

Grayscale-Based Image Encryption Considering Color Sub-sampling Operation for Encryption-then-Compression Systems

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Abstract—A new grayscale-based block scrambling image encryption scheme is presented to enhance the security of Encryption-then-Compression (EtC) systems, which are used to securely transmit images through an untrusted channel provider. The proposed scheme enables the use of a smaller block size and a larger number of blocks than the conventional scheme. Images encrypted using the proposed scheme include less color information due to the use of grayscale images even when the original image has three color channels. These features enhance security against various attacks, such as jigsaw puzzle solver and brute-force attacks. Moreover, it allows the use of color sub-sampling, which can improve the compression performance, although the encrypted images have no color information. In an experiment, encrypted images were uploaded to and then downloaded from Facebook and Twitter, and the results demonstrated that the proposed scheme is effective for EtC systems, while maintaining a high compression performance.

Index Terms—Compression, encryption, EtC systems

I. INTRODUCTION

The use of images and video sequences has greatly increased because of rapid growth of the Internet and multimedia systems. A lot of studies on secure, efficient and flexible communications have been reported [1]–[3]. For securing multimedia data, full encryption with provable security (like RSA, AES, etc) is the most secure options. However, many multimedia applications have been seeking a trade-off in security to enable other requirements, e.g., low processing demands, retaining bitstream compliance, and signal processing in the encrypted domain.

Encryption-then-Compression (EtC) systems with JPEG compression [3]–[6] have been proposed to be applied to Social Network Services (SNS) and Cloud Photo Storage Services (CPSS). However, the color-based image encryption schemes for EtC systems [7]–[10] cannot provide the robustness against color sub-sampling used for JPEG compression because an encrypted image is a full-color image. In order to solve this issue, the grayscale-based images encryption has been proposed [11], [12] to encrypt a full-color image as a grayscale-based image. Even if the grayscale-based image encryption [11] can avoid the effect of color sub-sampling, it is impossible to consider color sub-sampling operation because the grayscale-based image is generated from RGB

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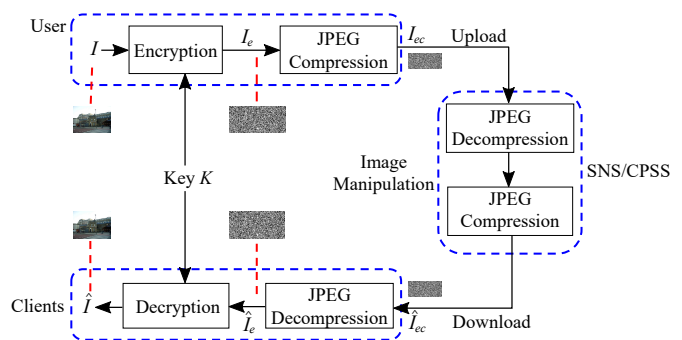


Fig. 1: EtC system

components. Moreover, compared to the color-based image encryption [7]–[10], the compression performance is strongly degraded. According to [12], the grayscale-based image encryption generated from YCbCr components and the quantization table for grayscale-based images have been proposed to provide the better compression performance. However, the color sub-sampling operation has not been considered.

This paper discusses and considers the color sub-sampling operation for grayscale-based image encryption. Instead of generating the grayscale-based image from RGB components, a full-color image in RGB color space is firstly transformed to YCbCr color space. Hence, color sub-sampling operation can be performed to generate grayscale-based images. Moreover, we describe scenario and requirements that image encryption have to satisfy. The enhancements of compression performance and robustness against color sub-sampling are evaluated in terms of Rate-Distortion (R-D) curves.

II. SCENARIO AND REQUIREMENTS

According to the image manipulation on Social Network Services (SNS) and Cloud Photo Storage Services (CPSS) [13], almost all providers manipulate every uploaded image as illustrated in Fig. 1. Because of such scenarios, the grayscale-based image encryption schemes for EtC system have been proposed [11], [12] as the extension of the color-based EtC systems [7]–[10].

There are three requirements that image encryption schemes have to satisfy: compression performance, security level, and robustness against image manipulation.

