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# A Data Embedding Method Considering the Finite Word-Length for High Quality Images

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**SUMMARY** A novel data embedding method for high-quality images, e.g., an image with a peak signal-to-noise ratio of better than 60 [dB] is proposed in this paper. The proposed method precisely generates a watermarked image of the desired and high quality for any images. To do this, this method considers the finite word-length of a luminance value of pixels, i.e., both quantization errors and the range limitation of luminance. The proposed method embeds a watermark sequence, modulated by the mechanism of a spread spectrum scheme, into the dc values of an image in the spatial domain. By employing spread spectrum technology as well as embedding a watermark into the dc values, this method guarantees the high image quality and, simultaneously, provides adequate JPEG tolerance.

***key words:*** *spatial domain, direct current, correlation-based, block-based, JPEG*

## 1. Introduction

Data embedding technologies have recently been studied widely [1], [2]. A data embedding method embeds data into a target image directly and generates a slightly degraded image referred to as a watermarked image. Usually, a small deterioration of image quality is desired, and improvements of image quality have been studied [3]–[8]. Several methods exploit the human vision system for improving subjective invisibility [3], [4], and the rest guarantee the objective quality of watermarked images [5]–[8]. In this paper, a novel and improved method classified as the latter type is proposed.

The latter methods generate watermarked images of the desired quality automatically, i.e., without trial and error. These methods fit applications in which the number of images or frames is quite large and the required image quality is regulated by a subjective measurement, e.g., the inside material managements at digital museums and digital broadcasting stations. Moreover, in such applications:

- required quality is often high, e.g., a peak signal-to-noise ratio (PSNR) of 56 [dB] [9].
- lossy compression such as JPEG is applied to images or frames.

In addition, lossy-compression schemes often degrade the quality of a watermarked image in comparison to that of an original image, thus the quality of a watermarked image should be high. Thus, for such applications, a data embedding method must meet the following requirements.

**Req 1.** Generation of the desired quality images for any images without trial and error.
**Req 2.** Generation of high quality images.
**Req 3.** Adequate tolerance to lossy-compressions such as JPEG unless a compressed image loses the certain quality, e.g., a PSNR of 40 [dB].

In practice use, conventional methods [5]–[8] do not satisfy Req 1. Since these methods embed data without considering that a luminance value of a pixel is represented with a finite number of bits, i.e., the finite word-length of the luminance value, pixels in watermarked images are rounded and clipped. These modifications make the quality of a watermarked image different from the desired quality. Moreover, the block-based methods [7], [8], which have the advantage of low computational complexity [7], do not satisfy Req 2.

While, a method dealing with the range of luminance values exists [10]. However, this method neither generates a desired quality image automatically nor considers that the luminance value is an integer. This method therefore does not satisfy Req 1.

This paper proposes a novel data embedding method that solves the problems of the conventional methods mentioned above and automatically generates watermarked images of the exact desired quality for any images. The proposed method does this by considering the finite word-length of a luminance value of pixels and embeds a watermark into an image in the spatial domain. The proposed method provides adequate JPEG tolerance given by Req 3. To generate high quality watermarked images and simultaneously provides such JPEG tolerance, the proposed method employs spread spectrum technology as well as embeds a watermark sequence into the dc values, i.e., the sum of pixel values.

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## 2. Image Quality and Conventional Methods Allowing Desired Image Quality

### 2.1 Data Embedding and Image Quality

Figure 1 illustrates a block diagram of data embedding. It is assumed that watermark $\mathbf{w}$ is a modulated signal of data to be embedded by a certain mechanism; by the mechanism of the parallel combinatorial spread spectrum (PC/SS) [5] and by the M-ary direct sequence spread spectrum (DS/SS) [7], [8].

First, embedding in the spatial domain is explained below. An original $X \times Y$ still image is denoted by $\mathbf{f} = [f(x, y)]$, where $f(x, y)$ represents an integer luminance value of a pixel quantized to $(a + 1)$ levels. The dynamic range of $f(x, y)$ is given by $a$; e.g., $a$ is equal to 255 in eight-bit quantized images. Embedding watermark $\mathbf{w}$ into image $\mathbf{f}$ in the spatial domain generates a watermarked image represented by $\hat{\mathbf{f}} = \left[\hat{f}(x, y)\right]$, and $\hat{\mathbf{f}}$ is degraded from original image $\mathbf{f}$. The PSNR between watermarked image $\hat{\mathbf{f}}$ and original image $\mathbf{f}$ is defined by

$$\mathrm{PSNR} = 10 \log_{10} \frac{\sum_{x=1}^{X} \sum_{y=1}^{Y} a^2}{\sum_{x=1}^{X} \sum_{y=1}^{Y} \left\{\hat{f}(x, y) - f(x, y)\right\}^2} \text{ [dB].} \quad (1)$$

Next, embedding in the transformed domain is explained as follows. Symbol $\mathbf{F}$, shown in Fig. 1, denotes an $U \times V$ transformed matrix of $\mathbf{f}$, where $\mathbf{F} = [F(u, v)]$. A transformed coefficient is represented by $F(u, v)$. Note that $F(u, v)$ is not restricted to be an integer. Hiding watermark $\mathbf{w}$ in transformed matrix $\mathbf{F}$ in the transformed domain generates a watermarked matrix represented by $\hat{\mathbf{F}}$, where $\hat{\mathbf{F}} = \left[\hat{F}(u, v)\right]$. Applying the inverse transformation to $\hat{\mathbf{F}}$ generates watermarked image $\hat{\mathbf{f}}$, then the PSNR between watermarked image $\hat{\mathbf{f}}$ and original image $\mathbf{f}$ is the same as that is given by Eq. (1).

