On the security defects of an image encryption scheme

Chengqing Li\textsuperscript{a,b}, Shujun Li\textsuperscript{c}, Muhammad Asim\textsuperscript{d}, Juana Nunez\textsuperscript{e}, Gonzalo Alvarez\textsuperscript{e}, Guanrong Chen\textsuperscript{a}

\textsuperscript{a}Department of Electronic Engineering, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon Tong, Hong Kong SAR, China
\textsuperscript{b}Department of Electronic and Information Engineering, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR, China
\textsuperscript{c}Fachbereich Informatik und Informationswissenschaft, Universität Konstanz, Universitätsstraße 10, 78457 Konstanz, Germany
\textsuperscript{d}Universiti Teknologi PETRONAS, 31750, Tronoh, Perak, Malaysia
\textsuperscript{e}Instituto de Física Aplicada, Consejo Superior de Investigaciones Científicas, Serrano 144, 28006 Madrid, Spain

Abstract

This paper studies the security of a recently-proposed chaos-based image encryption scheme, and points out the following problems: 1) there exist a number of invalid keys and weak keys, and some keys are partially equivalent for encryption/decryption; 2) given one chosen plain-image, a subkey $K_{10}$ can be guessed with a smaller computational complexity than that of the simple brute-force attack; 3) given at most 128 chosen plain-images, a chosen-plaintext attack can possibly break the following part of the secret key: $\{K_i \mod 128\}_{i=0}^{10}$, which works very well when $K_{10}$ is not too large; 4) when $K_{10}$ is relatively small, a known-plaintext attack can be carried out with only one known plain-image to recover some visual information of any other plain-images encrypted by the same key.

Keywords: cryptanalysis, image encryption, chaos, known-plaintext attack, chosen-plaintext attack

1. Introduction

Spurred by the rapid development of multimedia and network technologies, multimedia data are being transmitted over networks more and more frequently. As a result, content protection of multimedia data is urgently needed in many applications, including both public and private services such as military information systems and multimedia messaging systems (MMS). Although any traditional data ciphers (such as DES and AES) can be used to meet this increasing demand of information security, they cannot provide satisfactory solutions to some special properties and requirements in many multimedia-related applications. For example, one requirement is perceptual encryption \cite{1}, meaning that the encrypted multimedia data can still be decoded by any standard-compliant codec and displayed, with a relatively low quality, which cannot be realized by simply employing a traditional cipher. As a response to this concern, a large number of specially-designed multimedia encryption schemes have been proposed \cite{2,3,4,5,6,7,8}. Meanwhile, security analysis on the proposed schemes have also been developed, and some of these schemes have been found insecure to a certain extent \cite{9,10,11,12,13,14}. For more discussions about multimedia data encryption techniques, readers are referred to some recent surveys \cite{15,16,17,18,19,20}.

Since 2003, Pareek et al. \cite{21,22,23} have proposed three different encryption schemes based on one or more one-dimensional chaotic maps, among which the one proposed in \cite{23} was designed for image encryption. Recent cryptanalysis results \cite{24,25} have shown that the two schemes proposed in \cite{21,22} are not secure. The present paper focuses on the security analysis of the image encryption scheme proposed in \cite{23}, and reports the following findings:

1. There are several types of security problems with the secret key, and each subkey is involved in at least one problem.
2. One subkey $K_{10}$ can be separately searched with a relatively small computational complexity, even when only one chosen plain-image is given.
3. The scheme is insecure against chosen-plaintext attack in the sense that using 128 chosen plain-images may be enough to break part of the key. The attack is especially feasible when $K_{10}$ is not too large.
4. When $K_{10}$ is relatively small and one plain-image is known, a known-plaintext attack can be used to reveal some visual information of any other plain-images encrypted with the same secret key.
The rest of the paper is organized as follows. The next section gives a brief introduction to the image encryption scheme under study. Section 3 is the main body of the paper, focusing on a comprehensive cryptanalysis, with both theoretical and experimental results. In the last section, some concluding remarks and conclusions are given.

2. The image encryption scheme under study

In this scheme, the plaintext is a color image with separate RGB channels. The plain-image is scanned in the raster order, and then divided into 16-pixel blocks. The encryption and decryption procedures are performed blockwise on the plain-image. Without loss of generality, assume that the size of the plain-image is $M \times N$, and that $MN$ can be exactly divided by 16. Then, the plain-image $I$ can be represented as a 1-D signal $(I(i))_{i=0}^{MN-1}$ with $N_b = MN/16$ blocks, namely, $I = \{I^{(i)}(k)\}_{k=0}^{15}$, where $I^{(i)}(k) = (I(16k+i))_{i=0}^{15}$. Similarly, the cipher-image is denoted by $I' = \{I'^{(i)}(k)\}_{k=0}^{15}$, where $I'^{(i)}(k) = (I'(16k+i))_{i=0}^{15}$.

The secret key of the encryption scheme under study is an 80-bit integer and can be represented as $K = K_1 \cdots K_{10}$, where each subkey $K_i \in \{0,\ldots,255\}$. Two chaotic systems are involved in the encryption scheme, and both are realized by iterating the Logistic map

$$f(x) = \mu x(1-x),$$

where $\mu$ is the control parameter and fixed to be 3.9999. One chaotic map runs globally throughout the whole encryption process, while another one runs locally for the encryption of each 16-pixel block. The initial condition of the global chaotic map is determined by the six subkeys $K_1 \sim K_6$ as follows:

$$X_0 = \left(\sum_{i=1}^{6} K_i \cdot 2^{8(i-4)}\right) \bmod 24 + \left(\sum_{j=0}^{9}(K_j \bmod 16) + [K_{16}\bmod 16]\right) \bmod 96,$$

and the local chaotic map corresponding to each block is initialized according to selected chaotic states of the global map. For the $k$-th block $I^{(i)}(k)$, the encryption process can be described by the following steps.

- **Step 1:** Determining the initial condition of the local chaotic map. Iterate the global chaotic map until 24 chaotic states within the interval $[0.1,0.9]$ are obtained. Denoting these chaotic states by $\{\hat{X}_j\}_{j=1}^{24}$, generate 24 integers $\{P_j\}_{j=1}^{24}$, where $P_j = 24(\hat{X}_j - 0.1)/0.8 + 1$.

Then, calculate $B_1 = \sum_{j=1}^{3} K_j \cdot 2^{8(1-j)}$ and set the initial condition of the local chaotic map as

$$Y_0 = \left(\frac{B_1 + \sum_{j=1}^{24} B_2[P_{j-1} \cdot 2^{1-j}] - 1}{2^{24}}\right) \bmod 1,$$

where $B_2[P_{j-1}]$ denotes the $P_{j-1}$-th bit of $B_2$.

- **Step 2:** Encrypting the $k$-th block $I^{(i)}(k)$. For each pixel in the block, iterate the local chaotic map to obtain $K_{10}$ consecutive chaotic states $\{\hat{Y}_j\}_{j=1}^{K_{10}}$ which fall into the interval $[0.1,0.9]$, and then encrypt the RGB values of the current pixel according to the following formulas:

$$R' = E_1(R) = g_{K_1,K_2,K_3,K_4,K_5,K_6} \circ \cdots \circ g_{K_1,K_2,K_3,K_4,K_5,K_6}(R),$$

$$G' = E_2(G) = g_{K_1,K_2,K_3,K_4,K_5,K_6} \circ \cdots \circ g_{K_1,K_2,K_3,K_4,K_5,K_6}(G),$$

$$B' = E_3(B) = g_{K_1,K_2,K_3,K_4,K_5,K_6} \circ \cdots \circ g_{K_1,K_2,K_3,K_4,K_5,K_6}(B),$$

where $\circ$ denotes the composition of two functions and $g_{a,b,c,d}(x)$ is a function under the control of $Y$ as shown in Table 1.

- **Step 3:** Updating subkeys $K_1,\ldots,K_9$. Perform the following updating operation for $i = 1 \sim 9$:

$$K_i = (K_i + K_{10}) \bmod 256.$$

The encryption procedure is similar to the above encryption procedure, except that Eqs. 4–6 in Step 2 are replaced by the following ones:

$$R = E_1^{-1}(R') = g_{K_1,K_2,K_3,K_4,K_5,K_6}^{-1} \circ \cdots \circ g_{K_1,K_2,K_3,K_4,K_5,K_6}^{-1}(R'),$$

$$G = E_2^{-1}(G') = g_{K_1,K_2,K_3,K_4,K_5,K_6}^{-1} \circ \cdots \circ g_{K_1,K_2,K_3,K_4,K_5,K_6}^{-1}(G'),$$

$$B = E_3^{-1}(B') = g_{K_1,K_2,K_3,K_4,K_5,K_6}^{-1} \circ \cdots \circ g_{K_1,K_2,K_3,K_4,K_5,K_6}^{-1}(B'),$$

where $g_{a,b,c,d}(x)$ is the inverse function of $g_{a,b,c,d}(x)$ with respect to $x$ as shown in Table 1.