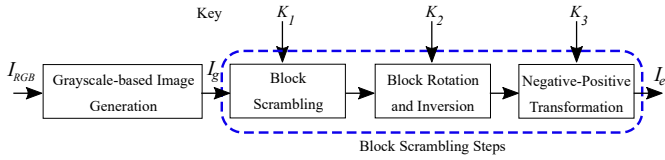


Fig. 2: Conventional grayscale-based block scrambling image encryption

1) *Compression Performance*: In order to apply an image encryption scheme to SNS and CPSS, it is necessary for encrypted JPEG images to have almost the same compression performance as the non-encrypted ones. The color-based encryption scheme [7]–[10] can provide almost the same compression performance as the non-encrypted JPEG images. However, it cannot be achieved by the conventional grayscale-based image encryption [11] because a grayscale-based image is generated from RGB components as shown in Fig. 2

2) *Security Level*: In this paper, we consider security against brute-force attack and jigsaw puzzle solver attacks as ciphertext-only attacks. It has been confirmed that the key space of block scrambling-based image encryption for EtC systems is huge enough against brute-force attack [9] and has the robustness against jigsaw puzzle solver attacks [11], [14]–[17].

This paper considers the extended jigsaw puzzle solver [16], [17] as ciphertext-only attacks. There are three metrics using for evaluating the robustness against jigsaw puzzle solver attacks [15], [18] which are described as follows:

- **Direct comparison** (D_c) is the ratio between the number of pieces which are placed in the correct position and the total number of pieces.
- **Neighbor comparison** (N_c) expresses the ratio of the number of pieces that are joined with the correct pattern and the total number of pieces.
- **Largest components** (L_c) refers to the ratio between the number of the largest joined blocks that are correctly adjacent and the number of pieces.

Note that $D_c, N_c, L_c \in [0, 1]$ and a larger value means a higher compatibility.

As images encrypted using the grayscale-based image encryption contain only one color channel [11], the smallest block size ($B_x \times B_y$) of the grayscale-based image encryption is 8×8 . Moreover, since the block size is smaller, and the number of blocks is larger than the color-based encryption scheme. As a result, grayscale-based encrypted images have stronger security and robustness against jigsaw puzzle solver attacks [17] than those with the color-based one.

3) *Robustness against Image Manipulation*: It is known that almost all SNS and CPSS providers manipulate every uploaded image when it satisfies their conditions [13]. Uploaded JPEG images are decompressed and sequentially recompressed with new compression parameters based on their algorithms. In recompression, as the color sub-sampling is usually carried out, the image encryption which has robustness against color sub-sampling is required. However, this requirement cannot be

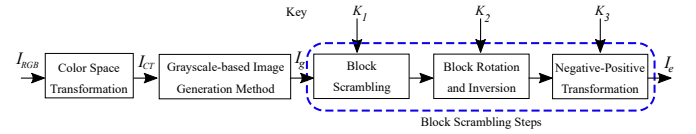


Fig. 3: Proposed grayscale-based block scrambling image encryption

achieved by the color-based encryption scheme [7]–[10] while the conventional grayscale-based image encryption [11], [12] has been proposed to avoid the effect of color sub-sampling.

III. PROPOSED GRAYSCALE-BASED IMAGE ENCRYPTION

This section describes an encryption procedure of the proposed grayscale-based image encryption and how the color sub-sampling operation is considered with the encryption scheme. Finally, the quantization table for grayscale-based images is discussed.

A. Encryption Procedure

Let us consider a full-color image (I_{RGB}) with $M \times N$ pixels. To encrypt I_{RGB} , the following six steps are carried out as follows (See Fig. 3).

Step1: I_{RGB} are transformed into the full-color image in YCbCr color space (I_{YCbCr}), so that $I_{CT} = I_{YCbCr}$.

Step2: Luminance (i_Y) and chrominance (i_{Cb} and i_{Cr}) are concatenated vertically or horizontally to generate the grayscale-based image (I_g) with $3(M \times N)$ pixels.

Step3: I_g with $M_g \times N_g$ pixels is divided into non-overlapping blocks each with $B_x \times B_y$. The number of divided blocks, N_b , is expressed by

$$N_b = \lfloor \frac{M_g}{B_x} \rfloor \times \lfloor \frac{N_g}{B_y} \rfloor \quad (1)$$

where $\lfloor \cdot \rfloor$ is the floor function that rounds down to the nearest integer.

Step4: Randomly permute the divided blocks based on a random integer which is generated by a secret key K_1 .