The PSNR can be defined in the transformed domain. By employing an orthogonal transformation such as some types of discrete cosine transformation (DCT) to generate transformed matrix $\mathbf{F}$ from image $\mathbf{f}$, Parseval's equation given as Eq. (2) is realized.

$$\sum_{u=1}^{U} \sum_{v=1}^{V} |F(u, v)|^2 = \sum_{x=1}^{X} \sum_{y=1}^{Y} f^2(x, y) \quad (2)$$

Therefore, the PSNR between watermarked image $\hat{\mathbf{f}}$ and original image $\mathbf{f}$ is given by using $\hat{\mathbf{F}}$ and $\mathbf{F}$ in the transformed domain as

$$\mathrm{PSNR} = 10 \log_{10} \frac{\sum_{u=1}^{U} \sum_{v=1}^{V} a^2}{\sum_{u=1}^{U} \sum_{v=1}^{V} \left|\hat{F}(u, v) - F(u, v)\right|^2} \text{ [dB],} \quad (3)$$

from Eqs. (1) and (2).

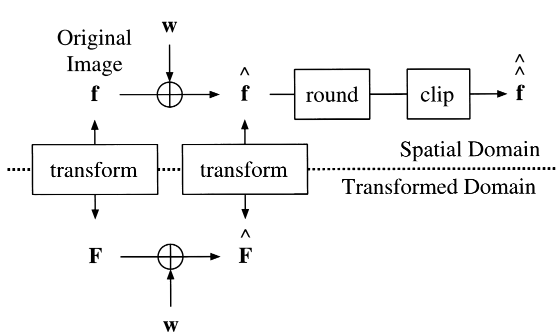



**Fig. 1** Block diagram of data embedding.

### 2.2 Conventional Methods Allowing Desired Image Quality and Its Limits

Several methods allowing desired image quality have been proposed [5]–[8]. A data-embedding method that generates a watermarked image with the desired quality automatically, i.e., without trial and error, is referred to "*a data-embedding method allowing the desired image quality*" in this paper. A data-embedding method allowing the desired image quality is required to have the following abilities.

1. Control of the noise energy caused by embedding watermark.
2. Determination of the control parameter for achieving the desired image quality.

For an example of a method allowing desired image quality, block-based methods proposed in [7], [8] are mentioned here. In these methods, original image $\mathbf{f}$ is divided into $B$ blocks, where a block consists of $X_B \times Y_B$ pixels, before applying two-dimensional DCT. To generate a watermarked image with the desired quality, these methods modify every block for embedding data and set the quality of every block to the desired quality. The quality of a watermarked block is controlled based on Eq. (3) in the DCT domain.

An $L$-length sequence represented by $\mathbf{w} = (w_1, w_2 \ldots, w_l, \ldots, w_L)$ is employed as a watermark. One real-number DCT coefficient, $F_b(u_b, v_b)$, is selected for embedding $w_b$ in the $b$-th $U_b \times V_b$ DCT matrix, $\mathbf{F}_b = [F_b(u, v)]$. Chosen coefficient $F_b(u_b, v_b)$ is the largest ac coefficient in terms of magnitude [7], but is the dc coefficient [8], respectively. The embedding equation used in these block-based methods is

$$\hat{F}_b(u, v) = \begin{cases} F_b(u, v) + \alpha_b F_b(u, v)\, w_b & u = u_b, v = v_b \\ F_b(u, v) & \text{otherwise,} \end{cases} \quad (4)$$

where the controlling parameter for the $b$-th block is represented by $\alpha_b$. Thus, these block-based methods control the noise energy caused by embedding watermark $\mathbf{w}$ using Eq. (4).

Therefore, the PSNR of the $b$-th block between original DCT matrix $\mathbf{F}_b$ and watermarked DCT matrix $\hat{\mathbf{F}}_b$ is given as

$$\begin{aligned}\mathrm{PSNR}_b &= 10\log_{10}\frac{\sum_{u=1}^{U_B}\sum_{v=1}^{V_B} a^2}{\sum_{u=1}^{U_B}\sum_{v=1}^{V_B}\left\{\hat{F}_b(u,v)-F_b(u,v)\right\}^2}\\ &= 10\log_{10}\frac{U_B V_B a^2}{\left\{\hat{F}_b(u_b,v_b)-F_b(u_b,v_b)\right\}^2}\\ &= 10\log_{10}\frac{U_B V_B a^2}{\alpha_b^2 F_b^2(u_b,v_b)\,w_b^2}\ [\mathrm{dB}],\end{aligned} \tag{5}$$

