TECHNIQUES FOR A SELECTIVE ENCRYPTION OF UNCOMPRESSED AND COMPRESSED IMAGES

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ABSTRACT

This paper describes several techniques to encrypt uncompressed and compressed images. We first present the aims of image encryption. In the usual ways to encryption, all the information is encrypted. But this is not mandatory. In this paper we follow the principles of a technique initially proposed by MAPLES *et al.* [1] and encrypt only a part of the image content in order to be able to visualize the encrypted images, although not with full precision. This concept leads to techniques that can simultaneously provide security functions and an overall visual check which might be suitable in some applications like, for example, searching through a shared image database. The principle of *selective encryption* is first applied to uncompressed images. Then we propose a simple technique applicable to the particular case of JPEG images. This technique is proven not to interfere with the decoding process in the sense that it achieves a constant bit rate and that bitstreams remain compliant to the JPEG specifications. Then we develop a scheme called *multiple selective encryption*, discuss its properties and conclude.

1. INTRODUCTION

In some applications, it is relevant to hide the content of a message when it enters an insecure channel. The initial message prepared by the sender is then converted into ciphertext prior to transmission. The process of converting plaintext into ciphertext is called *encryption* (see [2] for a review on encryption techniques). The encryption process requires an encryption *algorithm* and a *key*. The process of recovering plaintext from ciphertext is called *decryption*. The accepted view among professional cryptographers (formalized in KIRKHOFF's law) is that the encryption algorithm should be published, whereas the key must be kept secret.

In the field of image cryptography, the focus has been put on steganography, and in particular on watermarking during the last years (see [3] for a review on watermarking). Watermarking, as opposed to steganography, has the additional requirement of robustness against possible image transformations. Watermarks are usually made invisible and should not be detectable.

In applications requiring transmission the image is first compressed, because it saves bandwidth. Then the image is encrypted, as depicted in Figure 1.

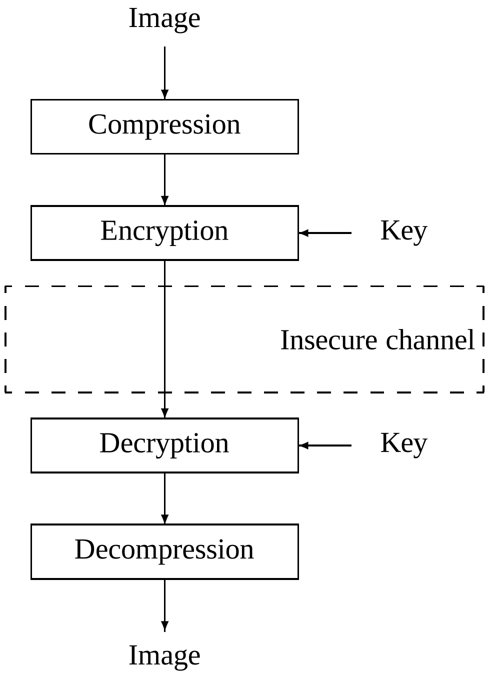


Figure 1: Encryption of an image.

The removal of redundancy enhances robustness as it squeezes out information that might be useful to a cryptanalyst. However it also introduces known patterns in the compressed bitstreams, like headers or synchronization stamps (called *markers*), that eases plaintext attacks on the signal. An alternative would be to compress after encryption, but it would not be as efficient in terms of bandwidth because encrypted information looks random and is therefore hard to compress. It is worth noting that, in schemes combining compression and encryption like the one shown in Figure 1,

- there are two kinds of information: the image and the key.
- the subjective significance of information contained in the image is ignored. For example, there is no distinction between Most Significant Bits (MSBs) and Least Significant Bits (LSBs).

From Figure 1, it is clear that the receiver should decrypt the information before it can decompress the image. This approach has the main drawback that it is impossible to access the smallest part of information without knowledge of the key. For example, it would impossible to search through a general database of fully encrypted images. A way to address this issue is to use a technique called *selective encryption*; it is depicted in Figure 2.

