	57
5	238	82	94	41	107	200	242	25	129	63	14	2	165	146	85	167
6	173	150	221	243	215	179	197	122	110	86	225	112	113	59	166	100
7	206	156	112	70	97	23	178	242	91	170	107	176	63	134	233	220
8	243	125	248	111	18	207	126	121	233	83	69	67	137	209	72	36
sum																
highest												4				

Table 14: DCA ranking of ATK #13.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	9	64	98	151	39	157	200	9	125	108	104	88	97	28	1	85
2	23	178	51	190	47	152	72	172	216	217	227	237	154	4	217	104
3	186	29	21	135	207	147	131	22	52	50	190	134	210	68	160	146
4	171	77	116	234	70	80	60	15	89	230	218	231	58	132	116	147
5	119	211	249	157	98	72	18	56	124	255	203	6	68	23	211	15
6	57	167	44	109	76	88	209	164	72	8	152	109	138	94	188	178
7	243	72	70	23	254	213	73	67	165	228	74	149	129	137	225	250
8	154	148	2	246	127	146	179	33	229	114	169	88	250	135	152	16
sum			9					3						6		
highest																

Table 15: DCA ranking of ATK #14.

KeyByte / TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	161	95	150	236	231	231	104	198	197	249	150	33	212	68	196	135
2	18	66	108	57	124	79	47	78	142	11	252	240	122	70	212	187
3	213	198	95	107	159	85	99	98	149	201	172	92	160	144	63	193
4	237	249	221	10	45	157	10	168	107	1	209	194	242	17	177	249
5	129	218	167	91	176	124	113	168	83	59	228	52	183	43	9	204
6	46	232	85	205	244	212	18	9	37	221	250	131	237	66	76	1
7	227	249	212	94	237	45	227	129	194	208	103	131	46	165	145	228
8	46	193	137	249	124	250	111	21	1	97	31	128	247	106	115	215
sum																
highest									1							4

Table 16: DCA ranking of ATK #15.

KeyByte / TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	212	109	141	19	99	141	19	141	240	99	227	56	43	194	135	54
2	189	233	193	146	95	81	166	136	135	123	88	214	97	86	43	167
3	226	103	232	250	254	160	61	128	35	194	89	228	172	192	86	150
4	161	195	3	255	109	254	96	53	199	47	18	111	139	236	120	2
5	198	197	46	242	124	255	141	113	165	81	250	243	255	251	192	114
6	121	202	246	208	256	179	35	176	71	1	229	222	47	49	10	182
7	35	107	136	123	42	49	126	199	72	198	9	191	140	253	106	174
8	191	85	34	240	14	27	38	130	33	66	37	63	216	62	32	38
sum																
highest										6						

Table 17: DCA ranking of ATK #16.

KeyByte / TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	249	211	108	234	8	193	122	61	184	168	145	42	223	252	53	124
2	35	243	32	170	155	176	116	147	37	256	70	72	22	189	253	214
3	248	202	140	63	154	162	221	128	73	123	235	101	196	103	33	70
4	232	113	92	92	103	110	18	28	197	87	137	231	84	186	47	129
5	40	200	163	185	165	6	159	3	24	38	66	125	233	156	127	145
6	105	136	28	130	8	123	180	175	86	126	34	210	22	65	192	99
7	106	141	52	102	139	152	67	108	147	83	21	42	243	193	38	80
8	128	123	216	11	90	58	114	125	146	208	141	52	101	50	17	99
sum																
highest								7								

Table 18: DCA ranking of ATK #17.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	54	242	59	27	127	171	9	174	249	72	135	151	31	28	12	256
2	23	33	64	195	85	104	154	216	226	31	222	137	173	225	132	113
3	151	145	221	80	126	238	11	134	236	181	224	250	154	30	12	203
4	255	237	62	63	20	217	160	218	225	101	197	125	207	134	16	211
5	209	93	107	204	11	194	92	254	220	18	110	223	106	154	38	224
6	197	132	211	252	151	173	7	50	71	49	39	29	212	20	3	177
7	138	161	220	246	16	60	251	46	223	199	35	158	196	129	1	209
8	159	192	204	13	120	237	231	253	202	71	72	45	142	251	10	238
sum															1	
highest															9	

Table 19: DCA ranking of ATK #18.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	174	52	230	105	91	122	229	39	84	194	213	221	118	38	158	32
2	158	176	107	84	22	190	56	61	33	228	197	123	44	125	97	16
3	202	30	239	254	181	142	201	23	21	190	147	117	22	242	185	248
4	8	132	252	126	232	29	95	20	41	126	12	254	72	155	166	91
5	134	62	79	110	163	5	6	88	1	256	24	88	137	196	174	122
6	243	147	88	27	68	184	72	212	133	246	196	83	176	145	18	239
7	193	222	162	168	45	26	225	234	242	73	144	92	181	6	34	167
8	252	192	67	39	141	31	21	129	119	147	14	215	151	158	154	160
sum									1							
highest									2							

Table 20: DCA ranking of ATK #19.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	96	105	114	66	156	117	3	147	249	12	42	173	31	150	56	224
2	95	215	13	72	225	161	25	136	135	66	206	153	45	6	69	143
3	151	97	136	229	91	217	100	26	120	56	106	145	110	83	171	75
4	59	22	173	31	125	5	47	15	181	66	153	197	7	240	20	200
5	105	153	124	102	51	90	249	238	137	79	219	99	207	83	184	249
6	256	36	56	45	66	122	211	243	13	219	61	167	207	255	186	88
7	28	143	135	148	187	51	190	207	188	237	19	219	209	124	108	233
8	193	122	197	185	3	160	191	76	134	161	231	251	139	46	167	51
sum																
highest																

Table 21: DCA ranking of ATK #20.

KeyByte TargetBit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	210	127	7	125	111	66	88	202	105	80	18	250	164	46	203	59
2	217	151	52	237	218	70	112	143	106	125	180	143	45	79	8	10
3	172	75	111	77	32	44	146	225	138	107	42	155	77	7	149	176
4	38	53	7	234	159	240	150	39	188	98	155	116	143	217	220	177
5	147	220	154	69	134	158	106	13	200	178	191	101	159	146	217	14
6	41	135	3	49	96	197	227	186	136	247	246	55	88	186	94	215
7	247	184	29	214	151	73	226	191	184	106	37	34	78	17	232	73
8	62	152	233	157	185	130	256	216	154	192	232	109	95	39	157	216
sum			3													
highest																