from Eqs. (3) and (4). Let $\alpha_b^2 F_b^2(u,v)\,w_b^2 = \Delta^2$ in every block, and the PSNR of the whole image is as the same as $\mathrm{PSNR}_b$, given as

$$\begin{aligned}&\mathrm{PSNR}\\ &= 10\log_{10}\frac{\sum_{u=1}^{U}\sum_{v=1}^{V} a^2}{\sum_{u=1}^{U}\sum_{v=1}^{V}\left\{\hat{F}(u,v)-F(u,v)\right\}^2}\\ &= 10\log_{10}\frac{\sum_{b=1}^{B}\sum_{u=1}^{U_B}\sum_{v=1}^{V_B} a^2}{\sum_{b=1}^{B}\sum_{u=1}^{U_B}\sum_{v=1}^{V_B}\left\{\hat{F}_b(u,v)-F_b(u,v)\right\}^2}\\ &= 10\log_{10}\frac{\sum_{b=1}^{B} U_B V_B a^2}{\sum_{b=1}^{B}\Delta^2}\\ &= 10\log_{10}\left(U_B V_B a^2/\Delta^2\right) = \mathrm{PSNR}_b\,[\mathrm{dB}]\end{aligned} \tag{6}$$

from Eq. (5). Consequently, the desired quality, the PSNR of $R$ [dB], is given; i.e., $\mathrm{PSNR}_b$ is set equal to $R$, as

$$R = \mathrm{PSNR}_b = 10\log_{10}\frac{U_B V_B a^2}{\alpha_b^2 F_b^2(u_b,v_b)\,w_b^2}\ [\mathrm{dB}], \tag{7}$$

then controlling parameter $\alpha_b$ is obtained as

$$\alpha_b = \sqrt{\frac{U_B V_B a^2}{10^{0.1R} F_b^2(u_b,v_b)\,w_b^2}} \tag{8}$$

from Eq. (5). These block-based embedding methods thus determine controlling parameter $\alpha_b$ using Eq. (8).

Consequently, the block-based methods proposed in [7], [8] have the required abilities mentioned above as following.

1. Control the noise energy caused by embedding watermark $\mathbf{w}$ using Eq. (4).
2. Determine control parameter $\alpha_b$ using Eq. (8).

Although conventional methods [5]–[8] seem to generate images of desired image quality, they suffer various problems. One serious problem is that watermarked image $\hat{\mathbf{f}}$ is not an image of the desired quality in practical use. Watermarked image $\hat{\mathbf{f}}$ is generated without considering that a luminance value is represented with a finite number of bits, i.e., the finite word-length of a luminance value:

- A luminance value of every pixel is an integer.
- and is restricted between zero and $a$.

Therefore, the following modifications are applied to $\hat{\mathbf{f}}$ in conventional methods.

(a) The luminance value of every pixel, $\hat{f}(x,y)$, is rounded to be an integer.
(b) and is clipped to be in a certain range, i.e., between zero and $a$.

Because the luminance value of $\hat{f}(x,y)$ is modified by such rounding and clipping, a different image, $\hat{\hat{\mathbf{f}}} = \left[\hat{\hat{f}}(x,y)\right]$, shown in Fig. 1, becomes the watermarked image. Thus, in practical use, $\hat{\hat{\mathbf{f}}}$, rather than $\hat{\mathbf{f}}$, is referred to as a watermarked image, and the PSNR between a watermarked image and original image $\mathbf{f}$ is

$$\mathrm{PSNR_{fin}} = 10\log_{10}\frac{\sum_{x=1}^{X}\sum_{y=1}^{Y} a^2}{\sum_{x=1}^{X}\sum_{y=1}^{Y}\left\{\hat{\hat{f}}(x,y)-f(x,y)\right\}^2}\ [\mathrm{dB}]. \tag{9}$$

Consequently, these conventional methods have problems in generating a watermarked image with the desired image quality precisely.

In addition, two more problems exist.

(c) When embedding a watermark into ac coefficients [7], JPEG tolerance is not held under the condition that the desired image-quality is high.
(d) When embedding a watermark into dc coefficients [8], the attainable image quality is limited.

It is shown in the Sect. 4 that embedding a watermark into ac coefficients has no tolerance under the condition that the desired image quality is high. In contrast, embedding a watermark into dc coefficients cannot produce a high-quality watermarked image, because modifying the dc coefficient affects all of the pixels uniformly in the spatial domain. For example, the highest PSNR achievable using blocks that each consist of $8\times 8$ pixels and have 256 levels from zero to 255 is calculated from Eq. (6) as

$$\mathrm{PSNR} = 10\log_{10}\left(8\times 8\times 255^2/1^2\right) \approx 48\,[\mathrm{dB}]. \tag{10}$$

In the next section, a novel data embedding method for high quality images that considers problems mentioned in this section is proposed. The proposed method precisely generates a watermarked image of the desired quality by considering the finite word-length.