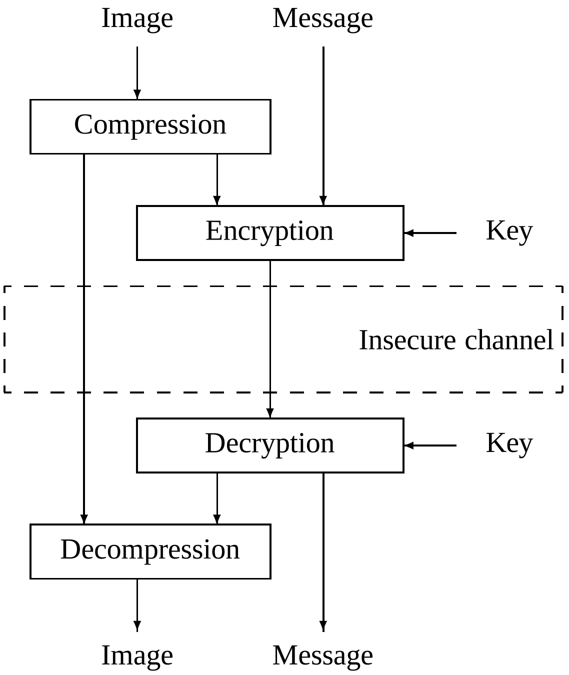


Figure 2: Selective encryption mechanism.

The general selective encryption mechanism works as follows. The image is first compressed (if needed). Afterwards the algorithm only encrypts part of the bitstream with a well-proven ciphering technique; incidentally a message (a watermark) can be added during this process. To guarantee a full compatibility with any decoder, the bitstream should only be altered at places where it does not compromise the compliance to the original format. This principle is sometimes referred to as *format compliance*. WEN et *al*. [4] have recently described a general framework for format-compliant encryption. In their simulations, they focus on MPEG-4 video error resilient mode with data partitioning and discuss which fields can be encrypted. They also pointed out that the encryption of a variable length code (VLC) codeword may not result in another valid codeword.

With the decryption key, the receiver decrypts the bitstream, and decompresses the image. In principle, there should be no difference between a decoded image and an image that has been encrypted and decrypted. However there might be a slight though invisible difference if a watermark message has been inserted in the image.

When the decrypting key is unknown, the receiver will still be able to decompress the image, but this image will significantly differ from the original. This scenario is depicted in Figure 3.

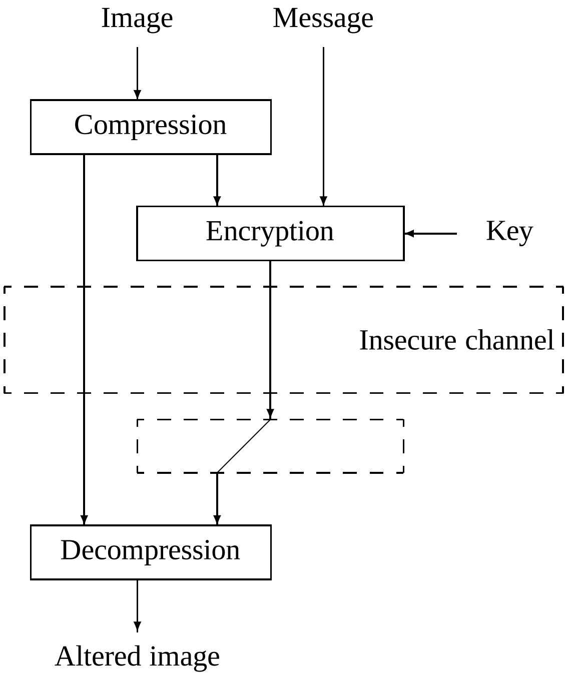


Figure 3: When the decryption key is unknown to the receiver.

2. SELECTIVE ENCRYPTION OF UNCOMPRESSED IMAGES

A very effective method to encrypt an image, which applies to a binary image, consists in mixing image data and a message (the key in some sense) that has the same size as the image: a XOR function is sufficient when the message is only used once. A generalization to gray level images is straightforward: encrypt each bitplane separately and reconstruct a gray level image. With this approach no distinction between bitplanes is introduced although the subjective relevance of each bitplane is not equal.