Step5: Rotate and invert each divided block randomly based on a random integer generate by a secret key K_2 .

Step6: Perform the negative-positive transformation to each divided block using a random binary integer generated by a secret key K_3 . A transformed pixel of i th block is represented by p' and can be expressed as

$$p' = \begin{cases} p & (r(i) = 0) \\ p \oplus (2^L - 1) & (r(i) = 1) \end{cases} \quad (2)$$

where $r(i)$ is a random binary integer generated by K_3 and p is the pixel value of an original image with L bits per pixel.

B. Color sub-sampling for Grayscale-based Images

As previously described in Section III-A that I_{RGB} is firstly transformed to I_{YCbCr} , this paper considers the color sub-sampling operation for the grayscale-based image encryption. Since human eyes are more sensitive to i_Y than i_{Cb} and i_{Cr} ,

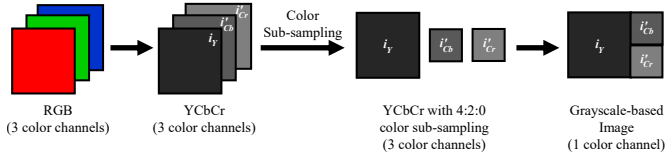


Fig. 4: Grayscale-based image generation method

we downsample i_{Cb} and i_{Cr} using 4:2:0 color sub-sampling operation provided by IJG software [19] as shown in Fig. 4. The sub-sampled chrominance components are represented by i'_{Cb} and i'_{Cr} . Eventually, i_Y , i'_{Cb} , and i'_{Cr} are combined to produce I_g with $\frac{3}{2}(M \times N)$ pixels. The example of I_g with 4:2:0 color sub-sampling is shown in Fig. 5(a). As I_g has only one color channel, the color sub-sampling operation is not carried out. Thus, the proposed scheme can provide the robustness against color sub-sampling and better compression performance.

C. Quantization Table for Grayscale-based Images

JPEG softwares, such as Independent JPEG Group (IJG) software [19], generally utilize two default quantization tables to quantize i_Y , i_{Cb} , and i_{Cr} of I_{YCbCr} where i_Y is quantized by the luminance quantization table (Y-table), and the chrominance quantization table (CbCr-table) is employed to quantize i_{Cb} and i_{Cr} . However, users are allowed to use other tables rather than the default ones. The image-dependent quantization table has been proposed to minimize the distortion of quantization process of each block [20]. However, since I_g is generated from i_Y , i_{Cb} , and i_{Cr} , those tables are not designed for I_g . Therefore, the quantization table called G-table has been proposed to improve the compression performance of I_g [12].

In JPEG compression, all pixel values in each block of I_g are mapped from $[0, 255]$ to $[-127, 128]$ by subtracting 128, then each block is transformed using Discrete Cosine Transform (DCT) to obtain DCT coefficients.

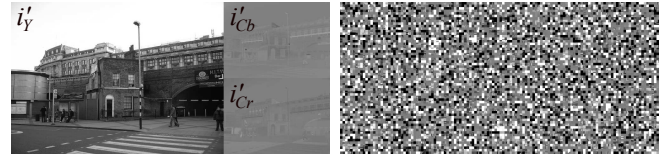
The DCT coefficients are employed to generating G-table. Let $D_n(i, j)$ be the DCT coefficient of the n^{th} block at the position (i, j) where $1 \leq i \leq 8$ and $1 \leq j \leq 8$. Considering every block of I_g , the Euclidean distance between the origin O and $D_n(i, j)$ is measured, and the arithmetic mean of the distance is expressed by

$$c(i, j) = \frac{1}{N_b} \sum_{n=1}^{N_b} |D_n(i, j) - O| \quad (3)$$

where I_g consists of N_b blocks.