## 3. Proposed Data Embedding Method

The data embedding method proposed in this section precisely allows the desired image quality in practical use. This method embeds a watermark into the dc components and the ac components of an image in the spatial domain, in contrast to the conventional methods that embed a watermark into one coefficient of the block in the transformed domain.

### 3.1 Embedding Algorithm

The embedding algorithm used by the proposed method is described in the following. It is assumed that original image $\mathbf{f} = [f(x,y)]$ is a gray-scale image and $f(x,y)$ is an integer between zero and $a$; i.e., $a$ is equal to 255 in eight-bits quantized images. Original image $\mathbf{f}$ is divided into $B$ blocks, where each block consists of $X_B \times Y_B$ pixels, before embedding a watermark. For simplicity, it is assumed that $X$ is a multiple of $X_B$ and $Y$ is a multiple of $Y_B$. An $L$-length real-number sequence represented by $\mathbf{w} = (w_1, w_2, \ldots, w_l, \ldots, w_L)$, where $w_l$ is an independent identically distributed sample drawn from a standard normal distribution, i.e., a zero-mean and unit-variance Gaussian distribution, is employed as a watermark sequence. It is assumed that data to be embedded is modulated by the mechanism of M-ary DS/SS and watermark sequence $\mathbf{w}$ is the modulated signal in this paper: however, it is allowed that other SS schemes, such as PC/SS, are employed for modulation.

This method embeds a watermark in an image using the following process. A more detailed description of the embedding process is given in the next section.

**Emb 1.** From a set of watermark sequences, $W = \{\mathbf{w}_m, 1 \le m \le M\}$, one watermark sequence, $\mathbf{w} \in W$, is chosen according to the data to be embedded.

**Emb 2.** The desired image quality is given as the PSNR of $R$ [dB] on condition that $\varepsilon^2$ given by Eq. (11) is an integer.

**Emb 3.** The allowable noise energy caused by embedding a watermark with considering the desired image quality, $R$ as

$$\varepsilon^2 = X_B Y_B a^2 / 10^{0.1R}, \tag{11}$$

where $\varepsilon^2$ denotes the allowable noise energy reperesented with an integer.

**Emb 4.** Divide original image $\mathbf{f}$ into blocks, where each consist of $X_B \times Y_B$ pixels. The $b$-th block is represented by $\mathbf{f}_b$, and $1 \le b \le XY/X_BY_B$. Set $b := 1$.

$$\left(\mathbf{f}_1, \mathbf{f}_2, \ldots, \mathbf{f}_b, \ldots, \mathbf{f}_{XY/X_BY_B}\right), \tag{12}$$

$$\mathbf{f}_b = [f_b(x,y)], 1 \le x \le X_B, 1 \le y \le Y_B. \tag{13}$$

**Emb 5.** Select one pair of $P_b$ and $e_{b,p}$ from possible pairs satisfying Eqs. (14) and (15).

$$\sum_{p=1}^{P_b} e_{b,p}^2 = \varepsilon^2, \tag{14}$$

$$1 \le P_b \le X_B Y_B, \quad 1 \le e_{b,p} \le a, \tag{15}$$

where $P_b$ and $e_{b,p}$ denote the number of pixels being modified and the difference in luminance of the $p$-th chosen pixel, respectively. It is noted that $P_b$ and $e_{b,p}$ are integers. Althourhg several pairs of $P_b$ and $e_{b,p}$ satisfying Eqs. (14) and (15) exist, any pair is able to be employed. No reembedding is required on condition that the chosen pair of $P_b$ and $e_{b,p}$ satisfies Eqs. (14) and (15). It is considered that a simple strategy letting $e_{b,p} := e_b$ for all $p$ and giving

$$P_b = \varepsilon^2 / e_b^2 \tag{16}$$

is usable for users, and is used for evaluations in Sect. 4. Moreover, beginnig at $e_b := 1$ is easy for users.

**Emb 6.** The scaling factor, $\beta_b$, for adjusting the magnitude of $w_b$ is obtained as

$$\beta_b = \frac{\sum_{p=1}^{P_b} e_{b,p}}{|w_b|}. \tag{17}$$

**Emb 7.** $P_b$ of the pixels being modified is chosen from $b$-th block $\mathbf{f}_b$, and set $p := 1$ and $\gamma_b := \beta_b$.

$$f_b(x_{b,p}, y_{b,p}), \quad 1 \le p \le P_b, \tag{18}$$

where $f_b(x_{b,p}, y_{b,p})$ represents the $p$-th chosen pixel. Several strategies for choosing pixels are available, however, the following strategy is employed here.

$$f_b(x_{b,p}, y_{b,p}) = \begin{cases} P_b \text{ of the largest pixels} & \gamma_b w_b < 0 \\ P_b \text{ of the smallest pixels} & \gamma_b w_b > 0 \end{cases} \tag{19}$$

**Emb 8.** The luminance of the $p$-th selected pixel, $f_b(x_{b,p}, y_{b,p})$, is modified according to the previously defined difference, $e_{b,p}$:

$$\hat{f}_b(x,y) = \begin{cases} f_b(x,y) + \mathrm{sgn}(w_b)\, e_{b,p} & x = x_{b,p}, y = y_{b,p} \\ f_b(x,y) & \text{otherwise}, \end{cases} \tag{20}$$

where $\mathrm{sgn}(i)$ represents the signum function that gives $-1$ if $i$ is negative and gives 1 if $i$ is positive. If $\hat{f}_b(x,y)$ is out of the range between zero and $a$, set $\gamma_b := -\gamma_b$ and go to Emb 7.