2.1. Description of a “naive” method

Figure 4 shows an image decomposed in its bitplanes.

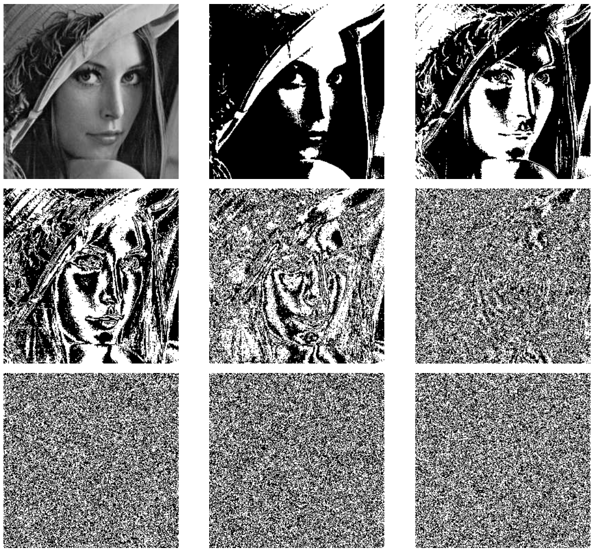
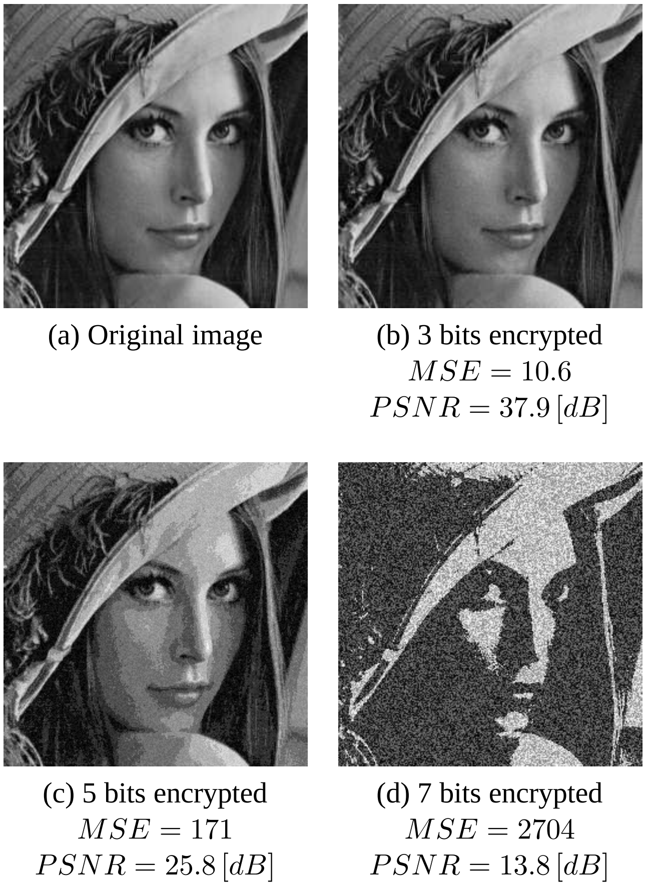


Figure 4: LENA and her bitplanes (i_7, ..., i_0) starting from the most significant bit.

The highest bitplanes exhibit some similarities with the gray level image, but the least significant bitplanes look random. Because encrypted bits also look random, the encryption of least significant bitplanes will add noise to the image. The first “naive” method we have implemented consists in the encryption of the least significant bits as illustrated in Table 1. In the same table, we provide two distortion measures as well: the *Mean Square Error* (MSE) and the *Peak Signal* to *Noise Ratio* (PSNR).

An advantage of the technique that encrypts the least significant bits is that plaintext attacks are harder on random like data.

It should be noted that the security is linked to the ability to guess the values of the encrypted data. For example, from a security point of view, it is preferable to encrypt the bits that look the most random. However in practice, the tradeoff is more difficult because the most relevant information, like DC coefficients in a JPEG encoded image, usually are highly predictable.