3. Cryptanalysis

In this section, we report our cryptanalysis results about the image encryption scheme under study. These include a comprehensive analysis on invalid keys, weak keys and partially equivalent keys, a chosen-plaintext attack to break $K_{10}$, a chosen-plaintext attack to break $\{K_i \bmod 128\}_{i=1}^{9}$, a known-plaintext attack, and some other minor security problems.

1. However, following this process, $P_j = 24$ when and only when $\hat{X}_j = 0.9$, which becomes a rare event and conflicts with the requirement that $P_j$ has a roughly uniform distribution over $\{1,\ldots,24\}$. Therefore, in this paper we changed the original process in [23] to a more reasonable one. Note that such a change does not affect the performance of the encryption scheme.
Table 1: The definition of $g_{a_0,b_0,a_1,b_1}(x)$, where $\mathcal{T}$ denotes the bitwise complement of $x$, and $\oplus$ denotes the bitwise XOR operation.

| $T \in \{0,1\}$ | $E_{\mathcal{G}_{a_0,b_0,a_1,b_1}}(x^{(1)})$ | $E_{\mathcal{G}_{a_0,b_0,a_1,b_1}}(x^{(2)})$ |
|------------------|---------------------------------|---------------------------------|
| $[0.10,0.15)$ | $(0.33,0.37) \cup [0.58,0.62)$ | $x \oplus a_0$ |
| $[0.13,0.16)$ | $(0.37,0.40) \cup [0.62,0.66)$ | $(x + a_0 + b_0) \mod 256$ |
| $[0.16,0.19)$ | $(0.40,0.43) \cup [0.66,0.70)$ | $(x + a_0 - b_0) \mod 256$ |
| $[0.19,0.22)$ | $(0.43,0.46) \cup [0.70,0.74)$ | $x \oplus a_0 = x \oplus (a_0 \oplus 255)$ |
| $[0.22,0.25)$ | $(0.46,0.49) \cup [0.74,0.78)$ | $x \oplus x_1$ |
| $[0.25,0.28)$ | $(0.49,0.52) \cup [0.78,0.82)$ | $(x + a_1 + b_1) \mod 256$ |
| $[0.28,0.31)$ | $(0.52,0.55) \cup [0.82,0.86)$ | $(x + a_1 - b_1) \mod 256$ |
| $[0.31,0.34)$ | $(0.55,0.58) \cup [0.86,0.90)$ | $x \oplus a_1 = x \oplus (a_1 \oplus 255) = x \oplus b_1$ |

3.1. Two properties of the scheme

To facilitate the description of the scheme below, we first point out two properties of the scheme under study in this subsection. One is about the subkey updating mechanism, and the other is about the essential equivalent presentation form of the encryption function.

To improve the security of the scheme, an updating mechanism is introduced for subkeys in Eq. (7) of [23]. Because the updating process is performed in a finite-state field, the sequence of each updated subkey produced by such a mechanism is always periodic (see Fact 1 below). As a result, the sequence of the dynamic keys is also periodic. Assuming that the period is $T$, the $N_0$ plain pixelblocks $\{f^{(1)}(k)\}_{k=0}^{N_0-1}$ can be divided into $T$ separate sets according to the values of these dynamically updated subkeys: $\{\mathbb{I}_j = \bigcup_{k=0}^{N_0-1} f^{(1)}(T \cdot k + j)\}_{j=0}^{T-1}$, where $N_T = \lceil N_0/T \rceil$. For blocks in the same set $\mathbb{I}_j$, all the updated subkeys are identical. In other words, for each set $\mathbb{I}_j$ ($1/T$ of the whole plain-image) one can consider that the secret key is fixed. Since $1/T$ of a plain-image may be enough to reveal essential information, one can turn to break any set $\mathbb{I}_j$ without considering the updating mechanism.

**Fact 1.** For $x,a \in \{0,\ldots,255\}$, the integer sequence $(y(i) = (x + ai) \mod 256)_{i=0}^{\text{len}}$, has period $T = 256/\gcd(a,256)$.

With respect to the encryption function, one can see from Table 1 that each encryption subfunction is represented in one of the following two formats:

1. $g_{a_0,b_0,a_1,b_1}(x) = x @ \alpha$, where $\alpha \in \{0,255,a_0,a_1,a_0 \oplus a_1\}$;
2. $g_{a_0,b_0,a_1,b_1}(x) = x + \beta$, where $x + \gamma$ denotes $(x + y) \mod 256$ (the same hereinafter), and $\beta \in \{a_0 + b_0,a_1 + b_1\} \subset \{0,\ldots,255\}$.

Because $(x @ \alpha_1) @ \alpha_2 = x @ (\alpha_1 @ \alpha_2)$ and $(x + \beta_1) + \beta_2 = x + (\beta_1 + \beta_2)$, consecutive encryption subfunctions of the same kind can be combined together, and those with $\alpha = 0$ or $\beta = 0$ can be simply ignored. As a result, each encryption function $E_i(x)$ is a composition of $\text{len} \leq K_{10}$ subfunctions: $[G_i(x)]_{i=0}^{\text{len}}$, where $G_i(x) = x @ \alpha_{(i/2)}$ or $x + \beta_{(i/2)}$, and $G_0(x)$, $G_{i+1}(x)$ are encryption subfunctions of different kinds. According to the types of $G_i(x)$ and $G_{i+1}(x)$, $E_i(x)$ has four different formats:

1. $E_i(x) = ((\cdots ((x + \beta_1)@\alpha_1)\cdots @\alpha_{(\text{len}-1)/2}) + \beta_{(\text{len}/2)}$;
2. $E_i(x) = ((\cdots ((x + \beta_1)@\alpha_1)\cdots ) + \beta_{(\text{len}-1)/2} @ \alpha_{(\text{len}/2)}$;
3. $E_i(x) = ((\cdots ((x @ \alpha_1) + \beta_1)\cdots ) + \alpha_{(\text{len}-1)/2} + \beta_{(\text{len}/2)}$;
4. $E_i(x) = ((\cdots ((x @ \alpha_1) + \beta_1)\cdots ) + \beta_{(\text{len}-1)/2} @ \alpha_{(\text{len}/2)}$.

Note that $\text{len}$ is generally less than $K_{10}$. Assuming that $\{Y\}$ distributes uniformly over the interval $[0.1,0.9]$, we can get the following inequality:

$$\text{Prob}[\text{len} = K_{10}] \leq \left\{ \begin{array}{ll}
\frac{2}{\frac{K_{10}}{\sum_{k=0}^{K_{10}}}} & \text{when } K_{10} \text{ is even},
\left(\frac{K_{10}}{2} + \frac{1}{2}\right) & \text{when } K_{10} \text{ is odd}.
\end{array} \right.$$

(11)

From the above equation, we can see that the probability decreases exponentially as $K_{10}$ increases. Because it is difficult to exactly estimate the probability that $\text{len}$ is equal to a given value less than $K_{10}$, we performed a number of random experiments for a 512 x 512 plain-image to investigate the possibilities. Figure 1 shows a result of 100 random keys when $K_{10} = 66$.

Figure 1: The number of subfunctions composed of $\text{len}$ subfunctions, when $K_{10} = 66$ and other subkeys were generated randomly for 100 times.

Since $G_i(x)$ is a composition of multiple functions $g_{a_0,b_0,a_1,b_1}(x)$ of the same kind, and since that $a_0 \oplus a_1 = ...
0 \leq a \leq 255 and \overline{a} = a \oplus a_1 \oplus 255, one can easily deduce that
\begin{equation}
\alpha_i \in \mathbb{A} = \{255, a_0, a_1, a_0 \oplus 255, a_1 \oplus 255, a_0 \oplus a_1, a_0 \oplus a_1 \oplus 255\}
\end{equation}
and
\begin{equation}
\beta_j \in \mathbb{B} = \{z_1(a_0 + b_0) + z_2(a_1 + b_1) \mid z_1, z_2 \in \{0, \ldots, K_{10}\} \text{ and } z_1 + z_2 \leq K_{10}\}.
\end{equation}

Note that \mathbb{A} has an interesting property: \forall x_1, x_2 \in \mathbb{A} \cup \{0\}, \ x_1 \oplus x_2 \in \mathbb{A} \cup \{0\}. This property concludes that \bigoplus_i \alpha_i \in \mathbb{A} \cup \{0\}, which will be used later in Sec. 3.5 for chosen-plaintext attack.