**Emb 9.** Set $p := p + 1$ and repeat by going to Emb 8 until $p = P_b$.

**Emb 10.** Set $b := b+1$ and repeat by going to Emb 5 until $b = B$.

**Emb 11.** All watermarked blocks are gathered to generate watermarked image $\hat{\mathbf{f}}$ with an exact PSNR of $R$ [dB].

It is noted that the degree of freedom for choosing a pair exist in Emb 5, but a watermarked image with the desired quality is obtained by using any pair satisfying Eqs. (11), (14), and (15).

One feature of this embedding algorithm is that a pair of $P_b$ and $e_{b,p}$ is selected by considering the desired quality shown as Eqs. (11) and (14). In addition, it is guaranteed by Eq. (15) that the luminance value of every pixel in watermarked images is an integer, and Eq. (19) assures that a luminance value of every pixel in watermarked images is between zero and $a$. These features enable the proposed method to exactly generate watermarked images of the desired quality without trial and error.

This method meets the requirements mentioned in the previous section:

1. Control the noise energy caused by embedding watermark $\mathbf{w}$ by Eq. (14).
2. Determine control parameter $\beta_b$ by Eq. (17).

### 3.2 Definite Description

#### A. Generation of Images of the Desired Quality without Trial and Error

The meanings of this proposed method for satisfying Req 1 is described in this clause.

The PSNR between watermarked block $\hat{\mathbf{f}}_b$ and its corresponding original block $\mathbf{f}_b$, PSNR$_b$, is given as

$$
\begin{aligned}
&10\log_{10}\frac{\sum_{x=1}^{X_B}\sum_{y=1}^{Y_B} a^2}{\sum_{x=1}^{X_B}\sum_{y=1}^{Y_B}\left\{\hat{f}_b(x,y)-f_b(x,y)\right\}^2}\\
&=10\log_{10}\frac{X_BY_Ba^2}{\sum_{p=1}^{P_b}\left\{\hat{f}_b(x_{b,p},y_{b,p})-f_b(x_{b,p},y_{b,p})\right\}^2}\\
&=10\log_{10}\frac{X_BY_Ba^2}{\sum_{p=1}^{P_b}\{\mathrm{sgn}(w_b)\,e_{b,p}\}^2}\\
&=10\log_{10}\frac{X_BY_Ba^2}{\sum_{p=1}^{P_b}e_{b,p}^2}\\
&=10\log_{10}\left(X_BY_Ba^2/\varepsilon^2\right)\ [\mathrm{dB}]
\end{aligned}
\tag{21}
$$

from Eqs. (14) and (20). Since the quality of every block is set to the PSNR of $R$ [dB] in the proposed method, the PSNR of a whole watermarked image is given as

$$
\begin{aligned}
\mathrm{PSNR}&=10\log_{10}\frac{\sum_{x=1}^{X}\sum_{y=1}^{Y} a^2}{\sum_{x=1}^{X}\sum_{y=1}^{Y}\left\{\hat{f}(x,y)-f(x,y)\right\}^2}\\
&=10\log_{10}\frac{\sum_{b=1}^{B}\sum_{x=1}^{X_B}\sum_{y=1}^{Y_B} a^2}{\sum_{b=1}^{B}\sum_{x=1}^{X_B}\sum_{y=1}^{Y_B}\left\{\hat{f}_b(x,y)-f_b(x,y)\right\}^2}\\
&=10\log_{10}\frac{\sum_{b=1}^{B}X_BY_Ba^2}{\sum_{b=1}^{B}\varepsilon^2}\\
&=10\log_{10}\left(X_BY_Ba^2/\varepsilon^2\right)=\mathrm{PSNR}_b\ [\mathrm{dB}]
\end{aligned}
\tag{22}
$$

from Eq. (21). Because $X_B$, $Y_B$, and $a$ in Eq. (22) are constant, PSNR in Eq. (22) depends on $\varepsilon^2$ that is independent from original image $\mathbf{f}$. Therefore, if $\varepsilon^2$ be constant, a watermarked image for any images is an image with the PSNR of $R$ [dB]. In contrast, if PSNR of $R$ [dB] is given, the restrictions on the pair, shown as Eqs. (11) and (14), are derived from Eq. (22).

Moreover, this proposed method generates an image of the exact desired quality. Equation (15) indicates a luminance value of every pixel in watermarked images is an integer, and Eq. (19) indicates that a luminance value of every pixel in watermarked images is between zero and $a$. Therefore, watermarked image $\hat{f}$ is an image with the exact desired quality, so it is concluded that the proposed method satisfies Req 1 exactly.

### 3.3 Generation of High-Quality Images

It is described that the proposed method satisfies Req 2.