(a) Original image

(b) 3 bits encrypted
$MSE = 10.6$
$PSNR = 37.9\,[dB]$

(c) 5 bits encrypted
$MSE = 171$
$PSNR = 25.8\,[dB]$

(d) 7 bits encrypted
$MSE = 2704$
$PSNR = 13.8\,[dB]$

Table 1: Illustration of a naive selective encryption method.

As can be seen from the images drawn in Table 1, we need to encrypt at least 4 to 5 bitplanes before the degradation is visible. In theory the naive method is relatively robust to plaintext attacks because it encrypts bitplanes that contain nearly uncorrelated bit values.

In the next section, we derive an analytical expression for the error that results from the encryption of least significant bits. Then we compare the theoretical values with the values given in Table 1.

2.2. Calculation of the error

We denote $o(x,y)$, $c(x,y)$ respectively the original image and the selectively encrypted image. The error function is defined as $e(x,y) = o(x,y) - c(x,y)$. For each location (x,y), we can write $e(x,y) = o(x,y) - c(x,y) = (o_0 - c_0) + 2(o_1 - c_1) + 4(o_2 - c_2) + \ldots = e_0 + 2e_1 + 4e_2 + \ldots$ where x_i denotes the ith bit of x starting from the least significant bit. Highest bitplanes exhibit some similarities with the gray level image, but the least significant bitplanes look random. In the following, bitplanes are supposed to be independent and to be the realization of a stationary ergodic process.

We can not assume that the probabilities of a 0 or a 1 in each bitplane of the original image, denoted respectively $p_o(0)$ and $p_o(1)$, are equal to $\frac{1}{2}$, except maybe for the LSBs. However the probabilities of a 0 or a 1 of the encrypted data, denoted $p_e(0)$ and $p_e(1)$, should approximatively be equal to $\frac{1}{2}$. For convenience, we use the probabilities $p_o(0) = \alpha$ and $p_o(1) = 1 - \alpha$.

Thanks to the assumptions of stationarity, the mean and variance of e_k, the error in bitplane k, are respectively equal to (after some calculation):

$$\mu_{e_k} = \frac{1}{2} - \alpha, \qquad \sigma_{e_k}^2 = -\alpha^2 + \alpha + \frac{1}{4} \qquad (1)$$

Although 1 bit of information has been encrypted in the bitplane, the error is not equal to 1 bit on average. This results from situations where the encrypted bit is equal to the original bit.

It is now possible to derive σ_e^2 from the $\sigma_{e_k}^2$. If we assume the independence between the bitplane values, $\sigma_e^2 = \sigma_{e_0}^2 + 4\sigma_{e_1}^2 + 16\sigma_{e_2}^2 + \ldots = \sum_{k=0}^{n-1} 2^{2k}\left(-\alpha_k^2 + \alpha_k + \frac{1}{4}\right)$ where n is the number of least significant bits that have been substituted. In the case of $p_o(0) = p_o(1) = \frac{1}{2}$, which is an assumption usually valid on the least significant bits of a natural image, $\mu_e = 0$ and

$$\sigma_e^2 = \frac{4^n - 1}{3} \times \frac{1}{2} = \frac{4^n - 1}{6} = \text{MSE} \qquad (2)$$

Table 2 compares theoretical MSE values with values computed on LENA and PHOTOGRAPH. It appears that theoretical values of σ_e^2 are close to the computed values even for a large number of encrypted bits.

From equation 2, PNSR decreases as

$$10 \log \sigma_e^2 \approx 10n \log 4 - 10 \log 6 \qquad (3)$$

$\sharp$	Theoretical MSE	MSE$_{\text{Lena}}$	MSE$_{\text{Photograph}}$
1	0.5	0.5	0.5
2	2.5	2.5	2.5
3	10.5	10.6	10.6
4	42.5	42.6	42.5
5	170.5	171	158.4
6	682.5	636.7	654.3
7	2730.5	2714.8	2584.7

Table 2: Comparison of MSEs for a number $\sharp$ of encrypted bitplanes.