### 3.2. Analysis of the key space

In this subsection, we report some invalid keys, weak keys and partially equivalent keys existing in the encryption scheme under study. Here, an invalid key means a key that cannot ensure the successful working of the encryption scheme, a weak key is a key that corresponds to one or more security defects, and partially equivalent keys generate the same encryption result for a certain part of the plain-image. When estimating the key space, invalid keys and weak keys should be excluded, and all keys that are partially equivalent to each other should be counted as one single key [26, Sec. 3.2].

#### 3.2.1. Invalid keys with respect to \( K_4 \sim K_9 \)

When \( X_0 = 0 \), the global chaotic map will fall into the fixed point 0, which disables the encryption process due to the lack of chaotic states lying in [0, 1, 0.9]. Now, let us see when \( X_0 = 0 \) can happen.

Observing Eq. (2), one can see that \( X_0 = 0 \) is equivalent to
\begin{equation}
\sum_{i=4}^{9} K_i \cdot 2^{8(i-4)} \equiv 0 \pmod{2^{24}}.
\end{equation}
By the fact that \( \sum_{i=4}^{9} K_i \cdot 2^{8(i-4)} \equiv 0 \pmod{2^{24}} \), the following equality also holds:
\begin{equation}
\text{FP}\left(\sum_{j=1}^{9} (K_j \mod 16) + \lceil K_j / 16 \rceil\right) / 96 \equiv 0 \pmod{2^{24}}.
\end{equation}

As a result, any key that satisfies Eqs. (15) and (16) simultaneously can lead to \( X_0 = 0 \). The number of such invalid subkeys \( (K_4, \ldots, K_9) \) can be calculated to be 5592046 = 2^{22.415}, where 5592046 = \lceil 16^6 / 3 \rceil is the number of distinct values of \( (K_7, K_8, K_9) \) satisfying Eq. (15), calculated according to the following Proposition [1].

**Proposition 1.** Given an \( n \)-dimensional vector \( \mathbf{A} = (a_1, \ldots, a_n) \in [0, \ldots, 15]^n \), the number of distinct values of \( \mathbf{A} \) that satisfy \( a_1 + \cdots + a_9 \equiv 0 \pmod{3} \) and \( 2 \equiv 0 \pmod{3} \) respectively.

**Proof.** This proposition can be proved by mathematical induction.

When \( n = 1 \), one can easily verify that the number of distinct values of \( \mathbf{A} \) that satisfy \( a_1 \equiv 0 \pmod{3} \) is 6, 5, 5, respectively. Since \( 6 \equiv 16 / 3 \) and \( 5 \equiv 16 / 3 \), the proposition is true.

Assuming that the position is true for \( 1 \leq n \leq k \), we prove the case for \( n = k + 1 \). First, rewrite \( a_1 + \cdots + a_k + 1 \) as \( A_k + a_{k+1} \), where \( A_k = a_1 + \cdots + a_k \). Then, observe that \( (A_k + a_{k+1}) \equiv 0 \pmod{3} \) is equivalent to \( A_k \equiv -a_{k+1} \pmod{3} \). Thus, the number of distinct values of \( \mathbf{A} \) that satisfying \( A_k + a_{k+1} \equiv 0 \pmod{3} \) is the following sum:
\begin{align*}
N[(A_k + a_{k+1}) \equiv 0] &= [16^6 / 3] \cdot [16 / 3] + 2[16^6 / 3] \cdot [16 / 3] \\
&= ([16^6 / 3] + 1) \cdot [16 / 3] + 2[16^6 / 3] \cdot [16 / 3] \\
&= 16 \cdot [16 / 3] + 6.
\end{align*}
Assume $16^k = (15 + 1)^k = 3C + 1$. Then, $16^{k+1} = 48C + 16$ and $[16^{k+1}/3] = 16C + [16/3] = 16C + 6$. Then $16 \cdot [16^k/3] + 6 = 16C + 6 = [16^{k+1}/3]$. Going through a similar process, one can easily get $N[(a_k + a_{k+1}) \mod 3 = 1] = N[(a_k + a_{k+1}) \mod 3 = 2] = [16^{k+1}/3]$. This completes the mathematical induction, hence finishes the proof of the proposition.

3.2.2. Invalid keys with respect to $K_1 \sim K_9$

For a given block $I^{(16)}(k)$, if $Y_0 = 0$, the local chaotic map will fall into the fixed point 0, which will also disable the encryption process of the corresponding block. According to Eq. (3), $Y_0 = 0$ when the following equality holds:

$$\left( B_2 + \sum_{j=1}^{24} B_2[P_j] \cdot 2^{j-1} \right) \mod 2^{24} = 0,$$

Since $0 \leq B_2 = \sum_{i=1}^{3} K_i \cdot 2^{8(i-1)} < 2^{24}$ and $0 \leq \sum_{j=1}^{24} B_2[P_j] \cdot 2^{j-1} < 2^{24}$, the above equality can be simplified as follows:

$$\sum_{j=1}^{24} B_2[P_j] \cdot 2^{j-1} = 2^{24} - B_2. \quad (17)$$

Assuming that $P_j$ distributes uniformly in $[1, \cdots, 24]$, $B_2$ and $(2^{24} - B_2)$ have $m$ and $n$-bits, respectively, the probability for Eq. (17) to hold is

$$p_s = \left( \frac{m}{2^4} \right)^n \frac{(2^4 - m)^{24-n}}{2^{24}}.$$

The relationship between the values of $p_s$ and $(25m + n)$ is shown in Fig. 2 from which one can see that the probability is not negligible for some values of $(m, n)$. In fact, because $p_s > 0$ holds for any value of $(m, n)$, we can say that any key is invalid from the strictest point of view. To resolve this problem, the original encryption scheme must be amended. One simple way to do so is setting $Y_0$ to be a pre-defined value once $Y_0 = 0$ occurs. In the following discussions of this paper and all experiments involved, we set $Y_0 = 1/2^{24}$ when such an event occurs.

3.2.3. Weak keys with respect to $K_{10}$

In the encryption scheme under study, the update process of subkeys $K_1 \sim K_9$ and the number of subfunctions $g_{a_0, b_0, a_1, b_1, y}(x)$ in each encryption function are both controlled by the subkey $K_{10}$. In the following, we discuss two weak-key problems with respect to $K_{10}$, which correspond to the above two processes controlled by $K_{10}$, respectively.

From Fact 1 one can see that the update of subkeys $K_i \sim K_9$ has an inherent weakness, i.e., the possible values for the period of the sequence of the updated subkeys is $2^2$, $i = 1 \sim 8$. For some values of $K_{10}$, this period can be very small, which weakens the updating mechanism considerably. The worst situation occurs when $K_{10} = 128$, which corresponds to period two. From the most conservative point of view, $T_{\text{max}} = 256$, which means that $K_{10}$ should be an odd number.

The other problem deals with the number of subfunctions $g_{a_0, b_0, a_1, b_1, y}(x)$ in each encryption function. When $K_{10} = 1$, the probability for a pixel to remain unchanged is $1/8$ (under the assumption that $Y_0$ distributes uniformly in the chaotic interval). Though the probability seems quite large, our experiments have shown that very little visual information leaks in the cipher-image. When $K_{10} \geq 2$, experiments have shown that it is almost impossible to distinguish any visual pattern from the cipher-image. As a result, in this case there exists only one major weak key: $K_{10} = 1$. To avoid other potential security defects, $K_{10} \geq 8$ is suggested.

3.2.4. Weak keys with respect to $K_4 \sim K_9$

Observing Table 1 one can see that the encryption subfunction $g_{a_0, a_1, b_0, b_1, y}(x) = x \oplus \bar{x}$ when the following requirements are satisfied:

$$a_0, a_1 \in [0, 255] \text{ and } a_0 + b_0 \equiv a_1 + b_1 \equiv 0 \pmod{256}. \quad (18)$$

For the sub-image $I_1$, if the subkeys corresponding to one encryption function $E_i(x)$ satisfy the above requirements, $E_i(x)$ will also be $x \oplus \bar{x}$. Assuming that the chaotic trajectory of the local chaotic map has a uniform distribution in the interval $[0, 1, 0.9]$, the probability of $g_{a_0, a_1, b_0, b_1, y}(x) = \bar{x}$ is $p = 3/8$. Then, according to Proposition 2, the probabilities of $E_i(x) = \bar{x}$ and $E_i(x) = x$ are $(1 - (1/4)^{K_{10}})/2$ and $(1 + (1/4)^{K_{10}})/2$, respectively. This means that about half of all plain-pixels in
Proposition 2. Given \( n > 1 \) functions, \( f_1(x), \ldots, f_n(x) \), assume that each function is \( x \oplus a \) with probability \( p \) and is \( x \) with probability \( 1 - p \), where \( a \in \mathbb{Z} \). Then, the probability of the composition function \( F(x) = f_1 \circ \ldots \circ f_n(x) = x \oplus a \) is \( P = (1 - (1 - 2p)^n)/2 \).