To generate a highest-quality image, let $P_b = 1$ and $e_{b,1} = 1$; i.e., 1 (or $-1$) is added to the luminance value of one pixel in one block, then $\varepsilon^2 = 1$ from Eq. (14). Under the conditions that one block consists of $8 \times 8$ pixels in an eight-bit quantized image, i.e., $X_B = Y_B = 8, a = 255$, the the PSNR of a watermarked image is

$$
\mathrm{PSNR} = 10\log_{10}\frac{8\times 8\times 255^2}{1^2} \approx 66\ [\mathrm{dB}] \tag{23}
$$

from Eq. (22). Thus, it is clear that the proposed method satisfies Req 2.

### 3.4 Tolerance to JPEG Lossy Compression

For describing that Req 3 is satisfied in the proposed method, the corresponding algorithm of the proposed method is studied in the DCT domain here.

The corresponding algorithm in the DCT domain embeds an element of a watermark sequence into both the dc component and ac comopnents in order to get the desired image quality, while conventional methods modify one coefficient in a block. This embedding and a consideration for the finite word-length of a luminance value, this proposed method provides JPEG tolerance as shown in Sect. 4. It is thus concluded that the proposed method satisfies Req 3.

Moreover, the proposed method implements the embedding algorithm in the spatial domain, so no transformation process is required. Thus, neither an extra computation is required for embedding a watermark nor an effect caused by the finite word-length occurs.

### 3.5 Extraction Algorithm

The proposed method extracts a watermark by using the following algorithm. It requires the dc value of the $b$-th block in an original image, $v_b$, and the scaling factor for the $b$-th block, $\beta_b$ as shown in the algorithm. For simplicity, it is assumed that the target image is watermarked image $\hat{\mathbf{f}}$ in the following.

**Ext 1.** Divide target image $\hat{\mathbf{f}}$ into blocks, where each consist of $X_B \times Y_B$ pixels. The $b$-th block is represented by $\hat{\mathbf{f}}_b$, and $1 \leq b \leq XY/X_BY_B$. Set $b := 1$.

$$\left(\hat{\mathbf{f}}_1, \hat{\mathbf{f}}_2, \ldots, \hat{\mathbf{f}}_b, \ldots, \hat{\mathbf{f}}_{XY/X_BY_B}\right), \tag{24}$$

$$\hat{\mathbf{f}} = \left[\hat{f}_b(x,y)\right], 1 \leq x \leq X_B, 1 \leq y \leq Y_B. \tag{25}$$

**Ext 2.** Calculate the difference between the dc value, i.e., the sum of a luminance value of pixels, of $\hat{\mathbf{f}}_b$ and that of the corresponding block in the original image, $\mathbf{f}_b$ as follows:

$$\begin{aligned} d_b &= v_b - \hat{v}_b \\ &= \sum_{x=1}^{X_B}\sum_{y=1}^{Y_B} \hat{f}_b(x,y) - \sum_{x=1}^{X_B}\sum_{y=1}^{Y_B} f_b(x,y) \\ &= \sum_{x=1}^{X_B}\sum_{y=1}^{Y_B}\left\{\hat{f}_b(x,y) - f_b(x,y)\right\} \\ &= \sum_{p=1}^{P_b}\left\{\hat{f}_b(x_{b,p}, y_{b,p}) - f_b(x_{b,p}, y_{b,p})\right\} \\ &= \sum_{p=1}^{P_b} \mathrm{sgn}(w_b)\, e_{b,p} \\ &= \mathrm{sgn}(w_b) \sum_{p=1}^{P_b} e_{b,p}, \end{aligned} \tag{26}$$

from Eq. (20), where $v_b$ and $\hat{v}_b$ denote the dc value of $\mathbf{f}_b$ and that of $\hat{\mathbf{f}}_b$, respectively. The difference between $\hat{v}_b$ and $v_b$ is represented by $d_b$. It should be noted that $v_b$ is required in this step but $\mathbf{f}_b$ is not.

**Ext 3.** The $b$-th element of the embedded watermark sequence, $w_b$, is obtained by dividing $d_b$ calculated in Ext 2 by $\beta_b$ determined in Emb 6 as follows:

$$\begin{aligned} \frac{d_b}{\beta_b} &= \frac{\mathrm{sgn}(w_b) \sum_{p=1}^{P_b} e_{b,p}}{\frac{\sum_{p=1}^{P_b} e_{b,p}}{|w_b|}} \\ &= \mathrm{sgn}(w_b)\,|w_b| \\ &= w_b, \end{aligned} \tag{27}$$

from Eqs. (17) and (26).