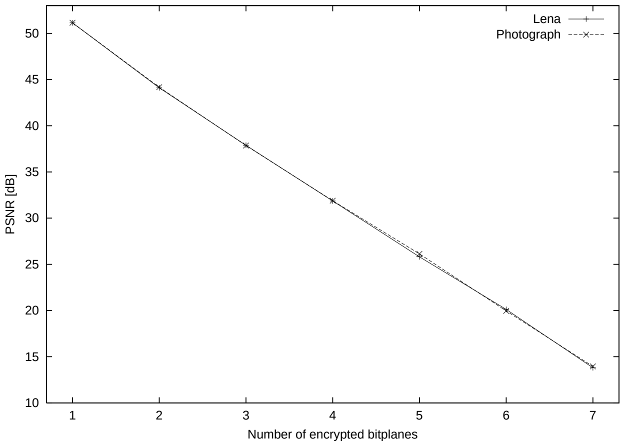


Figure 5: PSNR values versus the number of encrypted bitplanes.

This linear behavior was confirmed in our experiments as can be seen from Figure 5.

If only the least significant bit is encrypted, σ_e is always ≤ 1, but for real images $\sigma_e \approx 0.7$. This means that although all bits have been encrypted, the error is less than 1 bit on average. This results from situations where the original bit and the encrypted bit are the same. As a consequence we need to encrypt more bits per pixel before the image looks degraded.

3. SELECTIVE ENCRYPTION OF COMPRESSED IMAGES

In the middle of the 90s there have been several papers on the selective encryption of MPEG streams. MAPLES et *al*. [1] proposed an algorithm which encrypts only the Intra (I) frames of an MPEG stream. However, AGI et *al.* [5] reported that the selective encryption of the I frames only offers a limited level of security, due mainly to the presence of blocks coded in intra mode in P or B frames, but also to the high correlation of P and B frames when they correspond to the same I frame.

Alternative encryption techniques were developed by other authors. In particular, several techniques have been proposed for the encryption of DCT based coded image. A method called *zig-zag permutation* was originated by TANG [6]. The basic idea is that instead of mapping the 8×8 block to a 1×64 vector in zig-zag order, the method reorders individual 8×8 blocks to 1×64 vectors according to a random permutation list. Although this scheme offers more security, it increases the overall bit rate. This is explained by the loss of correlation between adjacent coefficients in reordered zig-zag vectors. As a consequence the HUFFMAN entropy coding that follows the reordering will result in a lower compression ratio.

Another algorithm, developed by QIAO and NAHRSTEDT, is based on the frequency distribution of pairs of two adjacent bytes in an MPEG bitstream [7]. In their method, the stream is divided into data segments of 128 bytes. Then two 64-byte lists are generated depending on the binary value of a 128-bit key. If the binary value is equal to 0 (resp. 1) then the corresponding byte is put in the first (resp. second) list. The lists are XORed and one of them is encrypted with a second key. As proven by the authors, this algorithm provides overall security, and size preservation, but does not meet the requirements of visual acceptance and bitstream compliance.

Most of the encryption methods either treat entire blocks or are integral part of the MPEG compression process. Moreover they are designed to hide all the information. We require the following *properties* from our methods:

- **[visual acceptance]** part of information may be visible but the encrypted image should look noisy,
- **[selective encryption]** encryption occurs after compression and leaves parts of the bitstream unencrypted,
- **[constant bit rate]** encryption should preserve the size of the bitstream, and
- **[bitstream compliance]** the encryption step should produce a *compliant bitstream* according to the chosen format definition.

Researchers have shown that selective encryption is not restricted to MPEG encoded images. For example POMMER et *al.* [8] recently proposed techniques for the selective encryption of wavelet packet subband structures.