Proof. Assume that \( k = \lceil n/2 \rceil \). Then, \( n = 2k - 1 \) when it is odd. To ensure \( F(x) = f_1 \circ \ldots \circ f_n(x) = x \oplus a \), the number of subfunctions that are equal to \( x \oplus a \) should be an odd integer. So,

\[
P = \sum_{i=1}^{k} \binom{n}{2i-1} (1 - p)^{2i-1} (1 - p)^{n - (2i - 1)}
\]

\[
= (1 - p)^n \cdot \sum_{i=1}^{k} \binom{n}{2i-1} (p/(1 - p))^{2i-1}
\]

\[
= (1 - p)^n \cdot \frac{(1 + p/(1 - p))^n - (1 - p/(1 - p))^n}{2}
\]

\[
= (1 - (1 - 2p)^n)/2.
\]

This completes the proof of the proposition.

By letting Eq. (15) hold for the three encryption functions \( E_1(x), E_2(x) \) and \( E_3(x) \), we found a list of weak keys of this kind, as shown in Table 2.

3.2.5. Partially equivalent keys with respect to \( K_7 \sim K_9 \): Class I

Observe Eq. (2), one can see that the value of \( X_0 \) remains unchanged if the following segments of \( K_7, K_8, K_9 \) exchange their values: \( K_7 \mod 16, [K_7/16], K_8 \mod 16, [K_8/16], K_9 \mod 16, [K_9/16] \). Now let us find out what will happen if we exchange \( K_9 \mod 16 \) and \([K_9/16], \) i.e., exchange the upper half and the lower half of \( K_9 \). In this case, since the encryption of the red value of each pixel is independent of \( K_9 \), the red channel of the cipher-image will remain unchanged. Similar results also exist for \( K_7 \) and \( K_8 \), which correspond to unchanged blue and green channels of the plain-image, respectively. This problem reduces the subkey-space of \( (K_7, K_8, K_9) \) from \( 256^3 \) to \((16 + (256 - 16)/2)^3 = 136^3\).

3.2.6. Partially equivalent keys with respect to \( K_7 \sim K_9 \): Class 2

As remarked in Sec. 3.1, each encryption subfunction \( g_{a_0,a_1,b_0,b_1}(x) \) can be represented in one of the following two formats: \( x \oplus a \) and \( x + b \). The following two facts about \( \oplus \) and \( + \) will lead us to construct another class of partially equivalent keys.

Fact 2. \( \forall a \in \{0, \ldots, 255\}, a \oplus 128 = a + 128. \)

Fact 3. \( \forall a, b \in \mathbb{Z}, (a \oplus 128) + b = (a + b) \oplus 128. \)

Fact 2.\[ means that a change in the MSB (most significant bit) of \( x \), \( a_0 \), \( a_1 \), \( b_0 \), \( b_1 \) of any encryption subfunction \( g_{a_0,a_1,b_0,b_1}(x) \) is equivalent to XORing 128 on the output of the composition function \( E_i(x) \).

Next, Fact 3 is used to figure out the second class of partially equivalent keys about \( K_7 \sim K_9 \). First, choose any two subkeys from \( K_7 \sim K_9 \). Without loss of generality, let us take \( K_7 \) and \( K_8 \). Then, given a secret key \( K \) that satisfies \( K_7 < 128 \) and \( K_8 \geq 128 \) (or, \( K_7 \geq 128 \) and \( K_8 < 128 \)), let us change it into another key \( K \) by setting \( K_7 = K_7 + 128 \) and \( K_8 = K_8 \oplus 128 \). From Eq. (2), it is easy to see that \( X_0 \) remains the same for the two keys. This means that both the global and the local chaotic maps have the same dynamics throughout the encryption procedure for the two keys, and that the difference on ciphertexts is determined only by the MSB-changes of \( K_7 \) and \( K_8 \). In the following, to analyze the influence of the MSB-changes on the ciphertexts, we consider the three color channels separately.

First, consider the encryption process of the green channel of the plain-image, in which \( K_7 \) is not involved at all. Assuming that the chaotic trajectory \( \{Y_j\} \) distributes uniformly within the interval \([0, 1, 0, 9]\), the probability that \( K_8 \) has an effect on each encryption subfunction is \( p = 3/8 \). If \( K_8 \) appears for an even number of times in the total \( 256 \) encryption subfunctions, then the value of \( E_3(G) \) will remain the same for the two keys \( K \) and \( K \); otherwise, \( E_3(G) \) changes its MSB. Thus, using the same deduction as given in the proof of Proposition 1, the probability that \( E_3(G) \) remains unchanged can be calculated to be \( P_2 = (1 + (1 - 2p)^{2n})/2 = \)

![Image](image-url)
Table 2: Some weak keys that cause leaking of visual information.

| Weak keys                              | Visual information leaked from |
|----------------------------------------|-------------------------------|
| \((K_4, K_5), (K_7, K_8) \in \{(0, 0), (255, 1)\}\) | Channel R                     |
| \((K_5, K_6), (K_8, K_9) \in \{(0, 0), (255, 1)\}\) | Channel G                     |
| \((K_6, K_4), (K_9, K_7) \in \{(0, 0), (255, 1)\}\) | Channel B                     |
| \((K_4, K_5, K_6, K_7, K_8, K_9) = (0, 0, 0, 0, 0, 0)\) | the whole plain-image         |

\((1 + 4^{-K_9})/2\). This means that more than half of all green pixel values in the ciphertexts are identical in probability for the two keys \(K\) and \(\tilde{K}\).

For the blue channel, \(K_8\) is not involved in the encryption process. So, following a similar deduction, the probability that \(E_3(B)\) remains unchanged is \(P_3 = (1 + 4^{-K_9})/2 = P_2\).

For the red channel, both \(K_7\) and \(K_8\) are involved, but their differences are neutralized for the encryption subfunction \(x + (K_7 + K_8)\). So, the probability that the differences in \(K_7\) and \(K_8\) have an effect on the ciphertext is reduced to be \(p = 2/8 = 1/4\). Thus, the probability that \(E_1(R)\) remains unchanged becomes \(P_1 = (1 + 2^{-K_8})/2 > P_2\).

Combining all the above analyses together, it is expected that more than half of all pixel values in the cipher-images will be identical for the two keys \(K\) and \(\tilde{K}\). In addition, for other different pixel values, the XOR difference is always equal to 128. By enumerating all possibilities about this security problem, one can conclude that the subkey-space of \((K_7, K_8, K_9)\) is reduced from \(256^3\) to \(4 \cdot 128^3 = 256^3/2\).

To verify the above theoretical results, we have carried out some experiments for a plain-image of size 512 \(\times\) 512. One result is shown in Fig. 4 in which the number of identical pixel values in red, green and blue channels are 131241 (50.06%), 130864 (49.92%) and 131383 (50.12%), respectively.

Finally, it is worth mentioning that there exists an internal relationship between the sub-images \(I_{\text{red}}\) and \(I_{\text{green}} \cup I_{\text{blue}}\), where \(j \in \{0, \ldots, T/2 - 1\}\), which can be easily deduced from the following fact about the updating process of the subkeys: \(K_i + K_{10} \cdot T/2 = K_i + 128 \cdot K_{10} / \gcd(K_{10}, 256) = K_i + 128 = K_i \oplus 128 \pmod{256}\).

3.2.7. Reduction of the key space

Based on the above analyses, we now summarize the influence of invalid, weak and equivalent keys on the key space in Table 3. According to the table, one can roughly estimate that the size of key space is reduced to \(2^{75}\), which is somewhat smaller than \(2^{80}\) (the one claimed in [23, Sec. 3.3]).

3.3. Guessing \(K_{10}\) and \(\{K_i\}_{i=1}^T\) separately

The encryption process of the first block \(I^{16}_j(0)\) depends only on the secret values \(Y_0\) and \(K_{10}\). In other words, for the first block one can consider \((Y_0, K_{10})\) as an equivalent to the original key \(K\). Then, by guessing the value of \((Y_0, K_{10})\) one can get the value of \(K_{10}\) with complexity \(O(2^{72})\). Thus, the other subkeys can be separately guessed with complexity \(O(2^{72})\). The total complexity of such an enhanced brute-force attack is \(O(2^{72} + 2^{72}) = O(2^{72})\), which is smaller than \(O(2^{80})\), the expected complexity of a simple brute-force attack.