**Ext 4.** Set $b := b + 1$ and repeat by going to Ext 2 until $b = B$.

**Ext 5.** All extracted elements are gathered to form extracted watermark sequence $\mathbf{w}$.

**Ext 6.** Search for $\mathbf{w}^*$ that maximizes the similarity between extracted watermark $\mathbf{w}$ and $\mathbf{w}_m \in W$, i.e.,

$$\mathbf{w}^* = \arg \max_{\mathbf{w}_m \in W} \mathrm{sim}(\mathbf{w}_m, \mathbf{w}), \tag{28}$$

$$\mathrm{sim}(\mathbf{w}_m, \mathbf{w}) = \frac{\mathbf{w}_m \cdot \mathbf{w}}{\sqrt{\mathbf{w} \cdot \mathbf{w}}}. \tag{29}$$

**Ext 7.** Demodulate data accordingly to $\mathbf{w}^*$.

## 4. Performance Evaluation

### 4.1 Common Evaluation Conditions

Six gray-scale images referred to as 'GIRL,' 'COUPLE,' 'MOON SURFACE,' 'AERIAL,' 'FACS DATA,' and 'PLANT-1' are selected from Standard Image Database (SIDBA) for evaluation. Each image consists of $256 \times 256$ pixels and has 256 levels from zero to 255. The image is divided into blocks so that each block consists of $8 \times 8$ pixels; thus, the image has 1024 blocks.

The length of each watermark sequence is set to 1024. Therefore, an element of a watermark sequence is embedded into each block of the image. 1024 randomly generated watermark sequences, of which only one matches the sequence embedded in the image, are prepared. Those conditions are concluded in Table 1 by using variables.

Performances are indicated by the CC-to-AC ratio (CAR) defined as

$$\mathrm{CAR} = \max(\mathrm{CC})\,/\mathrm{AC}, \tag{30}$$

$$\mathrm{AC} = \mathrm{sim}(\mathbf{w}_i, \mathbf{w}_i), 1 \leq i \leq M, \tag{31}$$

$$\mathrm{CC} = \mathrm{sim}(\mathbf{w}_i, \mathbf{w}_j), i \neq j, 1 \leq i, j \leq M, \tag{32}$$

i.e., AC and CC denote auto-correlation and cross-correlations. Therefore, the CAR represents the difficulty of identifying the extracted watermark from a

**Table 1** Common evaluation conditions by using variables.

| | | |
|---|---|---|
| Dynamic range of the image | $a$ | 255 |
| Horizontal size of the image | $X$ | 256 |
| Vertical size of the image | $Y$ | 256 |
| Horizontal size of blocks | $X_B$ | 8 |
| Vertical size of blocks | $Y_B$ | 8 |
| The number of blocks | $B$ | 1024 |
| The length of watermark sequence | $L$ | 1024 |
| The number of watermark sequence | $M$ | 1024 |

**Table 2** Generation of images with the exact desired quality.

| Target PSNR [dB] | Avg.((the actual PSNR) - (the target PSNR)) | | |
|---|---|---|---|
| | Proposed | Conv., ac | Conv., dc |
| 42.1102 | 0 | −0.4736 | 0.0227 |
| 48.1308 | 0 | 0.5235 | 0 |
| 49.9601 | 0 | −0.3144 | N/A |
| 56.1926 | 0 | −2.5662 | N/A |
| 57.1617 | 0 | 5.0236 | N/A |
| 59.2029 | 0 | 7.1904 | N/A |
| 60.1720 | 0 | N/A | N/A |
| 66.1926 | 0 | N/A | N/A |

**Table 3** High PSNR capability.

| Target PSNR [dB] | Average CAR | | |
|---|---|---|---|
| | Proposed | Conv., ac | Conv., dc |
| 42.1102 | 0.0991 | 0.0944 | 0.1043 |
| 48.1308 | 0.0936 | 0.0942 | 0.1041 |
| 49.9601 | 0.0946 | 0.0945 | N/A |
| 56.1926 | 0.0946 | 0.1032 | N/A |
| 57.1617 | 0.0946 | 0.2604 | N/A |
| 59.2029 | 0.0946 | 0.2536 | N/A |
| 60.1720 | 0.0946 | N/A | N/A |
| 66.1926 | 0.0946 | N/A | N/A |

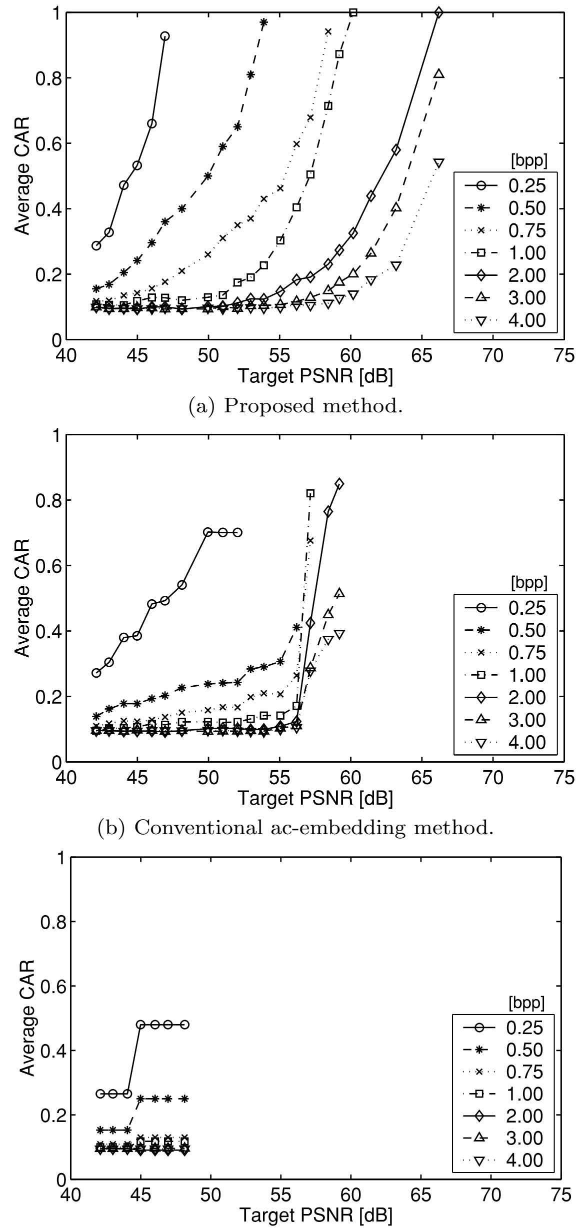
set of watermark sequences. From its definition, if the CAR is greater than or equal to zero, but less than one, the extracted watermark is correctly identified from a set of watermark sequences in an assumption that all images carry a watermark sequence in this paper.