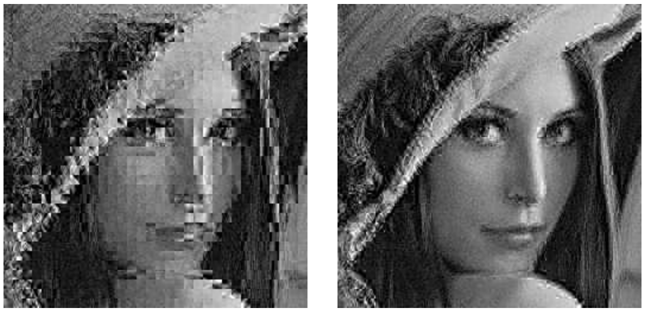
3.1. A method for the selective encryption of JPEG images

The method we propose for the selective encryption of JPEG images is based on the encryption of DCT coefficients. The encryption of the quantified coefficients prior to the HUFFMAN entropy coding would be inefficient in terms of compression. But it is possible to modify the way coefficients are encoded.

3.1.1. Description of the method

In JPEG, the HUFFMAN coder aggregates zero coefficients into runs of zeros. In order to approach the entropy, it also uses symbols that combine the run of zeros with magnitude categories for the non-zero coefficients that terminate the runs (see [9] for a complete explanation of the JPEG encoding). 8-bit code words are assigned by the HUFFMAN coder to these symbols. These code words are followed by appended bits that fully specify the sign and magnitude of the non-zero coefficients. We decided to leave the code words but to encrypt the appended bits. The reasons are that code words are essential for synchronization and that it does not make much sense to replace zero coefficients by non-zero coefficients. Therefore it was essential to preserve the run values. Also, it is not effective to encrypt DC coefficients because they carry important visible information and are highly predictable.

Our algorithm encrypts appended bits corresponding to a selected number of AC coefficients. Figure 6 illustrates two cases: all coefficients are encrypted except (a) the DC coefficient or (b) the DC, AC_0, $\dots$, AC_4 coefficients.



(a) DC
$MSE = 1096$
$PSNR = 17.7\,[dB]$

(b) DC, AC_0, $\dots$, AC_4
$MSE = 348$
$PSNR = 22.7\,[dB]$

Figure 6: JPEG encrypted images.

3.1.2. *Image quality*

The degradation of the selectively encrypted image was again estimated with the PSNR. Typical values are drawn in Figure 7.

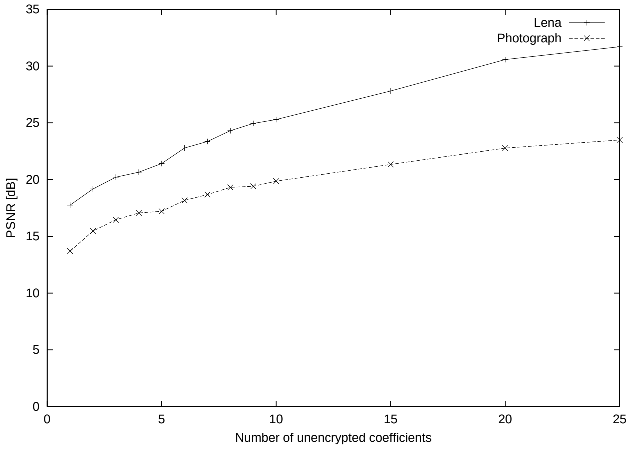


Figure 7: PSNR values versus the number of coefficients left unencrypted (including the DC coefficient).

The absolute PSNR will depend on the original JPEG image, on its compression ratio, and on the amplitude of DCT coefficients. As a rule of thumb, we found that the number of coefficients left unencrypted should be less than 5.

3.1.3. *Performances*

Our method does not require the encryption to occur inside the coder. In our experiments, the compression and encryption steps have been separated. Although this leads to a slight overhead in execution speed, it has the advantage that the code is reusable for any encoded JPEG image. For this implementation, the encryption steps are:

- read the JPEG bitstream,
- build the Huffman tables as specified in the image,
- extract DCT coefficients,
- proceed to encryption, and
- replace the bits in the bitstream.

Real-time processing is easily achievable. Table 3 provides the execution times obtained for LENA (512×512, 24-bit color image) on a 1.33 GHz Pentium. The first column mentions the number of bit per pixel (*bpp*) of the JPEG encoded image. Execution times were measured for three different encryption algorithms (DES, triple-DES and IDEA).