3.4. Guessing \(K_{10}\) with a chosen plain-image

As remarked in Sec. 3.1, all 16-channel blocks in \(I_{\text{red}} = \bigcup_{j=0}^{N-1} I^{16}_j(T \cdot k + j)\) are encrypted with the same subkeys. If these blocks also correspond to the same values of \(Y_0\), then all the three encryption functions for the R, G, B channels will become identical. Precisely, given two identical blocks, \(I^{16}_j(k_0)\) and \(I^{16}_j(k_1)\), one can see that the corresponding cipher-blocks will also become identical, if the following two requirements are satisfied:

(A) the distance of the two blocks is a multiple of \(T\), i.e., \((k_0 - k_1) \mid T\);  
(B) \(Y_0^{(k_0)} = Y_0^{(k_1)}\), where \(Y_0^{(k_0)}\) and \(Y_0^{(k_1)}\) denote the values of \(Y_0\) corresponding to the two 16-channel blocks.

Therefore, if the probability of the two cipher-blocks to be identical is sufficiently large, one may use the distance between them to determine the value of \(T\) and narrow down the search space of \(K_{10}\).

It should be noted that the following two cases can both ensure the requirement (B): 1) the sequences \(\{P_j\}\) corresponding to the two blocks are identical; 2) the sequences \(\{P_j\}\) corresponding to the two blocks are different (which may have \(t \in \{0, \ldots, 23\}\) identical elements), but the values of \(Y_0\) are still identical. The second case is tightly related to the ratio of 0-bits and 1-bits in \(B_2\). As an extreme example, when \(B_2 = 0\) or \(2^{24} - 1\) (all the bits of \(B_2\) are 0 or 1), \(B_2[\{P_j\}]\) will be fixed to be 0 or 1, respectively. Assuming that the number of 1-bits in \(B_2\) is \(m\), one can easily calculate the probability of \(B_2[\{P_j\}] = B_2[\{P_j\}]\) to be \((m/24)^2 + (1-m/24)^2\), and then the probability of \(Y_0^{(k_0)} = Y_0^{(k_1)}\) be \(P_B = ((m/24)^2 + (1-m/24)^2)^{24}\). We have carried out a large number of experiments to verify this theoretical estimation and the results are shown in Fig. 5. In these experiments, all possible values of \(B_2\) were exhaustively generated to estimate the probability (as the mean value) for \(\min(m, 24 - m) \leq 4\), and \(\binom{24}{4} = 10,626\) random keys were generated for \(\min(m, 24 - m) > 4\).
Figure 4: The decryption result with partially equivalent keys of Class 2: a) the plain-image “Lenna”; b) the cipher-image corresponding to \( K = "1A93DF25CF78DC44E160" \); c) the decryption result of subfigure b with a different key \( \tilde{K} = "1A93DF25CF785CC4E160" \).

Table 3: Reduction of the key space due to the existence of invalid keys, weak keys and partially equivalent keys.

| Subkeys | Size of reduced subkey-space | Reason |
|---------|-----------------------------|--------|
| \( K_1 \approx K_3 \) | - | \( Y_0 \approx 0 \) |
| \( K_4 \approx K_9 \) | \( 2^{48} - 5592406 \approx 2^{48} \) | \( X_0 \approx 0 \) |
| \( K_7 \approx K_9 \) | \( 136^7/2 = 2^{20.2624} \) | Equivalent key of Classes 1 and 2 |
| \( K_{10} \) | \( < (255 - 128 - 1) = 126 \) | Weak keys about \( K_{10} \) |

Figure 5: Probability of \( Y_{(k_0)} = Y_{(k_1)} \) with respect to the number of 1-bits in \( B_2 \).
Since Prob((k_0 - k_1) | T) is 1/T, the final probability that both requirements hold is P_a/T. According to Fig. 5, this probability may be large enough for an attacker to find some identical blocks in the same set $\mathcal{I}_j$, especially when min(m, 24 - m) and T are both relatively small.

To show how the attack works, we chose a 512 x 512 plain-image in which all blocks are identical but all pixels in each block are different from each other, and performed the attack for a secret key $K = "2A84BCF35D706664E4740"$. As a result, we found 9 pairs of identical blocks whose indices are listed in Table 4. Because all these indices should satisfy the requirement $(k_0 - k_1) | T$, we can get an upper bound of T by solving their greatest common divisor of the differences of the 9 indices. Thus, one immediately gets gcd(3161 - 1941, 7083 - 2015, 15255 - 3023, 9163 - 4159, 12113 - 5061, 16355 - 5507, 12454 - 9166, 12259 - 9655, 13102 - 11090) = 4. This means $T \in \{2, 4\}$, thus immediately leading to gcd($K_{10}$, 256) $\in \{128, 64\}$ and $K_{10} \in \{64, 128, 192\}$ according to Fact 1. As can be seen, in this example the size of the subkey space corresponding to $K_{10}$ is reduced from 256 to 3, which is quite significant.

3.5. Breaking $K_i \mod 128$ with chosen-plaintext attack

This subsection presents one of the most important results of this work, since it shows how to partially break the encryption algorithm using a very cost-effective chosen-plaintext attack, in which 128 or even less plain-images are created. First, in Sec. 3.5.1, some mathematical devices are introduced. Next, in Sec. 3.5.2, the steps used to recover subkeys $K_i \mod 128$ are described in detail. Finally some experimental results are given in Sec. 3.5.3 to validate the proposed attacks.

3.5.1. Preliminaries

First, we prove some useful properties related to the composite functions $F_i(x)$. These properties are essential for the attack to be introduced below in this subsection.

**Theorem 1.** Let $F(x) = G_{2m+1} \circ \ldots \circ G_1(x)$ be a composite function defined over $\{0, \ldots, 2^n - 1\}$, where $m, n \in \mathbb{Z}^+$, $G_{2i+1}(x) = x \oplus \alpha_i$, for $i = 1 \sim m$, $G_{2i+1}(x) = (x + \beta_i) \mod 2^n$, for $i = 0 \sim m$ and $\alpha_i, \beta_i \in \{0, \ldots, 2^n - 1\}$. If $F(x) = x \oplus \gamma$ for some $\gamma \in \{0, \ldots, 2^n - 1\}$, then $\gamma \equiv \sum_{i=1}^{m} \alpha_i \ (\text{mod} \ 2^n)$.

**Proof.** Let $x = \sum_{j=0}^{n-1} x_j \cdot 2^j$, $\alpha_i = \sum_{j=0}^{n-1} \alpha_i \cdot j \cdot 2^j$, $\beta_i = \sum_{j=0}^{n-1} \beta_i \cdot j \cdot 2^j$, and $F(x) = \sum_{j=0}^{n-1} F_j(x) \cdot 2^j$.

The proof is based on the following fact. If $F$ verifies $F(x) = x \oplus \gamma$ for some $\gamma = \sum_{j=0}^{n-1} x_j \cdot 2^j$, then, for any $j = 0 \sim n - 1$, the result of the computation of $F(x)$ depends only on the value of the $j$-th bit of $x$, that is, $x_j$. In other words, the value of $F_j(x)$ is independent of $F_p$ if $j \neq p$.

We are going to check the computation of $F(x)$ starting from the least significant bit. To get the value of $F_0(x)$, we only need to calculate $F_0(x) = (\cdots (x_0 \oplus \beta_{m_0} \oplus \alpha_1 \cdots \oplus \alpha_{m_1}) \oplus \cdots \oplus \alpha_{m_0} \oplus \beta_{m_0})$, and then get the least significant bit of $F_0(x)$. Note that the carry bit generated in each + operation influences only the most significant bits $F_1(x) \sim F_{n-1}(x)$, and for the least significant bit of $F_0(x)$ the operation + is equivalent to $\oplus$. Therefore, we immediately get $F_0(x) = x_0 \oplus \beta_{m_0} \oplus \alpha_1 \oplus \beta_1 \cdots \oplus \alpha_{m_1} \oplus \beta_{m_0} = x_0 \oplus (\alpha_1 \oplus \cdots \oplus \alpha_{m_0}) \oplus (\beta_{m_0} \oplus \cdots \oplus \beta_{m_0})$.

Then, let us study how the carry bits generated by + operations in the calculation on $F_0(x)$ affect the value of $F_1(x)$, as an effort to determine the value of $\beta_{m_0} \oplus \cdots \oplus \beta_{m_0}$. Note the following two facts about carry bits:

- when $\beta_{m_0} = 0$, no carry bit appears for any value of $x_0$;
- when $\beta_{m_0} = 1$, a carry bit appears when $x_0 = 0$ or 1 after the operation $\oplus$.

Denoting the number of $\beta_{m_0}$ whose value equals to 1 by $N_0$, the above facts mean that $N_0$ can be obtained by counting carry bits when $x_0 = 0$ and when $x_0 = 1$. That is, $N_0 = \sum_{x_0 \in \{0,1\}} N_0(x_0) = N_0(0) + N_0(1)$, where $N_0(x_0)$ denotes the number of carry bits generated in the calculation process on $F_0(x)$ with respect to $x_0$.