### 4.2 Generation of Images with the Exact Desired Quality

The ability to precisely generate watermarked images of the desired quality is evaluated and the results are listed in Table 2. “N/A” is indicated for the impossible PSNR’s. The image qualities in the conventional block-based methods [7], [8], in particular, in the conventional ac-embedding [7], fluctuate, because of the effect of the finite word-length. Even the conventional dc-embedding [8], which is better than the conventional ac-embedding for generating images of the desired quality, cannot generate images of the exact desired quality. However, it is clear that the actual quality of the watermarked image is exactly identical to the target quality in the proposed method.

### 4.3 High PSNR Capability

Table 3 shows that the high PSNR capability of the proposed method and conventional block-based methods. Only both the quantization errors and luminance-range limitation are considered in this capability evaluation. CAR’s are listed for the actually achieved PSNR, and “N/A” is indicated for the impossible PSNR’s. Whereas the proposed method generates a high-quality images, such as PSNR of 66 [dB], the conventional methods have a limited attainable PSNR. It is clear that the limit of the achievable PSNR by the conventional ac-embedding is 59 [dB]. In addition, Table 3 shows that the conventional dc-embedding method has a limited attainable PSNR, 48 [dB], that corresponds to the theoretical one given by Eq. (10).




(a) Proposed method.

(b) Conventional ac-embedding method.

(c) Conventional dc-embedding method.

**Fig. 2** JPEG tolerance versus the target quality of a watermarked image in the case of (a) the proposed method, (b) conventional ac-embedding method, and (c) conventional dc-embedding method.

### 4.4 JPEG Tolerance

JPEG tolerance versus the target PSNR of a watermarked image generated by the proposed method and by conventional block-based methods is plotted in Fig. 2. To realize results easily, results on condition

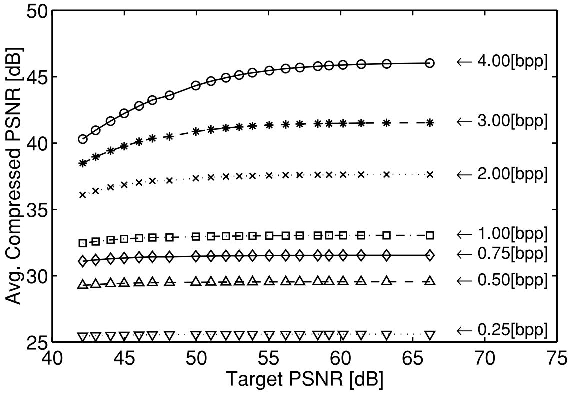



**Fig. 3** Quality of compressed image.

that correct extraction of watermark is done are plotted. The compression rate is represented by the bit per pixel (bpp). The qualities of compressed images by the proposed method are displayed in Fig. 3. Although it is generally known that embedding a watermark in the spatial domain is not robust [11], [12], compared to JPEG tolerance by the conventional methods, that by the proposed method is equal or superior in the case where the watermarked image quality is more than 56 [dB]. Furthermore, the proposed method still extracts embedded watermark correctly on condition that the quality of compressed image is degraded to 40 [dB], thus, it is concluded that the proposed method provides adequate JPEG tolerance for the target application, e.g., the inside material management at digital museum and digital broadcasting stations in the practical use.

## 5. Conclusions

A novel data embedding method allowing high and exact image-quality for any images has been proposed in this paper. To exactly generate watermarked images of the desired quality without trial and error, this method take into account the finite word-length of a luminance value of pixels. By employing spread spectrum technology and by embedding a watermark sequence into dc values, the proposed method keeps image quality high and, simultaneously, provides adequate JPEG tolerance in practical use.

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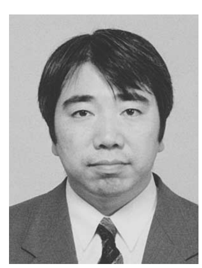

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