As a set of grayscale-based images which consists of R images is utilized to determine G-table, we define $c_n(i, j)$ as $c(i, j)$ of the n^{th} image and calculate the average of every $c(i, j)$ from R grayscale-based images. The average $\bar{c}(i, j)$ is calculated as follow.

$$\bar{c}(i, j) = \frac{1}{R} \sum_{n=1}^R c_n(i, j) \quad (4)$$



(a) Grayscale-based image with 4:2:0 color sub-sampling

(b) Image encrypted by grayscale-based image encryption considering 4:2:0 color sub-sampling

Fig. 5: Example images

17	26	32	40	47	56	70	92
26	36	43	52	59	69	84	110
34	44	52	61	70	80	98	125
43	54	63	72	82	95	113	142
52	65	74	84	95	109	129	159
63	78	88	99	110	126	149	182
79	97	109	119	132	150	176	213
102	124	137	149	164	183	213	254

Fig. 6: G-table for grayscale-based images

To obtain G-table, $q(i, j)$ represents the quantization step size at (i, j) and is derived from the ratio between $\bar{c}(1, 1)$ and $\bar{c}(i, j)$. The step size can be calculated by

$$q(i, j) = \left\lceil \frac{\bar{c}(1, 1)}{\bar{c}(i, j)} \right\rceil + \epsilon \quad (5)$$

where ϵ is set to 16 for adjusting the Y-table step size at $(1, 1)$ as for IJG software [19].

IV. EXPERIMENTS

A. Experimental Set-up

To evaluate the performance of the grayscale-based image encryption considering color sub-sampling operation, this paper utilizes two datasets as below.

- 20 images from MIT dataset (672×480) [15]
- 1338 images from Uncompressed Color Image Database (UCID) [21]

All images in Dataset (a) were encrypted using the proposed scheme and conventional one with $B_x = B_y = 8$. Then, all encrypted images were compressed with specific quality factors, $Q_f \in [70, 100]$, using the JPEG standard from IJG software [19].

All images in dataset (b) were compressed using IJG software [19] to obtain compressed grayscale-based images. Note that DCT coefficients are extracted during this JPEG compression. According to the procedures in section III-C, G-table was designed by using the DCT coefficients whereas $N_b = 4608$, $R = 1338$, and $\epsilon = 16$. As a result, G-table is shown in Fig. 6. We conduct two experiments: without color sub-sampling (4:4:4) and with color sub-sampling (4:2:0). All JPEG images were decompressed and measure Peak-Signal-to-Noise Ratio (PSNR), respectively.

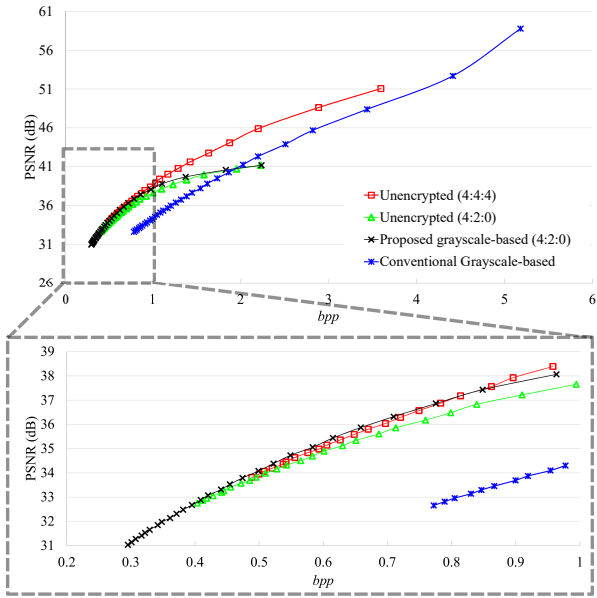


Fig. 7: R-D curves of JPEG images

B. Results and Discussions

We evaluated the compression performance and robustness against color sub-sampling of the proposed scheme based on Rate-Distortion (R-D) curves which are the relation between the arithmetic mean PSNR of the images and bits per pixel (bpp) of JPEG images. The proposed grayscale-based image encryption was compared with the non-encrypted images.

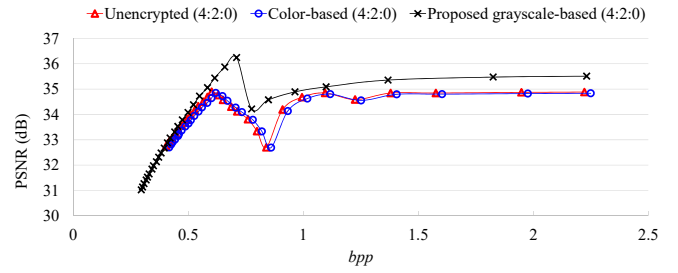
1) *Compression Performance of Uploaded Images:* Figure 7 shows that the proposed scheme has almost the same compression performance as non-encrypted ones with 4:2:0 color sub-sampling and also outperforms those without any color sub-sampling and the conventional one. The proposed encryption scheme allows us to avoid the effect of color sub-sampling and also improve compression performance of JPEG compression.