The independence of $F_1(x)$ of $x_0$ means that $N_0(0) = N_0(1)$, and as a result $N_0 = N_0(0) + N_0(1) = 2N_0(0)$ is an even number. This immediately leads to the conclusion $\beta_{m_0} \oplus \cdots \oplus \beta_{m_0} = 0$. Thus, $F_0(x) = x_0 \oplus (\alpha_1 \oplus \cdots \oplus \alpha_{m_0})$.

Next, consider $F_1(x)$. In this case, $F_1(x) = (\cdots ((x_1 \oplus \beta_1 + CB_0(x_0)) \oplus \alpha_1 \oplus \beta_1 + CB_1(x_0)) \oplus \cdots \oplus \alpha_{m_1} \oplus \beta_{m_0} + CB_m(x_0))$, where $CB_0(x_0)$ denotes the bit carrying from $F_0(x)$ during the i-th + operation (which is equal to 0 when a carry bit does not exist). Then, due to the same reason as in the case of $F_0(x)$, we have $F_1(x) = x_1 \oplus (\alpha_1 \oplus \cdots \oplus \alpha_{m_1}) \oplus (\beta_1 \oplus CB_0(x_0) \cdots \oplus \beta_{m_1} \oplus CB_m(x_0))$. Observing the expression of $F_1(x)$, we can easily note the following facts:

- when $\beta_1 = CB_0(x_0) = 0$: no carry bit appears for any value of $x_1$;
- when $\beta_1 = CB_0(x_0) = 1$: one carry bit always appears for any value of $x_1$;
- when $\beta_1 = 0$, $CB_0(x_0) = 1$, or when $\beta_1 = 1$, $CB_0(x_0) = 0$: one carry bit appears for only one value of $x_1$.\(^2\)

\(^2\)Here, $\pm 2^n$ is replaced by $\pm$ in the calculation process, because mod$2^n$ does not affect any bit of $F(x)$.

To be more precise, if there is a carry bit when $x_0 = 0$, then there will not be a carry bit when $x_0 = 1$ and vice versa.
As a summary, only one carry bit may be generated from a pair of \( \beta_l \) and \( CB_l(x_0) \), which means that one can consider \( \beta_l + CB_l(x_0) \) as a single value \( \beta'_l(x_0) \).

Denoting the number of \( \beta'_l \) whose value equals to 1 by \( N_l(x_0) \), the above facts imply that \( N_l(x_0) = \sum_{i \in [0,1]} N_l(x_0, x_1) = N_l(x_0, 0) + N_l(x_0, 1) \), where \( N_l(x_0, x_1) \) means the number of carry bits generated in the calculation process on \( \overline{F}(x) \) with respect to \( x_0 \) and \( x_1 \). Then, because the value of \( F_2(x) \) is independent of \( x_1 \), we can get \( N_l(x_0, 0) = N_l(x_0) \) and \( N_l(x_0, 1) \) is even. This means that \( \beta_{0,1} \oplus CB_l(x_0) \cdots \oplus \beta_{m,1} \oplus CB_m(x_0) = 0 \) and so \( F_1(x) = x \oplus (\alpha_{1,1} \cdots \oplus \alpha_{1,n}) \).

The above deduction can be simply applied to other bits \( F_2(x) \sim F_{m-1}(x) \). As a result, we get \( F_i(x) = x \oplus (\alpha_{i,1} \cdots \oplus \alpha_{i,n}), \forall i \in [0, n-1] \).

Finally, combining all the cases together, we have the result that \( F_i(x) \equiv x \oplus (\alpha_{i,1} \cdots \oplus \alpha_{i,n}) \pmod{2^{n-1}} \). This means that \( \gamma \equiv \bigoplus_{i=1}^{n} \alpha_{i} \pmod{2^{n-1}} \) and the theorem is thus proved.

**Corollary 1.** For the image encryption scheme under study, if there exists \( \gamma \in \{0, \ldots, 255\} \) such that \( E_i(x) = x \oplus \gamma \), then \( \gamma \in \bigoplus_{i=1}^{n} \alpha_{i} \oplus \bigoplus_{i=1}^{n} \alpha_{i} \oplus 128 \).

**Proof.** Consider the four classes of \( E_i(x) \) as shown in Sec. 3.1.

1. \( E_i(x) = ((\cdots((x + \beta_i) \oplus \alpha_i) \cdots) + \alpha_{(i-1)/2}) + \beta_{(i-1)/2} \): From Theorem 1, one has \( \gamma \in \bigoplus_{i=1}^{(i-1)/2} \alpha_{i} + \bigoplus_{i=1}^{(i-1)/2} \alpha_{i} + 128 \).

2. \( E_i(x) = ((\cdots((x + \beta_i) \oplus \alpha_i) \cdots) + \alpha_{(i-1)/2}) + \alpha_{(i-1)/2} \): From Theorem 1, one has \( \alpha_{(i-1)/2} \oplus \gamma \in \bigoplus_{i=1}^{(i-1)/2} \alpha_{i} + \bigoplus_{i=1}^{(i-1)/2} \alpha_{i} + 128 \), which means \( \gamma \equiv \bigoplus_{i=1}^{(i-1)/2} \alpha_{i} \pmod{128} \).

3. \( E_i(x) = ((\cdots((x + \alpha_i) \oplus \beta_i) \cdots) + \beta_{(i-1)/2}) + \beta_{(i-1)/2} \): Assuming \( x' = x \oplus \gamma \), we have \( E_i(x') = x' \oplus \gamma = x \oplus (\alpha_i + \gamma) \).

4. \( E_i(x) = ((\cdots((x \oplus \alpha_i) \oplus \beta_i) \cdots) + \beta_{(i-1)/2}) + \alpha_{(i-1)/2} \): Using a similar process to the above class, one gets \( \gamma \equiv \bigoplus_{i=1}^{(i-1)/2} \alpha_{i} \pmod{128} \).

The above four conditions together complete the proof of the corollary.

From Corollary 1 and Eq. (12), we get the following result:

\[
\gamma \mod 128 = \bigoplus_{i} \alpha_{i} \mod 128
\]

\( \in \mathcal{A}^* = \{x \mod 128 \mid x \in \mathcal{A} \cup \{0\}\} \).  \hspace{1cm} (19)

Assuming that \( a_0^* = a_0 \mod 128 \) and \( a_1^* = a_1 \mod 128 \), we have

\[
\mathcal{A}^* = \{0, 127, a_0^*, a_1^* \oplus 127, a_0^* \oplus 127, a_0^* \oplus a_1^* \oplus 127\}. \hspace{1cm} (20)
\]

Observing the above equation, we can easily notice the following facts:

1. when \( a_0^* = a_1^* \in \{0, 127\} \), \( \#(\mathcal{A}^*) = 2 \);
2. when \( a_0^* \in \{0, 127\} \) and \( a_1^* \notin \{0, 127\} \) (or \( a_1^* \in \{0, 127\} \) and \( a_0^* \notin \{0, 127\} \)), \( \#(\mathcal{A}^*) = 4 \);
3. when \( a_0^*, a_1^* \notin \{0, 127\} \), \( a_0^* \oplus a_1^* \in \{0, 127\} \), \( \#(\mathcal{A}^*) = 4 \);
4. when \( a_0^* \notin \{0, 127\} \) and \( a_1^* \in \{0, 127\} \), \( \#(\mathcal{A}^*) = 8 \).

Apparently, if we can get the set \( \mathcal{A}^* \), it will be possible to get the values of \( a_0^* \) and \( a_1^* \). The complexity of such a process is summarized as follows:

1. when \( \#(\mathcal{A}^*) = 2 \), there are only 2 possible values of \( (a_0^*, a_1^*) : (0, 127) \) or \( (127, 0) \);
2. when \( \#(\mathcal{A}^*) = 4 \), assuming that \( \mathcal{A}^* = \{0, 127, a, a \oplus 127\} \), there are 8 possible values of \( (a_0^*, a_1^*) : (0, a), (0, a \oplus 127), (127, a), (127, a \oplus 127), (a, a), (a, a \oplus 127), (a, 127, a), (a \oplus 127, a) \);
3. when \( \#(\mathcal{A}^*) = 8 \), there are 24 possible values of \( (a_0^*, a_1^*) : (0, 127) \) and \( a_1^* \oplus a_0^* \in \mathcal{A}^* \).

One can see that in any case the complexity is much smaller than \( 2^2 \times 2^2 = 2^4 \), the complexity of exhaustively searching all the bits of \( a_0^* \) and \( a_1^* \). This idea is the key for the chosen-plaintext attack proposed in this subsection.

Next, let us find out how to distinguish XOR-equivalent encryption functions. According to Proposition 3, one can achieve such a goal by checking the following 255 equalities: \( F(x_1) \oplus F(x_1 \oplus i) = i \), where \( x_1 \) is an arbitrary integer in \( \{0, \ldots, 255\} \) and \( i = 1 \sim 255 \).