	Encrypted bits		Execution speed [ms]		
bpp	total	per bloc	DES	3-DES	IDEA
3.62	275904	22.45	77	82	75
2.14	135744	11.05	45	48	44
1.01	52864	8.6	19	20	19
0.49	13760	2.24	8	9	8

Table 3: Execution times in [ms] (see [10]).

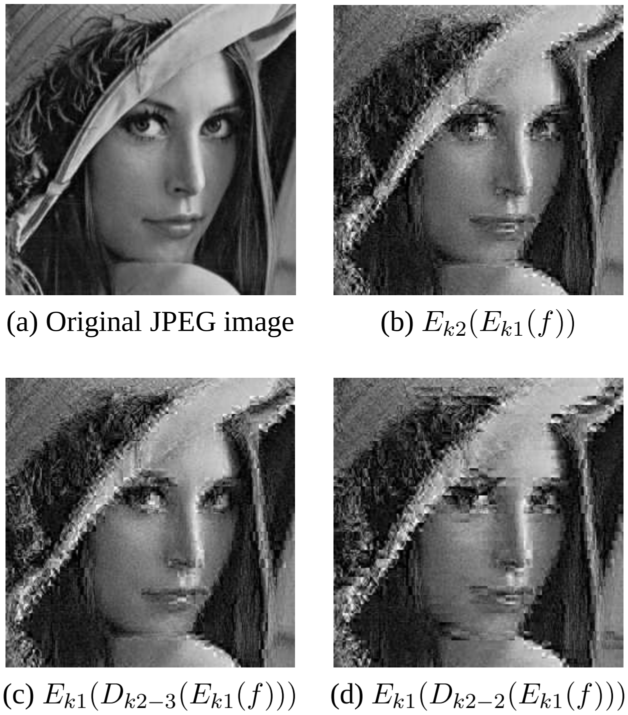
3.1.4. *Note on security*

As in other cases, some coefficients may be correctly guessed. That will allow a plaintext attack in which a known message is send to the encoder. Therefore we should choose an encryption method that is not sensible to this kind of attack. But this is a general requirement, not particular to our method.

3.2. Multiple selective encryption

In some applications, images have several copyright owners. Suppose the first copyright owner applies the selective DCT encryption algorithm on the JPEG image f with a key $k1$. The resulting image is $g = E_{k1}(f)$. The decryption algorithm D is able to recompute f when $k1$ is known: $f = D_{k1}(E_{k1}(f))$. If there is a second copyright owner, he could be given the opportunity to encrypt the image too, with his own key $k2$. The image sent on the network is then $h = E_{k2}(E_{k1}(f))$. We called this principle *"multiple selective encryption"* as it was inspired by *multiple watermarking* described by SHEPPARD *et al.* in [11]. In fact, TUCHMAN [12] proposed a technique called *over-encryption* that corresponds to $E_{k1}(D_{k2}(E_{k1}(f)))$. According to SCHNEIER [2], this last scheme offers better performances than $E_{k2}(E_{k1}(f))$ in terms of robustness against attacks.

The ideas of *multiple selective encryption* or *selective over-encryption* are illustrated in Figure 8. In this example, 3 coefficients were left unencrypted except for $D_{k2}()$ of image 8(d) for which we only preserved 2 coefficients. Many variations can be worked out just by modifying the number of coefficients and the order of $E()$ or $D()$ steps.



(a) Original JPEG image

(b) $E_{k2}(E_{k1}(f))$

(c) $E_{k1}(D_{k2-3}(E_{k1}(f)))$

(d) $E_{k1}(D_{k2-2}(E_{k1}(f)))$

Figure 8: Illustration of techniques called *multiple selective encryption* (b) and *selective over-encryption* (c-d).

4. CONCLUSIONS

In this paper, we proposed two methods for the *selective encryption* of an image. The first method is applicable to raster images. The second method is an adaptation of the JPEG compression scheme that offers both a constant bit rate and format compliance. It consists in the encryption of the sign and magnitude of non-zero DCT coefficients. We also explain how it can be used for *multiple* selective encryption.

5. REFERENCES

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