2) *Compression Performance of Downloaded Images:* According to image manipulation carried out by SNS providers [13], an uploaded image is decoded and compressed respectively based on their specifications when the uploaded image is satisfied the conditions of SNS providers.

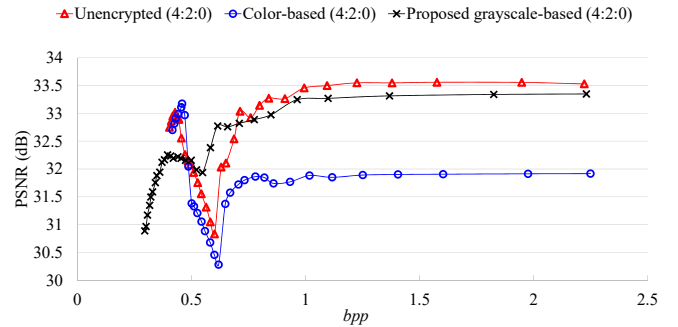
In Fig. 8(a) and (b), the performance of the color-based image encryption and the proposed scheme was compared in terms of compression performance of downloaded images from Twitter and Facebook, respectively. Note that $B_x = B_y = 16$ is used as a block size for the color-based image encryption to avoid block distortion.

Twitter recompresses the uploaded JPEG images with 4:2:0 color sub-sampling when $Q_{fu} \geq 85$ to the new JPEG images with 4:2:0 sub-sampling ratio and $Q_{fu} = 85$. As shown in Fig. 8(a), the proposed scheme provided higher compression performance than those with the color-based image encryption and non-encrypted ones.

In Facebook, every uploaded JPEG image is recompressed



(a) Twitter



(b) Facebook

Fig. 8: R-D curves of downloaded JPEG images



(a) Color-based image encryption scheme with $B_x = B_y = 8$ and 4:2:0 sub-sampling (PSNR=26.21dB)



(b) Proposed scheme with $B_x = B_y = 8$ (PSNR=31.85dB)

Fig. 9: Example of decrypted images downloaded from Twitter

to the new JPEG image with 4:2:0 sub-sampling ratio and $Q_{fu} \in [71, 85]$. The images encrypted by the color-based encryption were heavily distorted by color sub-sampling carried out by Facebook. In comparison, the proposed one provided higher image quality compared with the color-based image encryption. Moreover, as shown in Fig. 8(b), when $bpp > 1$, PSNR values of the non-encrypted images were higher than those with the proposed scheme approximately 0.2 dB. This



(a) Color-based image encryption scheme with $B_x = B_y = 8$ and 4:2:0 sub-sampling (PSNR=23.34dB)



(b) Proposed scheme with $B_x = B_y = 8$ (PSNR=29.96dB)

Fig. 10: Example of decrypted images downloaded from Facebook

is because every grayscale JPEG image uploaded to Facebook is recompressed to the new grayscale JPEG image with $Q_{f_u} = 71$ while Facebook recompresses JPEG color JPEG images with $Q_{f_u} \in [71, 85]$.

Figures 9 and 10 show the example of decrypted images downloaded from Twitter and Facebook, respectively. Since $B_x = B_y = 8$, the images encrypted by using color-based image encryption were strongly distorted by the color sub-sampling carried out by the providers. In comparison, the images encrypted by using the proposed scheme did not include any distortion.

Considering color sub-sampling operation to the grayscale-based images encryption does not affect the compression performance of JPEG images. The results also proved that the proposed scheme can avoid the effects of color sub-sampling carried out by SNS providers.

V. CONCLUSION

This paper considered color sub-sampling operation on the grayscale-based image encryption for EtC systems. Firstly, the scenario and requirements of the image encryption were described. Moreover, we proposed to generate the grayscale-based image from the luminance and sub-sampled chrominance components. A lot of images was compressed with 4:4:4 and 4:2:0 color sub-sampling ratio and decompressed to evaluate the compression performance and the robustness against color sub-sampling. The results proved that considering color sub-sampling operation to the grayscale-based image encryption does not affect the compression performance and also provides the robustness against color sub-sampling.

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