**Proposition 3.** Let \( F(x) \) be a function defined over \( \{0, \ldots, 2^n - 1\} \), where \( n \in \mathbb{Z}^+ \). Then, \( F(x) = x \oplus \gamma \) for any \( x \in \{0, \ldots, 2^n - 1\} \) if and only if the following requirement holds: there exists \( x_1 \in \{0, \ldots, 2^n - 1\} \) such that \( F(x_1) \oplus F(x_1 \oplus i) = i \), \( \forall i \in \{1, \ldots, 2^n - 1\} \).
Proof. The “only if” part is obvious. Now, let us prove the “if” part. Note that $F(x_1) \oplus F(x_1 \oplus i) = i$ also holds when $i = 0$. So, when $i = x \oplus x_1$, we have $F(x_1 \oplus x \oplus x_1) = F(x) = F(x_1) \oplus x \oplus x_1 = x \oplus (x_1 \oplus F(x_1))$. When $i = x_1$, we have $F(x_1) \oplus F(x_1 \oplus x_1) = x_1$ and then get $x_1 \oplus F(x_1) = F(0)$. Therefore, $F(x) = x \oplus F(0)$, where $F(0) = \gamma$ is a fixed value.

For the encryption functions $E_i(x)$ composed of $\oplus$ and $\cdot$, the above result can be further simplified. From Proposition 4, it is enough to check the following 127 equalities: $F(x_1) \oplus F(x_1 \oplus d) = d$, where $x_1$ is an arbitrary integer in $\{0, \ldots, 255\}$ and $d \in \{1, \ldots, 127\}$.

**Proposition 4.** Consider any encryption function $E_i(x)$ ($i = 1 \sim 3$) defined in Eqs. (4) – (6). If there exists $x_1 \in \{0, \ldots, 255\}$ such that $E_i(x_1) \oplus E_i(x_1 \oplus d) \neq d$, $\forall d \in \{1, \ldots, 127\}$, then $E_i(x) = x \oplus E_i(0)$.

Proof. From Fact 3 one has $E_i(x_1) \oplus E_i(x_1 \oplus 128) = 128$ and $E_i(x_1) \oplus E_i(x_1 \oplus j \oplus 128) = j \oplus 128$ for $j = 1 \sim 127$. This means that $E_i(x_1) \oplus E_i(x_1 \oplus j) = j$ holds $\forall j \in \{1, \ldots, 255\}$. Then, from Proposition 3 $E_i(x) = x \oplus E_i(0)$.

Next, let us investigate the probability that a given encryption $E_i(x)$ is equivalent to $x \oplus \gamma$. Again, because the theoretical analysis is quite difficult, we carried out a number of random experiments with a 512 x 512 plain-image for different values of $K_{10}$, where $K_1 \sim K_9$ were generated at random. Generally speaking, this probability becomes smaller when $K_{10}$ increases, but it fluctuates in a wide range for different values of $K_1 \cdots K_9$. Two typical examples are shown in Fig. 6 in which the XOR-equivalent encryption functions involving the second kind of encryption subfunctions (i.e., functions of the form $x + \beta$) and those not involving these encryption subfunctions were counted separately.

3.5.2. Description of the attack

Based on the above discussions, a chosen-plaintext attack can be developed by choosing 128 plain-images $\{I_i\}_{i=0}^{127}$ of size $M \times N$ as follows: $I_i = I_0 \oplus \Gamma$ where $I_0$ can be freely chosen. To facilitate the following description about the attack, denote the encryption function $E_i(x)$ corresponding to the $j$-th pixel of the $k$-th block by $E_{i,k,j}(x)$, and the parameters $\alpha_0, \alpha_1$ corresponding to the $k$-th block by $\alpha_{0,k}, \alpha_{1,k}$, respectively. Similarly, for each updated subkey $K_j$, the value corresponding to the $k$-th block is denoted by $K_{j,k}$. Then, according to the discussion in Sec. 3.2.6, we have the following:

\[\text{In this paper, we use } L = l_0 \oplus l \text{ to denote the following facts: } \forall i \neq MN - 1, R_i(i) = R_0(i) \oplus l, G_i(i) = G_0(i) \oplus l \text{ and } B_i(i) = B_0(i) \oplus l.\]
THEN, if there exists $k \in \{0, \cdots , T/2 - 1\}$ such that $\#(\overline{\mathcal{A}}_{k_{1k}}) \not\in \{2, 4, 8\}$, one can immediately conclude that the current value of $K_{10}$ is wrong and then remove it from the list of candidate values for $K_{10}$.

The output of this step includes a list of $N$ candidate values of $K_{10}$ and at most $3T/2$ sets $\{\overline{\mathcal{A}}_{k_{1k}}\}_{k_{1k}=1}^{128}$ for each candidate value of $K_{10}$. The total number of memory units required is not greater than $6 \times 3NT/2 = 9NT \leq 12 \times 256 \times 128 = 294912 \approx 2^{18.2}$, which is practical for a PC to store the intermediate data. Here, note that 0 and 127 are always in $\overline{\mathcal{A}}_{k}$, so they do not need to be kept.

**Step 3** – Determining $(K_{i} \mod 128)_{i=4}^{10}$

For each color channel, choosing the set $\overline{\mathcal{A}}_{k_{ik}}$ of the greatest size, one can exhaustively search all possible values of $(a_{0,0,k_{0}}, a_{1,0,k_{0}})$, i.e., search all possible values of $a_{0,0,0} = (a_{0,0,k_{0}} - k_{0} \cdot K_{10}) \mod 128$ and $a_{1,0,0} = (a_{1,0,k_{0}} - k_{0} \cdot K_{10}) \mod 128$. Note that $a_{0,0,0} = K_{0} \mod 128$ and $a_{1,0,0} = K_{7} \mod 128$ (red channel), $a_{0,2,0} = K_{5} \mod 128$ and $a_{1,2,0} = K_{2} \mod 128$ (green channel), $a_{0,3,0} = K_{6} \mod 128$ and $a_{1,3,0} = K_{9} \mod 128$ (blue channel).

All the guessed values of $(a_{0,0,0}, a_{1,0,0})$ are verified by employing the relationship between $\overline{\mathcal{A}}_{k_{ik}}$ and the other sets $\{\overline{\mathcal{A}}_{k_{ik}}\}_{k_{ik} \neq k_{ik}}$. If all possible values of $(a_{0,0,0}, a_{1,0,0})$ are eliminated, the current value of $K_{10}$ can also be eliminated. Note that the other three values of a valid candidate $(a_{0,0,0}, a_{1,0,0} \oplus 128, K_{10} \mod 128) = (u, v, w)$ will also pass the verification process due to Fact 5 below: $(u \oplus 127, v \oplus 127, 128 - w), (v, u, w), (v \oplus 127, u \oplus 127, 128 - w)$.

**Fact 5.** Given $a, c \in \{0, \cdots , 127\}$, $x + ac \equiv (x \oplus 127 + (128 - ac)) \oplus 127 \mod 128$.

The output of this step is a list of candidate values of

$$K_{i} = (K_{i} \mod 128, \cdots , K_{9} \mod 128, K_{10} \mod 128).$$

In the worst case, the number of all possible values is $N \times 24^{3} \leq 256 \times 24^{3} = 3538944 \approx 2^{11.6}$, which is still much smaller than the number of all possible values of the subkey $K_{i}^{*} = 2^{6x7+8} = 2^{50}$. In the best case, the number of candidate values is only $2 \times 2^{3} = 16$ (according to Fact 5).

### 3.5.3. Experimental Results

To validate the feasibility of the above attack, we have carried out a real attack with a randomly-generated secret key $K = \text{"2A84BCF25E6A664E4C41"}$. As a result, we got the following output from Step 2:

- $K_{10} \in \{1, 3, \cdots , 255\}$,
- $K_{0,0} = \{0, 127, 108, 20, 7, 107, 120, 108\}$,
- $K_{0,28} = \{0, 127, 115, 125, 14, 0, 12, 113\}$,
- $K_{0,79} = \{0, 127, 116, 117, 1, 10, 112, 126\}$,
- $K_{1,19} = \{0, 127, 16, 33, 49, 111, 94, 78\}$,
- $K_{1,28} = \{0, 127, 106, 122, 21, 5, 111, 16\}$,
- $K_{2,7} = \{0, 127, 19, 78, 108, 49, 34, 93\}$,
- $K_{2,18} = \{0, 127, 34, 93, 3, 33, 124, 94\}$.

The final output of the attack (i.e., the output of Step 3) is shown in Table 5.

| $K_{10} \mod 128$ | $(K_{i} \mod 128)_{i=4}^{10}$ |
|-------------------|----------------------------------|
| 63                | i = 4 | i = 7 | i = 5 | i = 8 | i = 6 | i = 9 |
| 25                | 13    | 33    | 49    | 51    | 21    | 51    |
|                   | 49    | 33    | 51    | 21    | 51    |       |
| 13                | 25    | 33    | 49    | 51    | 21    | 51    |
|                   | 49    | 33    | 51    | 21    | 51    |       |
| 102               | 114   | 94    | 78    | 76    | 106   | 76    |
|                   | 78    | 94    | 76    | 106   | 76    |       |
| 65                | 114   | 94    | 78    | 76    | 106   | 76    |
|                   | 78    | 94    | 76    | 106   | 76    |       |

Finally, note that one may also be able to distinguish some XOR-equivalent encryption functions even with less than 128 chosen plain-images. To investigate such a possibility, we have carried out some experiments by choosing the following $(n + 1) < 128$ plain-images instead: $\{I_{l}\}_{l=0}^{n}$, where $I_{l} = I_{0} \oplus l$ for any $l > 0$. Let $N(n)$ be the number of XOR-equivalent encryption functions detected with the above $n+1$ chosen plain-images. The ratio $r(n) = N(127)/N(n)$ gives an estimation of the probability that a detected XOR-equivalent encryption function is real. For three randomly-generated keys, the values of $r(n)$ with respect to different values of $n$ are shown in Fig. 7 from which one can see that the value of $r(n)$ always increases significantly when $n$ increases from $2^{i} - 1$ to $2^{i}$ ($i = 1 \sim 6$). We also carried out experiments...
for other random keys, and found out that this fact holds for most of them. According to this experimental result, we can choose the following 13 plain-images to minimize the number of chosen plaintexts: \( I_0, I_1 = I_0 \oplus 1, I_2 = I_0 \oplus 2, I_3 = I_0 \oplus 3, I_4 = I_0 \oplus 4, I_5 = I_0 \oplus 7, I_6 = I_0 \oplus 8, I_7 = I_0 \oplus 15, I_8 = I_0 \oplus 16, I_9 = I_0 \oplus 31, I_{10} = I_0 \oplus 32, I_{11} = I_0 \oplus 63 \) and \( I_{12} = I_0 \oplus 64 \). Then, for 1,000 randomly-generated secret keys, our experiments show that the average value of \( r^* = N(127)/N^* \) is about 0.825, where \( N^* \) denotes the number of detected XOR-equivalent encryption functions with the 13 chosen plain-images. Note that the value of \( r^* \) is not accurate when \( N^* \) is too small. If only those keys corresponding to \( N^* \geq 100 \) are considered, the average value of \( r^* \) increases to about 0.9234. If only those keys corresponding to \( N(n) \geq 1000 \) are counted, the average value of \( r^* \) becomes about 0.9826. In practice, one may have to use more than 13 chosen plain-images to run the proposed attack, but it is expected that \( O(20) \) chosen plain-images are enough in most cases.

![Figure 7: The values of \( r(n) \) with respect to different values of \( n = 1 \sim 127 \), where the three lines correspond to the results of three randomly-generated keys.](image)

3.6. Known-plaintext attack based on a masking image

According to the results shown in Fig. 7, we know that many encryption functions are equivalent to XOR operations. Therefore, we consider all the encryption functions as XOR-equivalent ones, then a masking image can be obtained by simply XORing a known plain-image and the corresponding cipher-image pixel by pixel. By using this masking image as an equivalent of the secret key to decrypt other cipher-images, all the pixels encrypted by real XOR-equivalent encryption functions will be correctly recovered. If the number of such correctly-recovered pixels is sufficiently large, some visual information about the plain-images may be obtained. It is expected that this known-plaintext attack can work well when \( K_{10} \) is relatively small. Figure 8 shows two examples of this attack when \( K_{10} = 6 \) and 30, from which one can see that some important visual information about the plain-image is revealed.
[3] T.-J. Chuang, J.-C. Lin, New approach to image encryption, J. Electronic Imaging 7 (2) (1998) 350–356.
[4] J.-I. Guo, J.-C. Yen, H.-F. Pai, New voice over Internet protocol technique with hierarchical data security protection, IEEE Proc. – Vis. Image Signal Process. 149 (4) (2002) 237–243.
[5] H.-C. Chen, J.-C. Yen, A new cryptography system and its VLSI realization, J. Systems Architecture 49 (2003) 355–367.
[6] K.-L. Chung, L.-C. Chang, Large encryption binary images with higher security, Pattern Recognition Letters 19 (5–6) (1998) 461–468.
[7] Y. Mao, G. Chen, S. Lian, A novel fast image encryption scheme based on 3D chaotic Baker maps, Int. J. Bifurcation and Chaos 14 (10) (2004) 3613–3624.
[8] G. Chen, Y. Mao, C. K. Chui, A symmetric image encryption scheme based on 3D chaotic cat maps, Chaos, Solitons & Fractals 21 (3) (2004) 749–761.
[9] S. Li, C. Li, G. Chen, N. G. Bourbakis, K.-T. Lo, A general quantitative cryptanalysis of permutation-only multimedia ciphers against plaintext attacks, Signal Processing: Image Communication 23 (3) (2008) 212–223.
[10] S. Li, C. Li, G. Chen, X. Mou, Cryptanalysis of the RCES/RSES image encryption scheme, Journal of Systems and Software 81 (7) (2008) aa–bb.
[11] C. Li, S. Li, D. Zhang, G. Chen, Cryptanalysis of a chaotic neural network based multimedia encryption scheme, in: Advances in Multimedia Information Processing - PCM 2004 Proceedings, Part III, Vol. 3333 of Lecture Notes in Computer Science, Springer-Verlag, 2004, pp. 418–425.
[12] S. Li, C. Li, K.-T. Lo, G. Chen, Cryptanalysis of an image encryption scheme, J. Electronic Imaging 15 (4) (2006) art. no. 043012.
[13] C. Li, S. Li, D. Zhang, G. Chen, Cryptanalysis of a data security protection scheme for VoIP, IEEE Proc. – Vis. Image Signal Process. 153 (1) (2006) 1–10.
[14] S. Li, C. Li, K.-T. Lo, G. Chen, Cryptanalysis of an image scrambling scheme without bandwidth expansion, IEEE Transactions on Circuits and Systems for Video Technology 18 (3) (2008) 338–349.
[15] S. Li, C. Li, K.-T. Lo, G. Chen, Cryptanalyzing an encryption scheme based on blind source separation, IEEE Transactions on Circuits and Systems I 55 (4) (2008) 1055–1063.
[16] S. Li, G. Chen, X. Zheng, Chaos-based encryption for digital images and videos, in: B. Furt, D. Kirovski (Eds.), Multimedia Security Handbook, CRC Press, 2004, Ch. 4, pp. 133–167, preprint is available at [http://www.hooklee.com/pub.html](http://www.hooklee.com/pub.html).
[17] B. Furt, D. Socek, A. M. Eskicioglu, Fundamentals of multimedia encryption techniques, in: B. Furt, D. Kirovski (Eds.), Multimedia Security Handbook, CRC Press, 2004, Ch. 3, pp. 93–132.
[18] A. Uhl, A. Pommer, Image and Video Encryption: From Digital Rights Management to Secured Personal Communication, Springer Science + Business Media Inc., Boston, 2005.
[19] B. Furt, E. Maharemagic, D. Socek (Eds.), Multimedia Encryption and Watermarking, Springer, New York, 2005.
[20] W. Zeng, H. Yu, C.-Y. Lin (Eds.), Multimedia Security Technologies for Digital Rights Management, Academic Press, Inc., Orlando, Florida, 2006.
[21] N. Pareek, V. Patidar, K. Sud, Discrete chaotic cryptography using external key, Physics Letters A 309 (1–2) (2003) 75–82.
[22] N. Pareek, V. Patidar, K. Sud, Cryptography using multiple one-dimensional chaotic maps, Communications in Nonlinear Science and Numerical Simulation 10 (7) (2005) 715–723.
[23] N. Pareek, V. Patidar, K. Sud, Image encryption using chaotic logistic map, Image and Vision Computing 24 (9) (2006) 926–934.
[24] G. Alvarez, F. Montoya, M. Romera, G. Pastor, Cryptanalysis of a discrete chaotic cryptosystem using external key, Physics Letters A 319 (3–4) (2003) 334–339.
[25] C. Li, S. Li, G. Alvarez, G. Chen, K.-T. Lo, Cryptanalysis of a chaotic block cipher with external key and its improved version, Chaos, Solitons & Fractals 37 (1) (2008) 299–307.
[26] G. Alvarez, S. Li, Some basic cryptographic requirements for chaos-based cryptosystems, Int. J. Bifurcation and Chaos 16 (8) (2006) 2129–2151.